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Original Research Article

Wood Density Variation among Dominant Tree Species of *Comberetum-Terminalia* Woodland in Northwest Dryforests of Ethiopia

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ABSTRACT

Wood density is among the key variables in biomass and carbon stock estimation models. Hence, better understanding of wood density variations within and between species is critical for enhancement of forest biomass and carbon flux estimating models. This study examine the inter and intra species wood density (ρ) variations to reduce sources of uncertainty in biomass estimations of *Combretum-Terminalia* woodlands of Northwest Ethiopia. For the determination of stem and branch densities, destructive sampling of 101 trees of the selected nine dominant tree species were taken. Three diameters at breast height and branch diameter classes (5–10, 11–15, and > 16 cm) represented tree population between 5 and 65 cm. The mean ρ of the studied tree species ranges from 0.308 to 0.612g cm^{-3} . While the branch and stem wood density of mixed–species was estimated at 0.498 and 0.509g cm^{-3}, respectively. Despite the absence of general trends within a tree, ρ decreased with stem height and branch thickness. Statistically significant variation in ρ was observed among the selected tree species signifying the need for applying species specific ρ in biomass models. The stem had higher ρ than the branch suggesting ρ derived from the branch with a diameter of 11–15 cm explained 92.3% variability of stem ρ. Some wood densities adopted to our dataset overestimated the biomass of mixed–species, by 27.5 to 33.6%. However, the best ρ based on averaging technique can be reliable to assess biomass and carbon stock dynamics Combretum-Terminalia woodlands and comparable vegetation formation with considering validation. Yet applying species specific ρ is recommended for accurate biomass estimation models given the significant inter-species variation.

Keywords: *Combretum-Terminalia* woodland, wood density, biomass, destructive sampling, Allometric models

INTRODUCTION

Globally, Forest ecosystems are recognized for their significant roles in the terrestrial carbon cycle (Hurteau, 2021). Forests uptake about 296 Giga tone (Gt) of atmospheric carbon dioxide and store in their structures (FAO, 2015). Thus, forests secuster about one fourth of anthropogenic carbondioxide emissions (Hurteau, 2021) making these ecosystems significant contributor for climate change mitigation (Canadell and Raupach, 2008; Keenan and Williams, 2018). Hence, a reliable estimate of carbon stocks is essential for monitoring carbon accounting in environmental initiatives involving forest management and result-based payment for environmental services (Prisley and Mortimer, 2004; FAO, 2017;). Forest biomass estimation models often used allometric variables such as diameter and height which requires additional parameters such as tree densities for better accuracy (Sebrala, 2022).

Wood density is utilized as a correction factor for converting stem volume estimated by diameter and heaight (Feamside, 1997; Chave et al. 2014; Sebrala, 2022). Thus, this variable is a key component in biomass models explaining part of variation in mixed species models (Chave et al. 2014; Abich et al. 2021). As a key functional trait of forest tree species, density have a strong correlation with biomass and hence carbon stock (Swenson & Enquist, 2007; Stegen et al., 2009). Given this importance of wood density as a principal measure for wood physical properties has led to global wood density (GWD) database establishment for tropical tree species (Reyes et al., 1992; Chave et al. 2006). However, such databases are more generic that do not reflect the specific climatic and growing conditions that affect wood density. Consequently, investigation on species and site specific wood density of tree species and communities as well as their variations become imperative in biomass and carbon stock modelling of forest ecosystems (Flores and Coomes, 2011).

Despite their critical importance, information on the wood density of most tropical forest trees remains scanty (Clark and Kellner, 2012). This has led to the use of an alternative approach of applying averaging wood densities of other species belonging to the genus and family, or a community-wide average (Slik, 2006). Recent experiences commonly apply the average wood density of closely related species for unknown densities of tree species (Flores and Coomes, 2011). This is explained by the strong phylogenetic conservatism states that closely related species can have more similar wood density than distantly related species (Chave et al., 2006). However, biomass estimate using this approach may introduce uncertainty (Přemyslovská et al., 2007; Swenson and Enquist, 2007). Moreover, variability of environmental conditions across sites can result in significant wood density differences within a given species (Muller-landau, 2004; Patiño et al., 2009; Henry et al., 2010; Ubuy et al., 2018) and hence contributing to uncertainity in biomass estimate (Baker et al., 2004).

Density of tree species derived from averaging technique are less useful predictor in the biomass model (Lima et al. 2012) due to the potential uncertainty (Sileshi, 2014). Such technique of averaging wood densities can also be critical factor for landscape biomass estimation (Abich et al., 2022). Enhancing the accuracy of biomass and carbon stocks thus require determination of species–specific wood density (Abich et al., 2022).This has a lso contribution to enrich the Global Wood Density (GWD) database (Flores and Coomes, 2011).

Combretum-Terminalia woodland (CTW) distributed in vast areas of the Ethiopian dryland ecosystems play significant role in climate change mitigation and preventing the encrochment of the Saharan desert (Tesfaye and Negash, 2018; Amsalu et al., 2018; Abich et al., 2022). It harbors diverse tree species of ecologically and socioeconomically valuable (Eshete et al., 2005; Lemenih et al., 2007), including highly hunted timber species and Non-timber forest product yielding species (Abich et al., 2018). Nevertheless, knowledge on the woody species physical properties including wood density is scanty contributing to inconsistencies in biomass and carbon estimations in CTW (eg. Sisay et al., 2017; Tesfaye and Negash, 2018). The use of community-averaged wood density in biomass assessment is also cited as one of the challenge in national forest carbon accounting (MEFCC, 2017).

In Ethiopia, few studies examined the range of variations of wood density across species and sites but concentrated in the dry Afromontane biomes context (Ubuy et al., 2018; Asrat et al., 2020) which are not applicable for CTW due to their unique environmental conditions. Althought the relationship between components of trees and their corresponding wood density is determined, evident descripancies among studies are observed (Okai et al., 2003; Swenson and Enquist; 2008). This need for clarification to generate unbiased biomass estimates and improvement in the method of wood density determination. Moreover, uncertainty in Above-ground Biomass (AGB) estimates associated with choice of wood density is rarely assessed in most forests of Ethiopia. Thus, species-specific wood density are highly demanded and investigation of their effects in biomass estimations as compared with a commonly used generic values from data bases and average values of similar species and genus. Hence, this study examine wood density variations among and within the dominant tree species. Further it aims to investigate the effects of using species and site specific density and generic values on CTW biomass estimation.

MATERIALS AND METHODS

Study Area Description

The study was conducted in the dryforests of Metema district of West Gondar administrative zone in Northwest Ethiopia. Geographically, the area is situated between 12^{o}10'30''–13^{o}26''45'' N latitude and 35^{o}32'0''–36^{o}48'15'' E longitude (Figure 1). The terrain is characterized by undulating terrain and plane areas with an altitude range of 481 to 1667 masl (Eshete et al., 2011). The annual rainfall reaches to 1128 mm and the area is characterized by higher temperature with mean monthly minimum and maximum temperature recorded at 19.31^{0}C and 35.65^{0}C (Wale et al.,2012). Vertisols and Luvisols are dominant soil types in the study area (Haile & Moog, 2016) . Empirical studies revealed that the soil of study site is characterized by deeper and more clay soil with good fertility in terms of nutrients (Eshete et al., 2011).

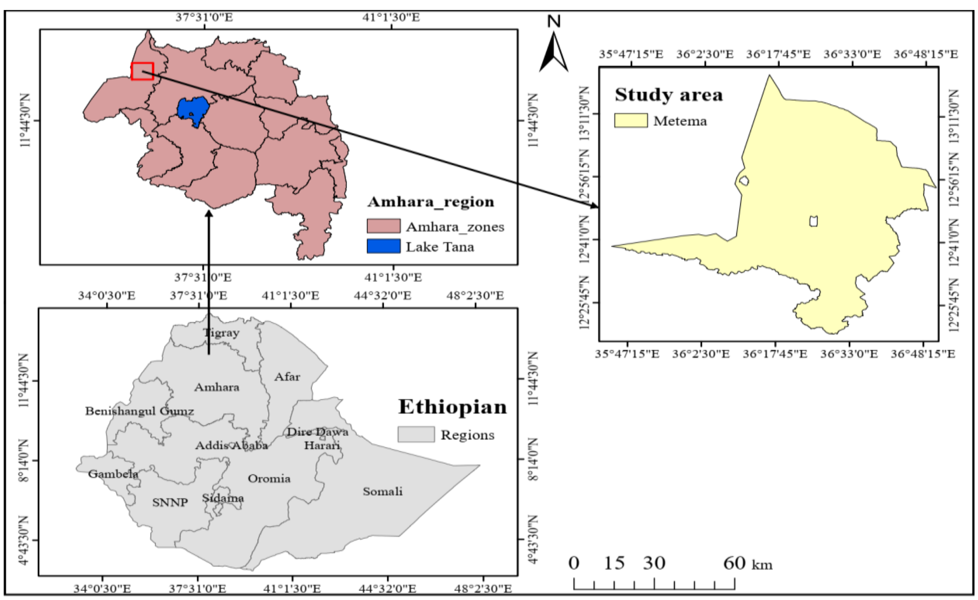

Figure 1: Map of the study area in Northwest Ethiopia.

Vegetation of the study area is classified as biome of Combretum-Terminalia woodland (Friis et al., 2010). It is characterized by small to moderate size woody plants with fairly large deciduous leaves. The woodlands are dominated by Combretaceae, Fabaceae, and Burseraceae families (Friis et al., 2010, Eshete et al., 2011, Wale et al., 2012).

Species selection

Different vegetation assessments indicated that the woodland in the specific stdy area comprised of 36-39 tree species (Eshete et al., 2011; Wale et al., 2012). Study by Eshete et al. (2011) reported that the mean abundance of the woodlands in the area ranges from 329 to 646 ha^{-1} and basal area of trees at a range of 7.6 to 16.4 m^2 ha^{-1}. Based on the previous vegeitation assessment and Importance Value Index (IVI) analysis (Eshete et al., 2011; Wale et al., 2012), the tree species were ranked in descending order as *Sterculea setigera, Boswellia papyrifera, Pterocarpus lucens, Lannea fruticosa, Anogeissus leiocarrpa, Terminalia laxiflora, Lanchocarpus laxifiora, Combretum molle, Combretum collinum* and *Combretum hartmannianum*. In addition, a rapid vegetation assessment was conducted in 9 plotes of 20 m x 30 m to verify the aforementioned IVI based ranking of the species. After the rapid verification, the top ranked nine tree species were considered for this particular wood density determinantion study.

Wood samples selection and measurement procedure

Age of the trees which can be measured by their diameters as a proxi indicator is one of the factors determining wood density (Ubuy et al., 2018). Diameter (D) of dominant tree species were grouped into seven classes based on Abich et al. (2021) as 5–10, 11–20, 21–30, 31–40, 41–50, 51–60, and 61–70 cm. The diameter class distribution was considered during the destructive sampling for proportional representation of the population (Roxburgh et al.,. 2015; Abich et al., 2021). Then, eight to thirteen trees were sampled from the selected tree species for harvesting by systematically distributing in each diameter class (Salis et al., 2006; Ngomanda et al., 2014). Accordingly, 101 individual trees were sampled and harvested for the wood density measurement of the tree components.

The sampled trees were harvested at a heights of 30 cm from the ground with a Chainsaw. Diameter at breast height (DBH), total height of standing trees before failing and total length of felled trees were measured. Felled trees were cross-cut and partitioned into stem and branch components. Further, the stem was partitioned into three parts following log diameter for latter examination of wood density variation alone tree heights. The first section of the stem (S1) was started from diameter at stump height (30 cm) to DBH. The second and third partitions of the stem were made based on personal judgment using log thickness variation towards stem height (Aosaar et al., 2011). Hence, the second section (S2) was started from D to a uniform shape was observed, whereas the third section (S3) was extended from the end (top) of the second section to top of the stem with a diameter of ≥ 5 cm. Then, following Basuki et al.(2009) and Aosaar et al. (2011) sample discs with bark were taken in the middle of each stem section. Branche samples were first grouped into three classes as >16 cm (C1), 11–15 cm (C2), and 5–10 cm (C3). In each class, a representative samples were considered where disc s were taken in the middle of each section.

The sampled discs were carefully transported to the laboratory of University of Gondar where their green volume and weight measured by weighing and measurement of the displaced water (cm^3). Then, the fresh weight of the discs measured in the field was converted to the corresponding green volume. All discs were labelled accordingly and dried under shed for six months. Subsequently, discs were oven-dried at 105°C for 24 hours until constant dry mass was observed. Finally, wood density (g/cm^3) of individual samples was calculated as the quotient of oven-dried mass of disc in gram and its corresponding green volume.

Data analyses

Two-ways Analysis of Variance (ANOVA) and mean comparisons (Tukey's method) were used for comparison of wood density differences within tree components (stem sections and branch classes). Difference in wood density among species was also analysed with ANOVA. Besides, a paired sample t-test was employed to compare the main stem and branch wood density. Then, regression analysis was used to estimate stem wood density from branch sections. Frequency distribution was also used to identify the most frequent wood density classes as an indication for average values for mixed species of the specific biome (Reyes et al., 1992). Then, the effect of the using the computed wood density in the accuracy of wood biomass and carbon estimation was validated comparing with the commonly used wood density values.

$$\text{MAPE\%} = \frac{100}{n}\left(\sum_{i=1}^{n}\frac{|X_{io} - X_{ip}|}{X_{io}}\right) \quad \text{Eq. (1)}$$

$$\text{RMSE (kg)} = \sqrt{\sum_{i=1}^{n}\frac{(X_{io} - X_{ip})^2}{n}} \quad \text{Eq. (2)}$$

$$\text{MPE\%} = \left(\frac{\frac{\sum_{n=1}^{n}(X_{io} - X_{ip})}{n}}{\overline{X_{io}}}\right) * 100 \quad \text{Eq. (3)}$$

Where, MAPE, RMSE, MPE, Xio, Xip, and n are absolute mean prediction error, root mean square error, mean prediction error, observed biomass, predicted biomass, and number of sample trees, respectively

Validation of biomass estimated by the Wood density determined

Stem and branch volume of the sampled individual trees with diameter ≥ 5 cm was multiplied by its wood density to estimate biomass of each species. Then, the estimated biomass of the species was summed to calculate biomass of the mixed–species and considered as observed biomass. The applicability of wood density (ρ) derived from global database was then tested to measure its reliability in biomass estimates of Combretum-Terminalia woodlands. We adopted wood density of 0.5 g cm^{-3} (Reyes et al., 1992), 0.645 g cm^{-3} (Chave et al., 2006), and 0.612 g cm^{-3} (MEFCC, 2017). Then, the volume of both stem and branch of individual trees was multiplied by those wood densities to estimate biomass of each species and the mixed-species. Then, the effects of wood density choice on biomass estimate of the species and mixed-species were measured against the observed biomass. Variation of biomass estimated based on the measured wood density and global data bases was validated based on mean absolute prediction error (MAPE%), root mean square error (RMSE, in kg) (Chave et al., 2005; Basuki et al., 2009), and mean prediction error (MPE%).

RESULT

Wood densities of tree components

The measured stem and branch wood densities (ρ) of the nine dominant tree species in the Combretum-Terminalia woodland is presented in Table 1 and Appendix A. Wood density of the studied tree species of ranges from 0.308-0.612 g cm^{-3}. Generally, wood density decreased along the tree height associated with the proportion of juvenile woods. Wood density of stem section 3 (S_3) significantly differed from S_1 and S_2 ($p < 0.001$) for *Pterocarpus lucens*. Despite these, the variation in ρ between stem sections (along the height of tree) were insignificant for the remaining studied tree species.

Branch wood density of the studied tree species also decreased with branch thickness (Table 1, Anex A). For *Pterocarpus lucens*, the ρ of branch class 1 (C_1) significantly differed from C_2 and C_3 (P<001). However, ρ of branch did not reveal significant variations with diameter thickness for rest of the species. With the exception of *Boswellia papyrifera* and *Sterculia setigera*, where the ρ of stem was numerically higher than that of the branch but still statistically non-significant. Despite the absence of general trends, ρ significantly differed between stem sections and branch classes among all tree species. The ρ of stem S_1 was significantly higher than that of branch C_3 for *Pterocarpus lucens*, *Lanchocarpus laxifiora*, and *Combretum hartmannianum* ($p < 0.05$).

Table 1. Wood density (g cm-3) of tree components, statistical parameters.

Species and family	n	Wood density of tree components: Stem Average	Stem Std.dev	Branch Average	Branch Std. dev
Anogeissus leiocarpa (Combretaceae)	10	0.580	0.058	0.578	0.040
Boswellia papyrifera (Burseraceae)	10	0.366	0.039	0.372	0.030
Combretum harotomannianum (Combretaceae)	13	0.538	0.049	0.521	0.029
Combretum molle (Combretaceae)	13	0.612	0.037	0.589	0.054
Lanchocarpus laxifiora (Fabaceae)	12	0.520	0.026	0.495	0.023
Lannea fruticosa (Anacardiaceae)	12	0.445	0.030	0.426	0.073
Pterocarpus lucens (Fabaceae)	11	0.587	0.019	0.565	0.020
Sterculia setigera (Sterculiaceae)	8	0.308	0.048	0.319	0.044
Terminalia laxiflora (Combretaceae)	12	0.539	0.063	0.551	0.063
Mixed species	101	0.509	0.101	0.498	0.095

Variation of wood density among tree species

The detailed account of wood density measurement results of tree components is presented in Appendix B. Statistically significant variation was observed between tree species, with the mean ρ ranging from 0.308 for *Sterculea setigera* to 0.612 g cm^{-3} for *Combretum molle* (Table 1). The wood densities of *Boswellia papyrifera*, *Lannea fruticose*, and *Sterculea setigera* significantly ($p < 0.0001$) differed from the rest of the tree species. Then, the tree species were clustered into five groups based on their proximate values of wood density. The first, second, and third clusteres contained single species with wood density of 0.308, 0.366, and 0.445 g cm^{-3}, respectively. Three tree species constitute the fourth and fifth groups with wood density of 0.520 to 0.539 g cm^{-3} and 0.579 to 0.612 g cm^{-3}, respectively. The measured wooddensity shows statistically significant difference between the cluseters (Figure 2). The groups are ordered with increasing wood density. Group 1, 2, and 3 represent *Sterculea setigera*, *Boswellia papyrifera*, and *Lannea fruticosa*, respectively. Group 3 consisting of *Combretum harotomannianum, Lanchocarpus laxifiora,* and *Terminalia laxiflora,* whereas group 5 containing *Anogeissus leiocarpa, Combretum molle,* and *Pterocarpus lucens.*

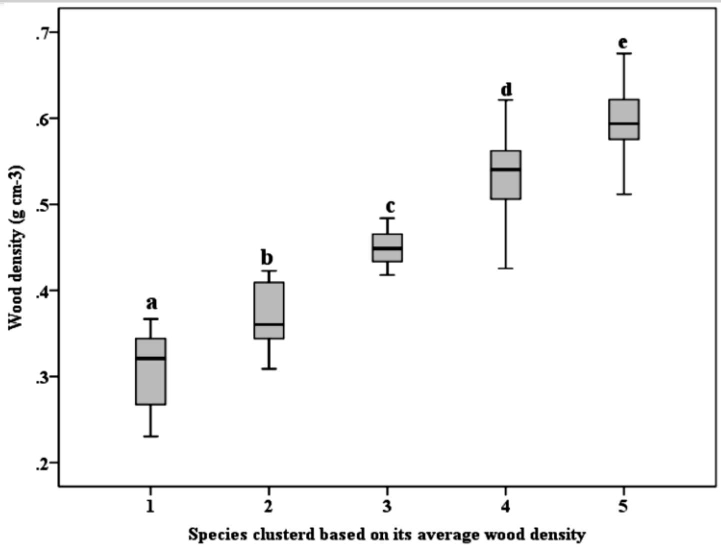

Figure 2. Comparison of average wood density (g cm^{-3}) between grouped species (95% confidence interval of the mean, the centre line is median; and the 75% (the upper box line) and 25% (lower box line) of the value of the data set is below line, whereas different letters indicate difference between the group ($p < 0.0001$).)

Figure 3 presents the summarized wood density result of the studied mixed tree species classified by frequency of occurrence of density classes. Most frequent wood densities in the samples ranged from 0.4 to 0.6 g cm^{-3} class, whereas 0.51 to 0.55 and 0.56 to 0.6 g cm^{-3} classes took the most dominant values in the data (Figure 3).

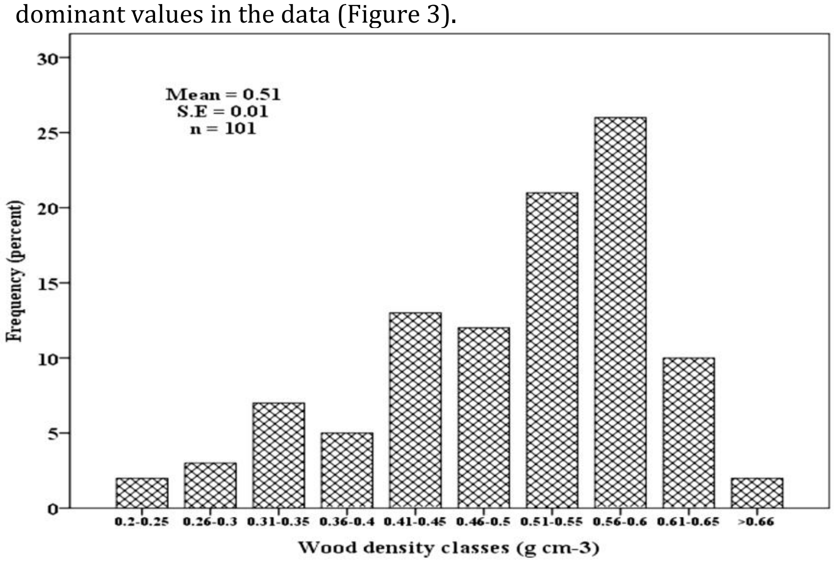

Figure 3. Frequency distribution of Combretum-Terminalia woodland species by wood density (g cm^{-3}) class in Northwest Ethiopia

For mixed species average wood density (mρ), a significant difference was not observed within stem sections and branch classes. The wood densities of stem sections S_1, S_2, and S_3 were 0.528, 0.512 and 0.487 g cm^{-3}, respectively. The ρ of branch sections C_1, C_2, and C_3 were 0.518, 0.509, and 0.483 g cm^{-3}, respectively (Table 1). The mean ρ of stem (0.509 g cm^{-3}) was significantly higher than that of branch (0.498g cm^{-3}). Then, the ρ of branch C_2 ($\hat{y}$), diameter class ranged from 10 to 15 cm, accurately explained

92.3% variability of mρ of the stem (Figure 4). Thus, the regression model was msρ = 0.960*ŷ + 0.026 (Adj. R^2 = 0.923).

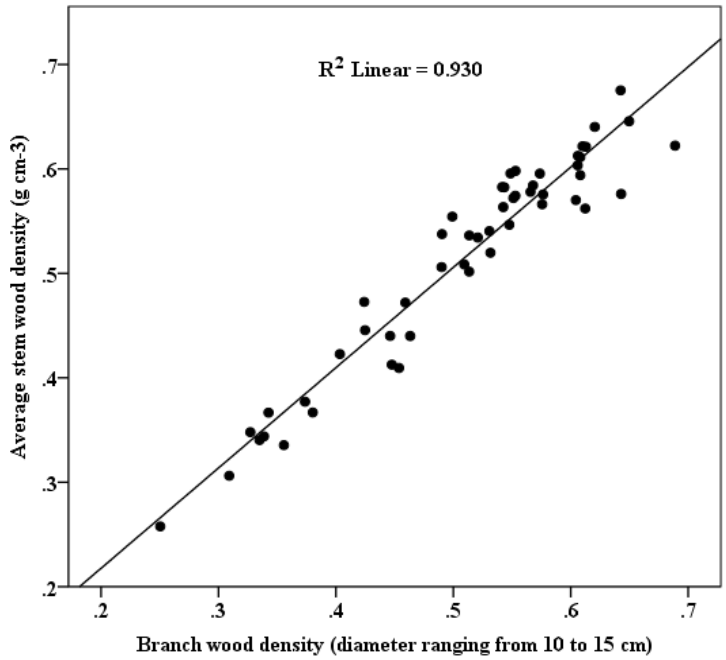

Figure 4. Linear regression of wood density (g cm^{-3}) of stems and branches (diameter ranged from 10 to 15 cm) of mixed–species in Combretum-Terminalia woodlands.

The effects of wood density choice on biomass estimation

In this study, the wood density was also grouped into family–based average wood density (F**ρ**). For mixed species, there was difference between observed and estimated biomass using Chave's (Chave et al., 2006) and Eth's ρ (MEFCC, 2017). However, the observed biomass did not significantly differ from biomass estimate based on Reyes's (Reyes et al., 1992) ρ, Gρ**,** and Fρ**.** Moreover, Gρ introduced lower values of MAPE (6.9%) and RMSE (31.3 kg) compared to others (Table 2).

Table 2: Comparison results of biomass estimates (kg/tree) based on wood density derived from this study and collated from literature.

		Statistical parameters						
				95% CI for Mean				
Wood density	Average biomass	Std. dev.	Std. Error	Lower Bound	Upper Bound	MAPE	RMSE	MPE
Oρ	214.8	304.8	30.3	154.7	275.0			
Fρ	224.3	344.8	34.3	156.3	292.4	13.8	98.5	-4.4
Gρ	205.8	286.3	28.5	149.3	262.3	6.9	31.3	4.2
Reyes's ρ	218.8	325.7	32.4	154.5	283.1	19.1	91.3	-1.8

Observed wood density (Oρ), family-based wood density (Fρ), grouped species wood density (Gρ), confidence interval (CI), Mean absolute prediction error (MAPE%), Root mean square error (RMSE, kg) and Mean prediction error (MPE%)

DISCUSSION

In the carbon flux assessments, wood density is one of the most important variable for converting forest volume to biomass (Feamside, 1997; Nogueira et al., 2007). In this study, the mixed–species wood density in CTW was estimated 0.509 g cm^{-3} which is lower than that of the generic values in global dat bases. Our estimate was consistent with the previous studies reported for the mixed-species of African vegetation (Reyes et al., 1992). In contrast, our estimate was lower than wood density of mixed–species reported for Amazonian forest (Feamside, 1997, Nogueira et al., 2007), Neotropical tree species (Chave et al., 2006), and Ethiopia (MEFCC, 2017). Similarly, the wood density of this study was lower than wood density reported for Ethiopian dry Afromontane forest (Ubuy et al., 2018). This may be explained by a difference in growing conditions between CTW and those forests as evident in previous studies (Yang et al., 2024). The result signifies the importance of using site and specific wood density values for landscape biomass estimations with better accuracy.

The significant variation in wood density observed between tree species of CTW indicate the presence of variation in anatomical features such as the proportions of vessel composition (Hacke et al., 2001; Worbes and Fichtler, 2010) between species. Similar to this study, variation in wood density between species was reported among tree species of tropical rain forest (Henry et al., 2010), Amazonian forest (Feamside, 1997), and African Savanna woodlands (Colgan et al., 2014). The difference in wood density may be associated with evolutional history including sapling and growth rate (Muller-landau, 2004) and tree size (Nogueira et al., 2007). It might also be attributed to anatomical wood features and genetic difference between species. It indicated that recognizing variations and utilization of species-specific wood density is crucial to enhance biomass estimation accuracy as compared with using genus level and global data base wood density values (Reyes et al., 1992; Feamside, 1997; Baker et al., 2004; Slik, 2006).

Despite the trends is inconsistent across the species that could be associated with the differences in the growth habits among species, wood density of stem gradually decreased as sampling height increases (along the height of tree) for all tree species. Higher wood density was measured at the lower part of the stem due to the highr composition of late and heart wood as confirmed by previous study (Wiemann and Williamson , 2014). This is due to the proportion of late and early woods in the lower section of the stems. The stem formation of juvenile and mature tree are altered to tipper form towards axial growth due to ageing process of cambial initials (Yang and Benson, 1997). This may be resulted from changes in the components of wood structure, including fine and short fibers, thin cell wall, and the occurrence of spiral grain, towards vertical position (Shmulsky and Jones, 2011). This inherent variability of anatomical features may contribute to 0.4–14.3% of relative differences in wood density along the height of trees. It was similar to study reporting that wood density at the base of the boles is 8–10% higher than at the top of the boles due to the higher proportion of late wood in the lower sections (Nogueira et al., 2007). Recognition of wood density variation along the height of the tree is essential for consideration of appropriate sampling as it accounted for sources of uncertainty in biomass estimate.

Associated with the differences in their wood structure, wood density was higher in stem than in branch. The presence of variation in wood structure between tree components is associated with the dominance of juvenile woods in the branches. It was consistent with previous study (Shmulsky and Jones, 2011). This difference in wood density may be associated with variation in vessels dimension, fibre contents, and porosity between stem and branches of trees (Wiedenhoeft, 2010; Worbes and Fichtler, 2010; Shmulsky and Jones, 2011). Result obtained here indicated that wood density of branch with a diameter thickness of 10 to 15 cm explained variation in stem ρ (Swenson and Enquist 2008). This result suggests the possibility of stem wood density derived from its branch in a lower destructive sampling procedures.

Wood density adopted in this study significantly overestimated biomass ($p<0.05$) of all species. This suggests that the use of community-wide wood density derived from the global database in biomass assessment produces bias estimate. Gρ and Fρ provided better biomass estimation but not consistent across the species. It appears that the technique of averaging wood density based on proximate wood density value or derived from family-wise averages is still critical.

For mixed-species biomass estimate, Gρ and Fρ produced accurate estimate with a lower value of MAPE and MPE. Similarly, the wood density of Reyes et al. (1992) introduced a lower uncertainty with MAPE and MPE of 19.1 and -1.8%, respectively. Our results suggest that Gρ and Fρ, and Reyes's ρ are important to predict landscape biomass of Combretum-Terminalia woodlands. However, wood densities of Chave et al. (2006) and MEFCC (2017) overestimated biomass of Combretum-Terminalia woodland by 33.6 and 27.5%, respectively.

CONCLUSION

The study provides baseline information on the wood density of tree species in dominant in the woodlands of Northwestern lowlands of Ethiopia. Wood density varied within trees across the tree components. Generally, wood density decreased along the height of the trees and branch thickness although statistically inconsistent patterns. Similarly, stem had higher wood density than branch, suggesting that components of trees are accounted for sources of variation in wood density. Understanding wood density variation within trees is thus crucial for accurate estimation of tree biomass. Wood density significantly varied between tree species, depicting the distinct ecological role and function of tree species. *Boswellia papyrifera*, *Lannea fruticose*, and *Sterculea setigera* had lower wood densities estimated at 0.366, 0.445, and 0.308 g cm^{-3}, respectively. For mixed-species, stem wood density also higher compared to branch density and therefore branch wood density, particularly diameter ranging from 10 to 15 cm, was the best predictor that explained greater than 92.3% variability of stem wood density. Thus, allometric models can be used to estimate stem wood density from branchs with diameter ranged from 10–15 cm thickness. The result showed that global wood density overestimated biomass of mixed–species by more than 27.5%, accounting for sources of uncertainty in carbon stock estimate within forests. However, the selected best wood densities in this study can be used for assessing biomass of Combretum-Terminalia woodlands and comparable vegetation formation.

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Authors' contributions: AA and AAA designed the study, AA collected the field data, both authors were involved in the data analysis and interpretation, AA prepared the first draft further enriched by AAA. AA and AAA reviewed and confirmed the final version of the manuscript

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REFERENCES

Abich, A., Alemu, A., Gebremariam, Y., Mucheye, T., Gurebiyaw, K., and Meseret, K. (2021). Allometric models for predicting aboveground biomass of Combretum-Terminalia woodlands in Amhara, Northwest Ethiopia. *Trees, Forests and People* [online], 5, 100122. Available from: https://doi.org/10.1016/j.tfp.2021.100122.

Abich, A., Alemu, A., Mucheye, T., Tebikew, M., and Gebremariam, Y. (2018). Woody species diversity, productivity and carbon stock potential of dry deciduous woodland in Alitash National Park, North West Ethiopia. *International Journal of Scientific Research and Management*, 06 (10): 80–98.

Abich, A., Negash, M., Alemu, A., and Gashaw, T. (2022). Aboveground Biomass Models in the Combretum-Terminalia Woodlands of Ethiopia: Testing Species and Site Variation Effects. *land*, 11 (811): 1–23.

Aosaar, J., Varik, M., Lõhmus, K., and Uri, V. (2011). Stemwood Density in Young Grey Alder (Alnus incana (L.) Moench) and Hybrid Alder (Alnus hybrida A . Br.) Stands Growing on Abandoned Agricultural Land. *Baltic Forestry*, 17 (2): 256–261.

Asrat, Z., Eid, T., Gobakken, T., and Negash, M. (2020). Modelling and quantifying tree biometric properties of dry Afromontane forests of south-central Ethiopia. *Trees* [online], 34 (6):1411–1426. Available from: https://doi.org/10.1007/s00468-020-02012-8.

Baker, T. R., Phillips, O. L., Malhi, Y., Almeida, S., Arroyo, L., Fiore, A. Di, Erwin, T. erry, Killeen, T. J., Laurance, S. G., Laurance, W. F., Lewis, S. L. ., Lloyd, J., Monteagudo, A., Neill, D. A., Patino, S., Pitman, N. C. A., Silva, M. N. ino, and Martinez, R. V. (2004). Variation in wood density determines spatial patterns in Amazonian forest biomass. *Global Change Biology*, 10: 545–562.

Basuki, T. M., Laake, P. E. Van, Skidmore, A. K., and Hussin, Y. A., (2009). Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. *Forest Ecology and Management*, 257: 1684–1694.

Canadell, J. G. and Raupach, M. R. (2008). Managing Forests for Climate Change Mitigation. *Science*, 320: 1456–1457.

Chave, J., Muller-Landau, H. C., Baker, T. R., Easdale, T. A., Steege, H., and Webb, C. O. (2006). Regional and phylogenetic variation of wood density across 2,456 neotropical tree species. *Ecological Applications*, 16: 2356 – 2367.

Chave, J., Rejou-Mechain, M., Burquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B. C., Duque, A., Eid, T., Fearnside, P. M., Goodman, R. C., Henry, M., Martinez-Yrizar, A., Mugasha, W. A., Landau, H. C. M.-, Mencuccini, M., Nelson, B. W., Ngomanda, A., Nogueira, E. M., Malavassi, E., Pelissier, R., Ploton, P., Ryan, C. M., Saldarriaga, J. G., and Vieilledent, G. (2014). Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, 20: 1–49.

Clark, D. B. and Kellner, J. R. (2012). Tropical forest biomass estimation and the fallacy of misplaced concreteness. *Journal of Vegetation Science*, 23: 1191–1196.

Colgan, M. S., Swemmer, T., and Asner, G. P., (2014). Structural relationships between form factor, wood density, and biomass in African savanna woodlands. *Trees*, 28 (1): 91–102.

Eshete, A., Sterck, F., and Bongers, F. (2011). Diversity and production of Ethiopian dry woodlands explained by climate- and soil-stress gradients. *Forest Ecology and Management* [online], 261 (9): 1499–1509. Available from: http://dx.doi.org/10.1016/j.foreco.2011.01.021.

Eshete, A., Teketay, D., and Hulten, H. (2005). The socio-economic importance and status of populations of Boswellia papyrifera (Del) Hochst. in Northern Ethiopia: The case of North

Gondar zone. *Forests , Trees and Livelihoods*, 15 (1): 55–74.

FAO. (2012). Global ecological zones for FAO forest reporting: 2010 update. Forest Resources Assessment Working Paper 179.

FAO. (2015). *Global Forest Resources Assessment 2015. Food and Agriculture Organization of the United Nations Rome, 2015, ISBN 978-92-5-108826-5, www.fao.org/forestry/fra*.

Feamside, P. M. 1997. Wood density for estimating forest biomass in Brazilian Amazonia. *Forest Ecology and Management*, 90: 59–87.

Flores, O. and Coomes, D. A. (2011). Estimating the wood density of species for carbon stock assessments. *Methods in Ecology and Evolution*, 2: 214–220.

Friis, I., Demissew, S., and van Breugel, P. (2010). *Atlas of the Potential Vegetation of Ethiopia. The Royal Danish Academy of Sciences and Letters*.

Hacke, U. G., Sperry, J. S., Pockman, W. T., Davis, S. D., and Mcculloh, K. A. (2001). Trends in wood density and structure are linked to prevention of xylem implosion by negative pressure. *Oecologia*, 126: 457–461.

Haile, A. L. and Moog, O. (2016). LARIMA. Deliverable 1.3: Top-down operative stream classification system (typology) for Ethiopian highlands.

Henry, M., Besnard, A., Asante, W. A., Eshun, J., Adu-bredu, S., Valentini, R., Bernoux, M., and Saint-andré, L. (2010). Wood density, phytomass variations within and among trees, and allometric equations in a tropical rainforest of Africa. *Forest Ecology and Management* [online], 260 (8): 1375–1388. Available from: http://dx.doi.org/10.1016/j.foreco.2010.07.040.

Hurteau, M.D. (2021). The role of forests in the carbon cycle and in climate change. In *Climate change* (pp. 561-579). Elsevier.

Keenan, T. F. and Williams, C. A. (2018). The Terrestrial Carbon Sink. *Annu. Rev. Environ. Resour*, 43: 219–43.

Lemenih, M., Feleke, S., and Tadesse, W. (2007). Constraints to smallholders production of frankincense in Metema district, North-western Ethiopia. *Journal of Arid Environments*, 71: 393–403.

Lima, A. J. N., Suwa, R., De Mello Ribeiro, G. H. P., Kajimoto, T., Dos Santos, J., Da Silva, R. P., De Souza, C. A. S., De Barros, P. C., Noguchi, H., Ishizuka, M., Higuchi, N., Henrique, G., Mello, P. De, Castro, P., Barros, D., Noguchi, H., Ishizuka, M., Higuchi, N., Kajimoto, T., Santos, J. dos, Silva, R. P. da, Souza, C. A. S. de, Barros, P. C. de, Noguchi, H., Ishizuka, M., and Higuch, N. (2012). Allometric models for estimating above-and below ground biomass in Amazonian forests at São Gabriel da Cachoeira in the upper Rio Negro, Brazil. *Forest Ecology and Management*, 277: 163–172.

MEFCC. (2017). Ethiopia's forest reference level submission to the United Nations Framework Convention on Climate Change (UNFCCC). Ministry of Environment Forest and Climate Change (MEFCC).

Muller-landau, H. C. (2004). Interspecific and Inter-site Variation in Wood Specific Gravity of Tropical Trees . *BIOTROPICA*, 36 (1): 20–32.

Ngomanda, A., Laurier, N., Obiang, E., Lebamba, J., Moundounga, Q., Gomat, H., Sidoine, G., Loumeto, J., Midoko, D., Kossi, F., Zinga, R., Henga, K., Bobé, B., Mikala, C., Nyangadouma, R., Lépengué, N., Mbatchi, B., and Picard, N. (2014). Site-specific versus pantropical allometric equations: Which option to estimate the biomass of a moist central African forest? *Forest Ecology and Management* [online], 312: 1–9. Available from: http://dx.doi.org/10.1016/j.foreco. 2013.10.029.

Nogueira, E. M., Fearnside, P. M., Nelson, B. W., and Franca, M. B. (2007). Wood density in forests of Brazil's' arc of deforestation': Implications for biomass and flux of carbon from land-use change in Amazonia. *Forest Ecology and Management*, 248: 119–135.

Okai, R., Frimpong-Mensah, K., and Yeboah, D. (2003). Characterization of moisture content and specific gravity of branchwood and stemwood of Aningeria robusta and Terminalia ivorensis. *Holz als Roh- und Werkstoff*, 61: 155–158.

Patiño, S., Lloyd, J., Paiva, R., Baker, T. R., Quesada, C. A., Mercado, L. M., Schmerler, J., Schwarz, M., Santos, A. J. B., Aguilar, A., Czimczik, C. I., Gallo, J., Horna, V., Hoyos, E. J., Jimenez, E. M., Palomino, W., Peacock, J., Peña-Cruz, A., Sarmiento, C., Sota, A., Turriago, J. D., Villanueva, B., Vitzthum, P., Alvarez, E., Arroyo, L., Baraloto, C., Bonal, D., Chave, J., Costa, A. C. L., Herrera, R., Higuchi, N., Killeen, T., Leal, E., Luizão, F., Meir, P., Monteagudo, A., Neil, D., Núñez-Vargas, P., Peñuela, M. C., Pitman, N., Priante Filho, N., Prieto, A., Panfil, S. N., Rudas, A., Salomão, R., Silva, N., Silveira, M., Soares deAlmeida, S., Torres-Lezama, A., Vásquez-Martínez, R., Vieira, I., Malhi, Y., and Phillips, O. L.,(2009). Branch xylem density variations across the Amazon Basin. *Biogeosciences* [online], 6(4): 545–568. Available from: https://bg.copernicus.org/articles /6/545/2009/ [Accessed 31 Jul 2021].

Přemyslovská, E. P., Lezingerová, J. Š., Ybníček, M. R., Ryc, V. G., Avrčík, H. V, and Raus, L. P. (2007). Basic density of wood in different forest type. *In*: Střelcová, K., Škvarenina, J., and Blaženec, M., eds. *"BIOCLIMATOLOGY AND NATURAL HAZARDS" International Scientific Conference, Poľana nad Detvou, Slovakia, September 17 - 20, 2007, ISBN 978-80-228-17-60-8*.

Prisley, S. P. and Mortimer, M. J. (2004). A synthesis of literature on evaluation of models for policy applications , with implications for forest carbon accounting. *Forest Ecology and Management*, 198: 89–103.

Reyes, G., Brown, S., Chapman, J., and Lugo, A. E. (1992). Wood densities of tropical tree species. Gen. Tech. Rep. SO-89 New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 15P.

Roxburgh, S. H., Paul, K. I., Clifford, D., England, J. R., and Paison, R. J. (2015). Guidelines for constructing allometric models for the prediction of woody biomass: How many individuals to harvest? *Ecosphere*, 6(3): 1–27.

Salis, S. M., Assis, M. A., Mattos, P. P., and Pião, A. C. S. (2006). Estimating the aboveground biomass and wood volume of savanna woodlands in Brazil's Pantanal wetlands based on allometric correlations. *Forest Ecology and Management*, 228 (1–3), 61–68.

Sebrala, H., Abich, A., Negash, M., Asrat, Z. and Lojka, B. (2022). Tree allometric equations for estimating biomass and volume of Ethiopian forests and establishing a database. *Trees, Forests and People*, *9*, p.100314.

Shmulsky, R. and Jones, P. D. (2011). *Forest Products and Wood Science: An Introduction, Sixth Edition*. John Wiley & Sons, Inc.

Sileshi, G. W. (2014). A critical review of forest biomass estimation models, common mistakes and corrective measures. *Forest Ecology and Management* [online], 329: 237–254. Available from: http://dx.doi.org/10.1016/j.foreco.2014.06.026.

Sisay, K., Thurnher, C., Belay, B., Lindner, G., and Hasenauer, H. (2017). Volume and carbon estimates for the forest area of the Amhara region in northwestern Ethiopia. *Forests*, 8 (4).

Slik, J. W. F. (2006). Estimating species-specific wood density from the genus average in Indonesian trees. *Journal of Tropical ecology*, 22: 481–482.

Stegen, J. C., Swenson, N. G., Valencia, R., Enquist, B. J., and Thompson, J. (2009). Above-ground forest biomass is not consistently related to wood density in tropical forests. *Global Ecology and Biogeography*, 1–9.

Swenson, N. G. and Enquist, B. J. (2007). Ecological and evolutionary determinants of key plant functional trait: Wood density and its community-wide variation across latitude and elevation. *American Journal of Botany*, 94 (3): 451–459.

Swenson, N. G. and Enquist, B. J. (2008). The relationship between stem and branch wood specific gravity and the ability of each measure to predict leaf area. *American Journal of Botany*, 95 (4): 516–519.

Tesfaye, M. and Negash, M. (2018). Combretum-Terminalia vegetation accumulates more carbon stocks in the soil than the biomass along the elevation ranges of dryland ecosystem in Southern Ethiopia. *Journal of Arid Environments* [online], 155: 59–64. Available from: https://doi.org/10.1016/j.jaridenv.2018.02.004.

Ubuy, M. H., Eid, T., and Martin, O. (2018). Variation in wood basic density within and between tree species and site conditions of exclosures in Tigray , northern Ethiopia. *Trees* [online], 32:, 967–983. Available from: http://dx.doi.org/10.1007/s00468-018-1689-9.

Wale, H., Bekele, T., and Dalle, G. (2012). Floristic diversity, regeneration status, and vegetation structure of woodlands in Metema Area, Amhara National Regional State, North- western Ethiopia. *Journal of Forestry Research*, 23 (3): 391–398.

White, F. (1983). *The vegetation of Africa. A descriptive memoir to accompany the Unesco AETFAT/UNSO vegetation map of Africa*.

Wiedenhoeft, A. (2010). Chapter 3 Structure and Function of Wood. *In*: *Forest Products Laboratory. 2010. Wood handbook—Wood as an engineering material. General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.508 p.*

Wiemann, M. C. and Williamson, G. B. (2014). Wood Specific Gravity Variation with Height and Its Implications for Biomass Estimation. Research Paper FPL-RP-677. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 9: 1–12.

Worbes, M. and Fichtler, E. (2010). Wood Anatomy and Tree-Ring Structure and Their Importance for Tropical Dendrochronology. *In*: *W.J. Junk et al. (eds.), Amazonian Floodplain Forests: Ecophysiology, Biodiversity and Sustainable Management, Ecological Studies 210:* 330–345.

Yang, H., Wang, S., Son, R., Lee, H., Benson, V., Zhang, W., Zhang, Y., Zhang, Y., Kattge, J., Boenisch, G., Schepaschenko, D., Karaszewski, Z., Stereńczak, K., Martínez, Á. M.-, Nabais, C., Birnbaum, P., Vieilledent, G., Weber, U., and Carvalhais, N. (2024). Global patterns of tree wood density. *Global Change Biology*, 30, e17224.

Yang, K. C. and Benson, C. A. (1997). Formation, distribution and its criteria for determining the juvenile-mature wood transition zone. *In*: *Proceedings of the CTIA/IUFRO International Wood Quality Workshop, August 18–22, Quebec, QC, IX–7*.