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ESTIMATING ABOVE GROUND BIOMASS IN PENAJAM PASER UTARA REGENCY, EAST KALIMANTAN: A NOVEL AND EFFECTIVE METHOD

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Estimating aboveground biomass (AGB) is important for understanding carbon sequestration. Allometric equations, primarily based on tree diameter and height, are widely used for biomass estimation, are used to offer precise evaluation of aboveground biomass across diverse landscapes in Kalimantan. It is necessary to conduct a rapid assessment of AGB which is cost effective and use non-destructive methods. Therefore, the aim of this study is to develop an allometric equation for estimating aboveground biomass in various landscapes in East Kalimantan, especially at Penajam Paser Utara Regency (PPU). This study examined four types of landscape: mixed gardens, plantation forests, secondary forests, and secondary mangrove forests. The diameter, height, and wood density measurements from 2066 trees (dbh ≥ 3.1 cm) across these landscapes were analysed. The AGB was calculated using 12 allometric models, both local and global. We later developed a new model suitable to study all landscape types, known as Model D^2H-1/H. The highest biomass was 254.73 Mg ha^{-1} for secondary lowland forest and 89.4 Mg ha^{-1} biomass for plantation forest. This research therefore, highlights the importance of fitted biomass estimation models for effective forest management in diverse landscapes.

Keywords: Allometric equation, forest management, New Model D^2H-1/H, fitted biomass estimation model

INTRODUCTION

Rising atmospheric CO_2 levels, driven by factors, such as pollution, deforestation, and fossil fuel combustion, are a major contributor to climate change (Pierrehumbert 2006, Nunes 2023). Tropical forests, covering approximately 12–15% of the earth's land area (Brandon 2014), are particularly noteworthy for their high biomass content (Karyati et al. 2023). Since the tropical biomass representing 50% of global biomass (Kindermann 2023), the accuracy of estimation on aboveground biomass (AGB) is crucial as an indicator of carbon resources and the potential for carbon sequestration in terrestrial ecosystems (Vasshum & Jayakumar 2012). The most widely used method for estimating forest biomass is the allometric equation. Holford and Anderson (2017) explained that allometric models are crucial for understanding dynamic ecosystems by estimating relationships between variables such as tree size and biomass. These models are essential for quantifying carbon storage, tailored to vegetation characteristics (Morel et al. 2011). In allometric equations tree diameter is commonly used since it is not only the main variable in collected data but also the easiest to measure, especially in tropical forest

(Chave et al. 2005). Most researchers measure only tree height (Feldpausch et al. 2012). The estimation of biomass entails destructive method and it is limited to small sized trees. It is also time consuming and impossible to be applied in large areas.

Estimating aboveground biomass (AGB) has been extensively developed across various landscapes. Walker (2016) and Karyati et al. (2019) mentioned that many developed allometric equations are site-specific. The data often rely on specific diameter ranges, which may lead to overestimation, especially in areas where sampling is inadequate. This limitation underscores the need for more comprehensive, location-specific sampling to ensure accurate biomass and carbon stock estimates. Brown (1997) proposed that different allometric models should be applied based on vegetation type and the availability of tree height data. Chave et al. (2005) further refined allometric equations to estimate biomass from tree diameter, wood density, and height. When total tree height is available, allometric models tend to produce more accurate biomass estimates. Basuki et al. (2009) developed allometric equation based on lowland dipterocarp forest data collected in East Kalimantan. They established the relationship among tree parameters, such as the diameter at breast height, height and wood density. Karyati et al. (2023) focused on developing the model for a 50-year-old secondary forest in East Kalimantan. This model used diameter and tree height to develop allometric equations. Ruslianto et al. (2019) developed allometric models only for species specific with diameter and height as the main parameter. However, tree height has often been overlooked in carbon accounting, as measuring it in closed-canopy forests presents significant challenges (Hunter et al. 2017, Larjavaara & Muller-Landau 2013). However, their applicability to diverse landscapes, such as those in East Kalimantan, remains limited. Therefore, to mitigate potential biases in biomass estimates, it is essential to carefully select allometric equations suited to the specific landscape under study.

East Kalimantan is one of the provinces in Kalimantan Island which represents the various landscapes both natural and artificial. Kalimantan, the second-largest island in Indonesia and the fourth largest globally, is known for its vast tropical forests and which play a crucial role in carbon absorption. In addition to its forests, Kalimantan features a variety of natural landscapes, including shrubs, mangroves, and peat swamp forests, which have significant carbon sequestration potential. Murdiyarso et al. (2009) showed that mangroves in Kalimantan can store an average of 968 Mg C ha^{-1}, with a range of 863–1073 Mg C ha^{-1}, while peat swamp forests can store an average of 894.3 Mg C ha^{-1}, ranging from 558 to 1213 Mg C ha^{-1}. Furthermore, Kalimantan's artificial landscapes, such as plantation forests, agricultural land, and mixed gardens around settlements, also contribute to carbon sequestration. Notably, mixed gardens in Kalimantan, which contain a diverse array of perennial trees, fruit trees, and shrubs, mimic the structure of natural forests and hold significant potential for carbon storage due to their high plant density and species diversity. Due to the diverse landscapes, it is necessary to conduct a rapid assessment of AGB (aboveground biomass) which is cost effective, and non-destructive. Therefore, the aim of this study is to develop an allometric equation for estimating aboveground biomass in various landscapes at Penajam Paser Utara Regency (PPU), East Kalimantan.

MATERIALS AND METHODS

Study areas

This research was conducted in East Kalimantan, especially at Penajam Paser Utara (PPU) Regency (Figure 1). It is located on 116° 19' 30"–116° 56' 35" East Longitude and 00° 48 '29"–01° 36' 37" South Latitude. Based on Regional Law No. 12/2022 on Planning of Industrial Development the land use in Penajam Paser Utara Regency has been divided as follows: forests (32.96%), plantation forests (17.11%), agricultural land (29.86%), bushes (8.77%), mangroves (8.71%) and other uses (2.59%). Studies have noted an annual decline in natural forest cover accompanied by an expansion in the area of plantations (Widjayatnika et al. 2017). In this research, the landscape chosen comprises a mixed garden (MG), plantation forest (PF), secondary lowland forest (SF), and secondary mangrove forest (SM). These four landscapes were selected because they are particularly

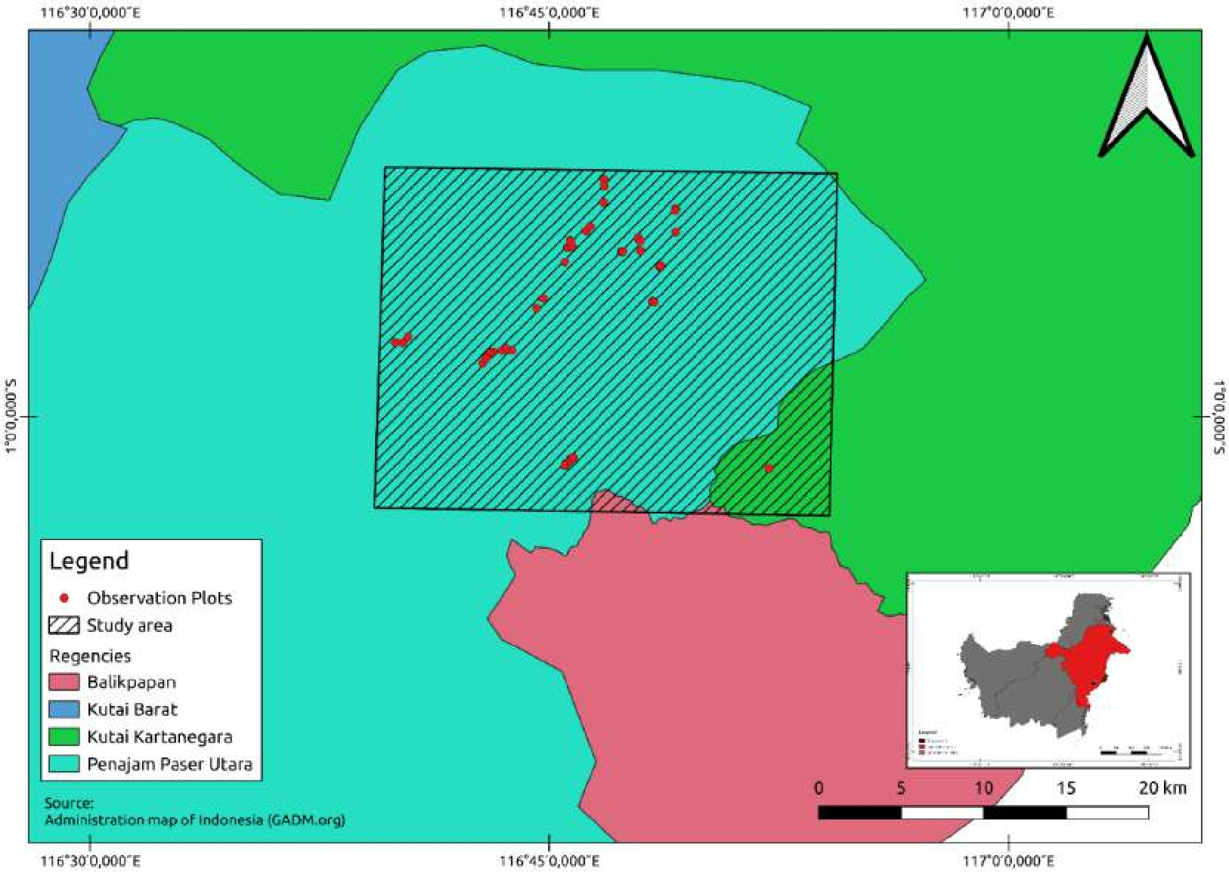

Figure 1 Study area in East Kalimantan (Most of plots are established in Penajam Paser Utara)

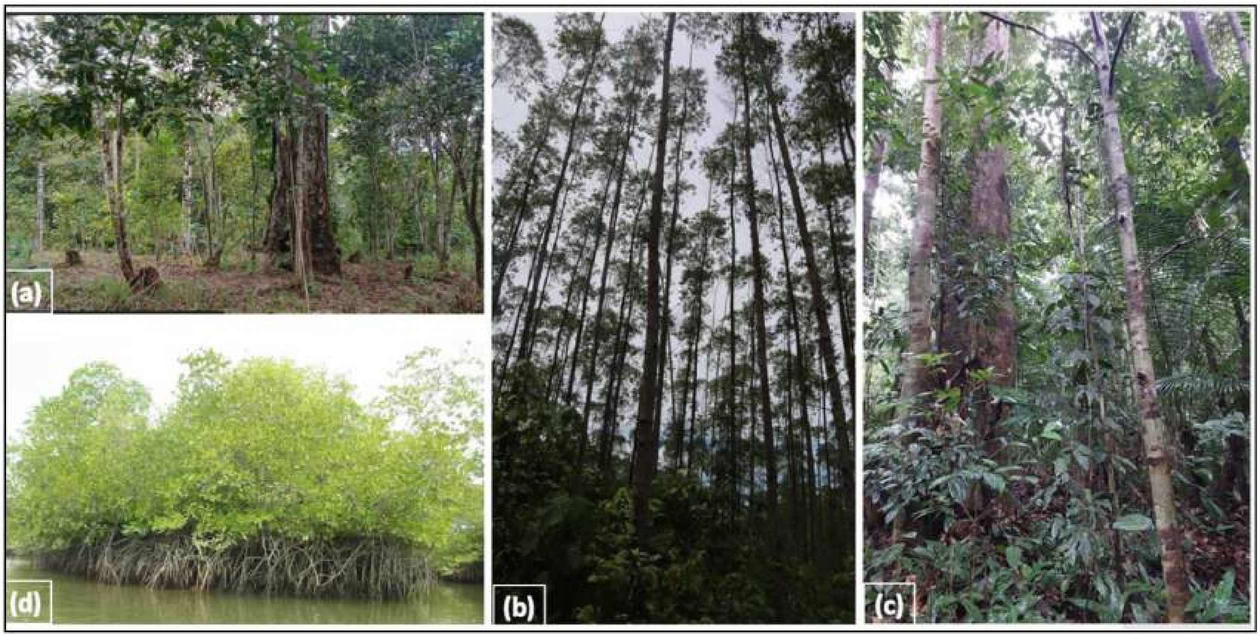

Figure 2 Vegetation cover conditions in each type of landscape: mixed garden (a), plantation forest (b), secondary lowland forest (c), and secondary mangrove forest (d)

sensitive to anthropogenic influences. In the study areas the dry season usually occurs from May through October while the rainy season occurs from November to April. Annual temperatures range from 21.3–32.7°C, average humidity 85% and precipitation ranges from 2,651–3,071 mm/year (Badan Pusat Statistik 2024).

The mixed gardens (MG) concept relates to gardens or yards owned by local communities, mostly planted with trees, such as *Aleurites moluccanus*, *Aquilaria* spp., *Vitex pinnata*, *Peronema canescens* and fruit-producing trees such as *Durio zibethinus*, *Parkia speciosa*, *Nephelium* sp. and *Dimocarpus longan*. Plantation forest (PF), on the other hand, comprises *Eucalyptus* sp., which were formerly industrial forest plantation areas. Secondary lowland forest (SF) represents a lowland mixed dipterocarp forest dominated by Dipterocarpaceae species, such as *Shorea laevis* and *Shorea rubra*, *Macaranga lowii* and *Madhuca kingiana*. The secondary mangrove forest (SM) consists of mangrove vegetation, which is dominated by young *Rhizophora apiculata* (Figure 2).

Data collection

We collected data from 26 plots, each with a size of 0.04 ha in mixed garden (MG), 9 plots with each size 0.04 ha in plantation forest (PF), 5 plots which each size 0.09 ha plots in secondary mangrove forest (SM), and 1 ha plot in secondary lowland forest (SF). There is variation in sampling areas due to differences in the total area of each landscape. The diameter at breast height (dbh) and total tree height (H) were measured on all individual trees with a minimum diameter of 3.18 cm.

Data Analysis

Biomass calculations were carried out using the aboveground biomass (AGB) equation based on stand volume (Brown 1997), shown in Equation (1), where AGB = aboveground biomass (kg), Vob = volume of the tree (m^3), Wd = wood density (kg m^{-3}), and BEF = Biomass Expansion Factor. Wood density was derived from 'BIOMASS' packages (Réjou-Méchain et al. 2017). The results from AGB_Vol are then assigned as the observed value.

The equation proposed by Brown (1997) was used because it is one of the earliest and most widely used equations, particularly relevant for regions similar to the study area. One of the data sources for this equation is from the tropics, specifically the Sarawak region of Borneo, which shares similar forest conditions in East Kalimantan. This equation allows for the calculation of total aboveground biomass using measurable stand volume, without the need for destructing sampling. However, it is important to note that variation in the results may occur depending on age of the tree and site-specific conditions.

The observed value (Equation 1) was then compared with the results of 12 developed allometric equations. We used four globally allometric equations (Equations 2–5) and eight locally known allometric equations (Equations 6–13). The 12 allometric equations are shown in Equation (2) to (13).Notes: Locality of the equation: 5–12 = Kalimantan, 13 = West Sulawesi, where AGB = aboveground biomass (kg), D = dbh (cm), H = tree height (m), and Wd = wood density (g cm^{-3}). The AGB values were obtained from these 12 allometric equations (assigned as predicted value) compared with AGB_Vol (assigned as observed value) using a linear regression model. The intercept should be around zero, the slope should be around one if the results between the observed and predicted values are similar (Manuri et al. 2016).

The 12 equations still required adjustment to achieve precise AGB values. A specific equation tailored for rapid assessment is needed. In this study, we developed a site-specific equation for the research location. In order to create this specific equation, we used a combination of datasets from each landscape type. The form of the equation that we tested is seen in Equations (14) to (19). These are based on the results of correlation and regression between each variable with the AGB_Vol value. Then

AGB_Vol (Brown 1997) $$AGB = Vob \times Wd \times BEF \qquad (1)$$

AGB_01 (Chave et al. 2014)	$AGB = 0.0673 \times (Wd \times H \times D^2)^{0.976}$	(2)
AGB_02 (Brown 1997)	$AGB = 42.69 - 12.8 \times D + 1.242 \times D^2$	(3)
AGB_03 (Brown 1997)	$AGB = exp(-2.134 + 2.53 \times lnD)$	(4)
AGB_04 (Chave et al. 2005)	$AGB = 0.0509 \times Wd \times D^2 \times H$	(5)
AGB_05 (Basuki et al. 2009)	$AGB = 0.318 \times D^{2.196}$	(6)
AGB_06 (Basuki et al. 2009)	$AGB = 0.4975 \times D^{2.188} \times Wd^{0.832}$	(7)
AGB_07 (Manuri et al. 2016)	$AGB = 0.125 \times D^{2.533}$	(8)
AGB_08 (Manuri et al. 2016)	$AGB = 0.068 \times D^{2.268} \times H^{0.483}$	(9)
AGB_09 (Manuri et al. 2016)	$AGB = 0.071 \times (D^2 \times Wd \times H)^{0.973}$	(10)
AGB_10 (Karyati et al. 2023)	$AGB = 53.279 \times (D^2 \times H)^{0.001}$	(11)
AGB_11 (Karyati et. al. 2023)	$AGB = 26.475 \times D^{0.055}$	(12)
AGB_12 (Ruslianto et al. 2019)	$AGB = 1.02 \times D^{0.949} \times H^{1.142}$	(13)

Notes: Locality of the equation: 5–12 = Kalimantan, 13 = West Sulawesi.

Model D^2	$ln(AGB) = a + b \times ln(D^2)$	(14)
Model DH	$ln(AGB) = a + b \times ln(D \times H)$	(15)
Model D^H	$ln(AGB) = a + b \times ln(D)^{ln(H)}$	(16)
Model D^2H-1/H	$ln(AGB) = a + b \times ln(D^2 \times H) + c \times \left(\frac{1}{ln(H)}\right)$	(17)
Model D-H	$ln(AGB) = a + b \times ln(D) + c \times ln(H)$	(18)
Model D^2-1/H	$ln(AGB) = a + b \times ln(D^2) + c \times \left(\frac{1}{ln(H)}\right)$	(19)

the equations were validated using Leave One-Out Cross Validation (LOOCV) from 'caret' packages (Kuhn 2008).

In order to determine the best equation, apart from the coefficient of determination (R^2), the statistical criteria, such as ratio performance to deviation (RPD), root mean square error (RMSE), and Akaike's information criterion-corrected (AICc) were used. The model was then classified into three different groups (Groups A, B and C) based on RPD value. The RPD value > 2.0 indicates that the equation is applicable (Group A), while for RPD value in the range of 1.4 to 2.0 is applicable with conditions (Group B) and the RPD value <1.4 is not applicable (Group C) (Chang et al. 2001). The AICc was chosen because the performance of this criterion is better when compared with AIC especially if the number of population is small (Manuri et al. 2016). The lower AICc value means that the performance of the equation is better compared with the others (Hurvich & Tsai 1989, Manuri et al. 2016). All statistical analysis and graphs were drawn using R version 4.3.2 with 'ggplot2' package version 3.4.4 (Wickham et al. 2016).

RESULTS

Forest stands characteristics

The observed landscapes were natural landscapes (SF and SM) and human-made landscapes (MG and PF). Each type of observed landscape has different forest stand characteristics. Generally, this study observed 2066 individual trees (Table 1), where the average tree diameter in SF and

Table 1 Characteristics of forest stands from different landscape types

	MG		PF		SF		SM	
	Diameter (cm)	Tree Height (m)	Diameter (cm)	Tree Height (m)	Diameter (cm)	Tree Height (m)	Diameter (cm)	Tree Height (m)
n	589		167		1144		385	
Minimum	3.1831	2.0	3.6000	4.0	4.7746	6.7	3.3104	4.5
Maximum	110.0000	35.0	22.4500	18.0	158.2637	52.0	39.2476	10.2
Mean	20.6783	8.6251	13.9202	10.9671	13.3701	13.5644	11.4675	6.4301
Std. Deviation	13.6034	3.7394	5.4368	3.7300	12.4616	6.7818	6.4167	0.8834

MG = mixed garden, PF = plantation forest, SF = secondary lowland forest, SM = secondary mangrove forest; n = number of samples

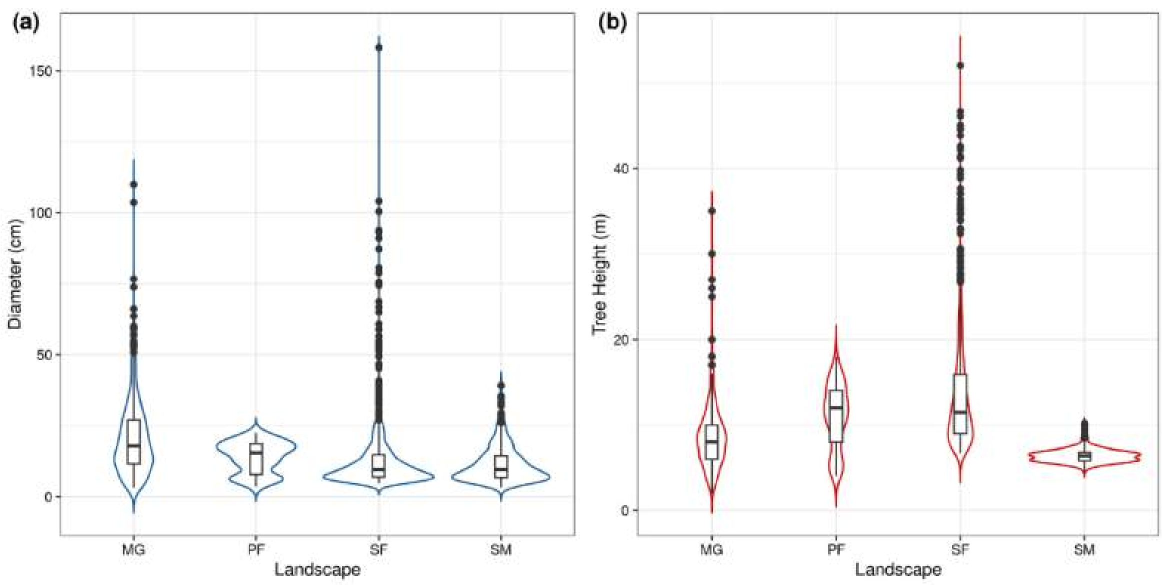

Figure 3 The range and distribution of variables across landscape types

SM was lower compared with MG and PF. Figure 3 shows that the range and distribution of variables across landscape types are diverse. The highest diameter (158.26 cm) and the largest number of individuals (1144) were found in SF. Tree heights vary across landscape types (Figure 3b), the largest variation can be found in SF, while PF relatively has an even height.

Screening of allometric equations

The AGB calculation results based on equation 1 suggest that the largest total AGB is SF (264.28 Mg ha^{-1}), followed by MG (133.19 Mg ha^{-1}), SM (122.54 Mg ha^{-1}) and PF (84.25 Mg ha^{-1}), respectively. The results from screening of allometric equations show that AGB_12 was performed as the equation that applies to MG, PF, SF, and SM landscape types (Table 2). When all datasets were combined into a single large dataset, the screening results also showed that the AGB_12 (Equation 13) could be applied to all types of landscapes found in the research area (Table 3). The estimation results using AGB_12 (Equation 13) show that the largest total AGB is SF (401.44 Mg ha^{-1}), followed by MG (140.99 Mg

Table 2 Summary of allometric equation screening for each landscape type

Equation	a	b	R^2	Adj.R^2	RPD	RMSE	AICc
Mixed garden (MG)							
AGB_01	180.6445	0.2829	0.6912	0.6907	1.8011	113.0945	7249.3780
AGB_02	146.8089	0.1641	0.7274	0.7269	1.9168	106.2673	7176.0277
AGB_03	166.5577	0.1383	0.6507	0.6501	1.6935	120.2788	7321.9287
AGB_04	184.6675	0.2768	0.6705	0.6699	1.7436	116.8266	7287.6237
AGB_05	142.0250	0.2372	0.7241	0.7236	1.9055	106.8994	7183.0142
AGB_06	140.2076	0.2826	0.7991	0.7988	2.2331	91.2159	6996.1140
AGB_07	166.7454	0.1291	0.6501	0.6495	1.6919	120.3954	7323.0704
AGB_08	164.0558	0.2053	0.7499	0.7495	2.0013	101.7828	7125.2366
AGB_09	180.1180	0.2784	0.6938	0.6933	1.8088	112.6138	7244.3597
AGB_10	-100487.9099	1875.9550	0.6498	0.6492	1.6912	120.4458	7323.5637
AGB_11	-4202.9769	143.4324	0.6318	0.6312	1.6494	123.4998	7353.0599
AGB_12	85.2582	0.6022	0.8787	0.8785	2.8735	70.8882	6699.1107
Plantation forest (PF)							
AGB_01	69.4214	1.3404	0.9498	0.9495	4.4779	20.2630	1486.9369
AGB_02	68.3119	0.7998	0.9416	0.9413	4.1517	21.8549	1512.1971
AGB_03	62.5442	1.0010	0.9526	0.9523	4.6057	19.7006	1477.5354
AGB_04	71.3783	1.4490	0.9454	0.9450	4.2917	21.1424	1501.1259
AGB_05	50.6781	1.0600	0.9673	0.9671	5.5503	16.3481	1415.2312
AGB_06	50.3568	1.2138	0.9676	0.9675	5.5765	16.2712	1413.6570
AGB_07	62.6391	0.9390	0.9524	0.9521	4.5985	19.7314	1478.0579
AGB_08	66.2117	1.0280	0.9556	0.9554	4.7624	19.0524	1466.3615
AGB_09	69.1718	1.3029	0.9504	0.9501	4.5025	20.1522	1485.1047
AGB_10	-65185.7522	1217.8526	0.9335	0.9331	3.8887	23.3335	1534.0621
AGB_11	-3143.8455	109.2305	0.9225	0.9220	3.6030	25.1836	1559.5473
AGB_12	36.9582	0.6660	0.9811	0.9810	7.2923	12.4427	1324.0567
Secondary lowland forest (SF)							
AGB_01	177.6136	0.1946	0.7559	0.7557	2.0248	165.7167	14946.8623

AGB_02	163.2897	0.2366	0.8225	0.8223	2.3745	141.3155	14582.4188
AGB_03	181.4122	0.1685	0.7065	0.7062	1.8466	181.7157	15157.7323
AGB_04	180.6620	0.1577	0.7391	0.7389	1.9586	171.3240	15022.9993
AGB_05	159.2922	0.3289	0.8059	0.8057	2.2705	147.7859	14684.8517
AGB_06	163.5249	0.3040	0.7949	0.7947	2.2091	151.8914	14747.5453
AGB_07	181.5675	0.1571	0.7056	0.7053	1.8438	181.9881	15161.1598
AGB_08	178.7647	0.1616	0.7326	0.7323	1.9345	173.4539	15051.2676
AGB_09	177.2149	0.1627	0.7580	0.7578	2.0336	165.0000	14936.9454
AGB_10	-170342.8980	3178.3341	0.6442	0.6439	1.6772	200.0689	15377.8806
AGB_11	-8225.2964	280.1165	0.6821	0.6819	1.7745	189.0975	15248.8390
AGB_12	74.3359	0.4465	0.9768	0.9768	6.5719	51.0580	12253.1587
Secondary mangrove forest (SM)							
AGB_01	85.5906	1.1515	0.8985	0.8982	3.1421	29.4463	3705.1918
AGB_02	93.0676	0.4550	0.8930	0.8927	3.0605	30.2313	3725.4505
AGB_03	91.8187	0.5402	0.8847	0.8844	2.9485	31.3800	3754.1646
AGB_04	87.7486	1.0334	0.8895	0.8892	3.0120	30.7185	3737.7610
AGB_05	80.0665	0.6565	0.9308	0.9307	3.8075	24.3004	3557.2931
AGB_06	80.4237	0.4990	0.9308	0.9307	3.8077	24.2992	3557.2553
AGB_07	91.9103	0.5061	0.8842	0.8839	2.9428	31.4408	3755.6572
AGB_08	89.4178	0.8047	0.8898	0.8895	3.0159	30.6788	3736.7639
AGB_09	85.3131	0.9507	0.8996	0.8993	3.1594	29.2856	3700.9784
AGB_10	-77947.5780	1456.2480	0.8880	0.8877	2.9913	30.9307	3743.0617
AGB_11	-2978.0682	103.8075	0.8811	0.8807	2.9033	31.8684	3766.0581
AGB_12	19.5655	1.3405	0.9861	0.9861	8.4946	10.8921	2939.4043

*a = intercept; b = regression slope

Table 3 Summary of allometric equation screening for all landscape types

Equation	a	b	R^2	Adj.R^2	RPD	RMSE	AICc
AGB_01	198.0843	0.2779	0.109	0.1086	1.0596	245.4528	33026.1513
AGB_02	146.2662	0.2188	0.7783	0.7782	2.124	122.4508	29709.1134
AGB_03	164.9066	0.1640	0.6824	0.6823	1.7748	146.5428	30565.8472
AGB_04	177.2715	0.1655	0.6911	0.691	1.7996	144.5278	30499.8031
AGB_05	141.6184	0.3081	0.7691	0.769	2.0814	124.9595	29805.8522
AGB_06	145.5068	0.3032	0.7863	0.7863	2.1639	120.1954	29620.4391
AGB_07	165.0739	0.1530	0.6816	0.6815	1.7726	146.7285	30571.8889
AGB_08	168.4244	0.1684	0.717	0.7168	1.88	138.3421	30291.1521
AGB_09	174.1503	0.1707	0.7118	0.7117	1.8633	139.5878	30333.9109
AGB_10	-128438.5318	2397.1799	0.5885	0.5883	1.5592	166.804	31183.5712
AGB_11	-5441.1054	186.0495	0.5513	0.5511	1.4931	174.1931	31390.3255
AGB_12	89.0493	0.4593	0.9379	0.9378	4.0124	64.82164	26675.0626

a = intercept, b = regression slope; RPD = ratio performance deviation, R^2 = coefficient of determination, RMSE = root mean square error, AICc = Akaike's information criterion-corrected

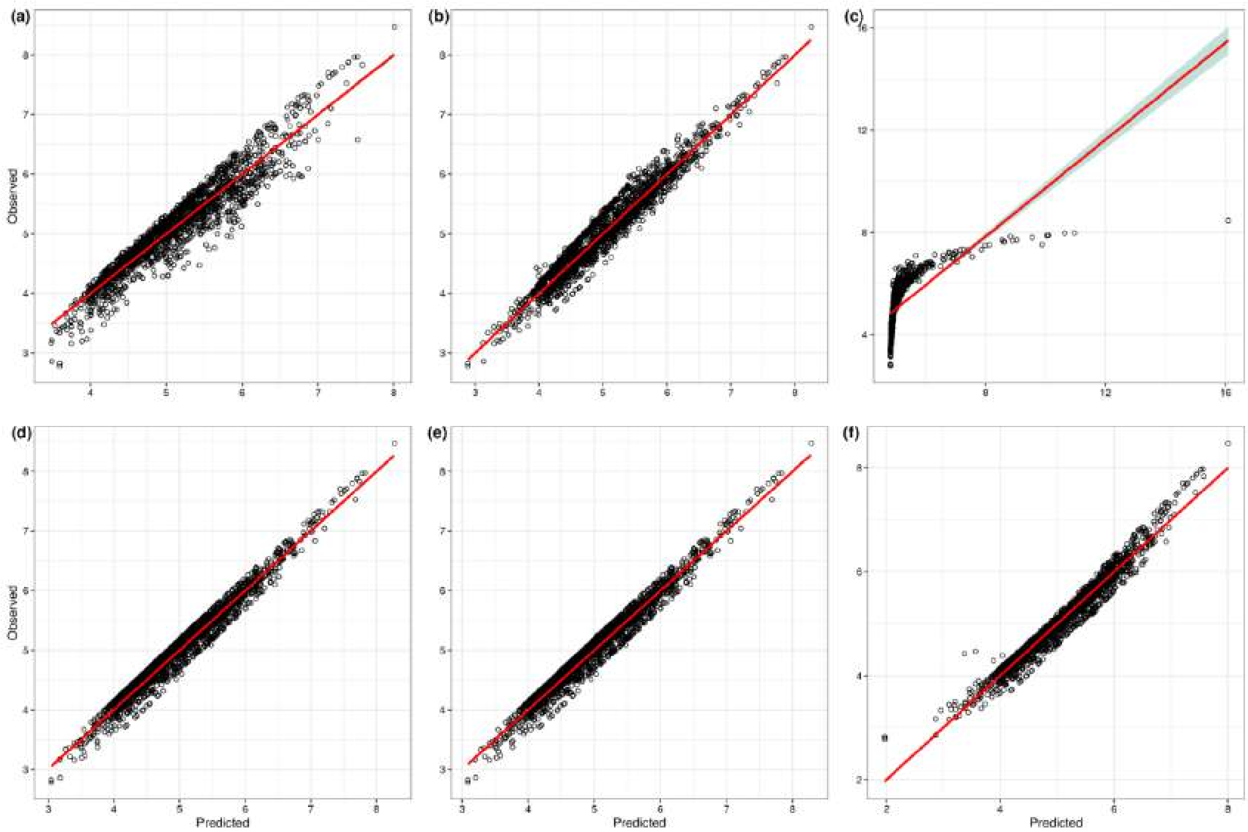

Figure 4 Linear regression results for Model: D^2 (a), DH (b), D^H (c), D^2H-1/H (d), D-H (e) and D^2-1/H (f)

ha^{-1}), PF (100.76 Mg ha^{-1}) and SM (78.93 Mg ha^{-1}) respectively. There is a difference of around 137 Mg ha^{-1} (SF), 8 Mg ha^{-1} (MG), 16.5 Mg ha^{-1} (PF), and 43.6 Mg ha^{-1} (SM), when compared with the AGB results from Equation 01.

Development of new allometric equations

The allometric equations are prepared according to Equations (14) to (19). The linear regression results between the observed and predicted values for each allometric equation are presented in Figure 4. The results (Figure 4) show data distribution around the fit curve. Fitting the linear model results shows that only Equation (16) has poor performance. The most applicable equation is Model D^2H-1/H (Equation 17) (Tables 4 and 5). We simplified the best performance model into Equation (20).

DISCUSSION

The results from the allometric equations screening indicate that all equations examined fall within Group A, with a notable prevalence in PF and SM landscape types. In contrast, the majority of previous allometric models in MG and SF landscape types are classified under Group B (Table 2). Particularly within the SF landscape type, the AGB_01 (Equation 2) and AGB_02 (Equation 3) are among the global equations assigned to Group A, whereas in the MG landscape type, all global models fall within Group B (Table 2). These findings endorsed the generally site-specific or even species-specific of previously developed global allometric models (Manuri et al. 2016, Karyati et al. 2023).

The local allometric equations AGB_06 (Equation 7), AGB_08 (Equation 9), and AGB_12 (Equation 13) performs well in MG. Moreover, AGB_05 (Equation 6) and AGB_06 (Equation 7) were only developed in secondary forest areas, so it would perform well for the SF landscape type. The AGB_10 (Equation 11) and AGB_11 (Equation 12), which were also developed from datasets of secondary forests in the East Kalimantan region, did not provide good performance for the SF landscape type

Model D^2-1/H $$AGB = 5.0657 \times (D^2 \times H)^{0.4737} \times 0.9342^{\frac{1}{\ln H}} \quad (20)$$

but performed well for PF and SM. The same conditions also apply to AGB_07 (Equation 8), AGB_08 (Equation 9), and AGB_09 (Equation 10) (Table 2). These three models were also developed based on data from the primary forest in the Kalimantan region (mostly western and northern parts of Kalimantan) (Manuri et al. 2016). The accuracy of these three models decreased possibly due to the different types of target species and range of tree diameter. This can occur due to differences in the sampling plots strategy and field measurement (ages of forest stands, range of diameter size, or even species observed) (Basuki et al. 2016), as well as the model assumptions used, e.g. correction factors (Manuri et al. 2016, Huy et al. 2019).

The AGB_12 (Equation 13) equation developed by Ruslianto et al. (2019) outperformed other AGB allometric models across all landscape types. The model originally was developed using a rigorous destructive sampling method for mangroves, especially *Rhizophora apiculata*. The findings of this study demonstrated that the AGB_12 (Equation 13) has shown applicability beyond mangrove ecosystems extending to various landscapes. This is indicated by the RPD values exceeding 2.0. Moreover, this model exhibits the highest R^2 value, lowest RMSE, and smallest AICc values (Tables 2 and 3).

Therefore, although AGB_12 (Equation 13) can be used to determine biomass in all landscape types, it needs to be converted using the regression equation with the intercept (a) and slope (b) values according to Table 3. Thus, we created 6 new models in order to get more accurate results. These six models are expected to become allometric models for estimating biomass in all landscape types. Our findings show that the 6 models we proposed performed well. Model D^2H-1/H (Equation 17), Model D-H (Equation 18), and Model D^2-1/H (Equation 19) outperformed when compared with the AGB_12 (Equation) results (Tables 4 and 5).

Table 4 Summary of the development of a new allometric equation for each landscape type data

Model	a	b	c	R^2	Adj.R^2	RPD	RMSE	AICc
Mixed Garden (MG)								
Model D	1.91	1.15	NA	0.93	0.93	3.66	0.22	-109.93
Model D^2	1.91	0.58	NA	0.93	0.93	3.66	0.22	-109.93
Model DH	1.29	0.79	NA	0.95	0.95	4.61	0.17	-383.84
Model D^H	4.74	0.04	NA	0.42	0.42	1.15	0.70	1256.60
Model D^2-H	**1.52**	**0.48**	**-0.08**	**0.97**	**0.97**	**5.70**	**0.14**	**-633.57**
Model D-H	1.42	0.96	0.50	0.97	0.97	5.70	0.14	-632.81
Model D^2H-H	2.98	0.50	-1.27	0.96	0.96	4.95	0.16	-467.09
Plantation Forest (PF)								
Model D	1.56	1.37		0.99	0.99	8.15	0.08	-356.03
Model D^2	1.56	0.68		0.99	0.99	8.15	0.08	-356.03
Model DH	1.31	0.76		1.00	1.00	14.65	0.05	-552.02
Model D^H	3.95	0.09		0.88	0.88	2.80	0.24	0.39
Model D^2-H	1.37	0.49	0.00	1.00	1.00	5.741×10^9	0.00	-7160.62
Model D-H	1.37	0.99	0.49	1.00	1.00	3.844×10^9	0.00	-7026.65
Model D^2H-H	3.14	0.53	-1.78	1.00	1.00	22.17	0.03	-690.36
Secondary lowland forest (SF)								
Model D	1.88	1.33	NA	0.98	0.98	7.31	0.11	-1858.79
Model D^2	1.88	0.66	NA	0.98	0.98	7.31	0.11	-1858.79
Model DH	1.22	0.78	NA	0.98	0.98	7.28	0.11	-1848.47
Model D^H	4.77	0.01	NA	0.54	0.54	1.43	0.55	1873.71
Model D^2-H	1.32	0.50	0.22	0.98	0.98	7.34	0.11	-1866.60
Model D-H	1.60	1.10	0.33	0.98	0.98	7.35	0.11	-1868.74

Model D^2H-H	**2.38**	**0.62**	**-0.76**	**0.98**	**0.98**	**7.35**	**0.11**	**-1870.45**
Secondary mangrove forest (SM)								
Model D	2.25	1.10	NA	0.99	0.99	12.01	0.05	-1263.03
Model D^2	2.25	0.55	NA	0.99	0.99	12.01	0.05	-1263.03
Model DH	1.04	0.90	NA	0.99	0.99	12.10	0.05	-1268.66
Model D^H	3.89	0.17	NA	0.89	0.89	2.91	0.19	-171.28
Model D^2-H	1.46	0.50	0.16	1.00	1.00	17.24	0.03	-1541.36
Model D-H	1.63	1.01	0.46	1.00	1.00	17.25	0.03	-1541.68
Model D^2H-H	3.31	0.51	-1.55	1.00	1.00	16.88	0.03	-1525.08

a = intercept, b and c = regression slope; RPD = ratio performance deviation, R^2 = coefficient of determination, RMSE = root mean square error, AICc = Akaike's information criterion-corrected

Table 5 Summary of the development of a new allometric equation for mixed landscape-type data

Model	a	b	c	R^2	Adj.R^2	RPD	RMSE	AICc
Model D^2	2.1380	0.5801	NA	0.9117	0.9117	3.3617	0.2245	-334.7119
Model DH	1.4111	0.7592	NA	0.9483	0.9483	4.3949	0.1717	-1559.4028
Model D^H	4.8011	0.0163	NA	0.4052	0.4049	1.2776	0.5907	4086.5655
Model D^2H-1/H	**1.6225**	**0.4737**	**-0.0681**	**0.9702**	**0.9701**	**5.7823**	**0.1305**	**-2813.2623**
Model D-H	1.5620	0.9483	0.4856	0.9701	0.9701	5.7796	0.1306	-2811.1034
Model D^2-1/H	3.3337	0.5061	-1.7993	0.9598	0.9598	4.9651	0.1520	-2116.8880

a = intercept, b, c, and d = regression slope, RPD = ratio performance deviation, R^2 = coefficient of determination, RMSE = root mean square error, AICc = Akaike's information criterion-corrected

Table 6 Comparison of AGB results between equation

Landscape Types	Aboveground Biomass (Mg ha^{-1})		
	Equation 01 (AGB_Vol)	Equation 13 (AGB_12)	Equation 17 (Model D^2H-1/H)
MG	133.1867	140.9953	140.6872
PF	84.2535	100.7641	89.4035
SF	264.2769	401.4443	254.7357
SM	122.5411	78.9262	103.8019

MG = mixed garden, PF = plantation forest, SF = secondary lowland forest, SM = secondary mangrove forest

We tested the proposed model, both for each landscape dataset separately and when the datasets were combined. The results show that Model D^2H-1/H (Equation 17) is the model with the best performance (Tables 4 and 5). This model was shown to be usable on each landscape type separately or when all datasets were combined (mixed landscape types). The AGB estimation is rarely used in a single model across various landscape types. Previous studies generally employed AGB specific to only one species or one type of landscape (Karyati et al. 2023, Manuri et al. 2016). Therefore, the sole model developed in this study is more efficient and powerful enough for assisting rapid assessment activities.

The total AGB across various landscape types indicates that both the Model D^2H-1/H (Equation 17) and AGB_12 (Equation 13) resulted in values within the range of common AGB in lowland landscape types (Table 6) (Kassa et. al 2022, Stas et. al. 2017, Karyati et. al 2019, Rovai et al. 2016, Senoaji & Hidayat 2016, Rafdinal et al. 2019, Dharmawan et al.

2023). The highest AGB value is found in the SF landscape type (264.28 Mg ha^{-1}) compared with other landscape types. This is due to the high diversity of plant species, varied diameter sizes, and wood density (Karyati et al. 2018, Lukman et al. 2022). This is in line with Malhi & Grace (2000) explained that accurate estimation of standing aboveground biomass can describe the well condition of the ecosystem.

The results of AGB calculations are also important in estimating carbon stocks. Based on Table 6, we can also see the accuracy of the AGB results produced by Equation 17 when compared to Equation 13. The accuracy of the above-ground biomass which obtained from this study are essential for estimating potential carbon stock losses and absorption whenever there are changes in land use (Verstegen et al. 2019, Zeng et al. 2022). This information is important in efforts to maintain the current composition of the ecosystem.

There are opportunities for the development of allometric equations specifically for certain local species that have the potential to be used as green corridor plants and for land restoration/reforestation. Future research can also focus on biomass estimation for species with specific ecological functions, namely those are tolerant to stress and species that have economic value for society (multi-purpose tree species).

CONCLUSION

This study has successfully developed an allometric equation for aboveground biomass (AGB) applicable to MG, PF, SF, and SM landscape types in Penajam Paser Utara Regency, East Kalimantan. The Model D^2H-1/H (Equation 20) demonstrates superior performance for AGB estimation. Precise evaluation of aboveground biomass across diverse landscape types is vital for informed decision-making and sustainable resource management. These findings could serve as considerations for environmentally friendly AGB rapid assessment for management practices.

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