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Non-destructive modeling using a drilling resistance tool to predict wood basic density of standing trees in a eucalypts plantation in North Sumatra, Indonesia

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Abstract. *Singh KP, Siregar IZ, Abad JIM, Karlinasari L. 2022. Non-destructive modeling using a drilling resistance tool to predict wood basic density of standing trees in a eucalypts plantation in North Sumatra, Indonesia. Biodiversitas 23: 6218-6226.* Eucalypts are globally selected as the main tree species for pulp and paper industries owing to their good potential growth and wood traits. Wood basic density, which is related to wood biomass yield, is one of the most important wood traits for pulp production and has become a focus in the tree improvement program. Evaluation of this trait in the field is needed to efficiently develop tree improvement programs. The aims of this study were to determine the distribution of basic density in the vertical direction of standing trees, including *Eucalyptus grandis*, *Eucalyptus urophylla*, and *E. grandis* × *E. urophylla* hybrid (commonly called "urograndis"), and to develop a model for predicting wood basic density using micro-drilling resistance tools of Resistograph®. The results showed that basic density traits varied within individual trees and within and between species. Average whole tree basic wood densities of 379.9 kg/m^3, 400.5 kg/m^3, and 440.6 kg/m^3 were found for *E. grandis*, hybrid urograndis, and *E. urophylla* at 44 months old, respectively. The model developed had a good correlation for predicting wood basic density at 1.3 m height and whole tree basic density, with the R^2 for model calibration ranging from 0.52 to 0.76 for 1.3 m wood basic density prediction and from 0.62 to 0.79 for whole tree wood basic density. This study found that the three species of eucalyptus could be used to create a combined model for predicting wood basic density that could be used for each individual species. The model for single and multiple species had a good validation with R^2 from 0.51 to 0.72.

Keywords: Biomass yield, *Eucalyptus grandis*, *Eucalyptus urophylla*, hybrid urograndis, resistograph

INTRODUCTION

Indonesia is the ninth largest pulp producer in the world and is able to supply 3% of the world's pulp needs. Forest plantations for raw materials for pulp and paper production were mainly established with *Eucalyptus* spp. and *Acacia* spp. in Indonesia. In addition to their wood properties (Zanuncio et al. 2016; Carrillo et al. 2017; Vieira et al. 2021), a benefit of using eucalypts is that these tree species are well adapted over a wide range of altitude, temperature, and annual precipitation (Orwa et al. 2009; Singh and Dakad 2018; Kaur and Monga 2021).

Eucalyptus grandis, which is originally from Australia, was established in forest plantations in Indonesia. *Eucalyptus urophylla*, which was originally distributed in the Lesser Sunda Islands, Indonesia, and endemic to East Nusa Tenggara, has also been used in forest plantations for pulp and paper production (Sumardi et al. 2016; Marimpan et al. 2022). *Eucalyptus pellita* and a *E. grandis* × *E. pellita* hybrid are mostly planted in low altitude areas (Leksono 2009; Hutajulu et al. 2015), while *E. grandis*, *Eucalyptus urophylla*, and a *E. grandis* × *E. urophylla* hybrid are used in high-altitude areas (900 to 2200 m asl) (Mindawati et al. 2010). The area around Lake Toba has a high altitude (900-2000 m asl) and a high annual rainfall (1000-4000 mL).

Hybrid eucalyptus trees were developed as a strategy to improve growth, productivity, pest and disease resistance, and wood properties (Rezende et al. 2014). The hybrid of *E. grandis* and *E. urophylla* is commonly called urograndis, and it has been grown in many countries, including Brazil (dos Santos et al. 2019), the Democratic Republic of the Congo (Bouvet et al. 2009), South Africa (Retief and Stanger 2009), southern China (Wu et al. 2011), and Indonesia (Mindawati et al. 2010).

Wood biomass is the most important trait for pulp production and economic return. High wood density can improve the consumption of specific wood types and optimize digester capacity in the pulping process (Miranda and Pereirat 2001; Magaton et al. 2009). There are two main objectives in industrial plantation forestry with regard to pulp and paper production: (1) optimizing forest productivity by increasing tree volume, rooting ability, survival, and tolerance of biotic and abiotic stress, and (2) reducing consumption of specific wood types by increasing pulp yield, basic density, and S/G lignin type ratio and decreasing lignin content in the wood (Rezende et al.

2014). Basic density, pulp yield, and fiber length are the key wood characteristics in pulp production (Raymond 2002).

Assessing of wood basic density in a standing tree would be helpful for selection activity in the tree improvement program and for operational plantation management before they are harvested. The use of the drilling resistance method, which uses a thin needle to penetrate the wood of standing trees (da Silva et al. 2020; Balasso et al. 2021; Li et al. 2022), can be an opportunity to assess the wood basic density (Gao et al. 2017; Fundova et al. 2018; Nickolas et al. 2020). The drilling resistance value is a unit that serves as an indicator of the basic wood density (Isik and Li 2003; Bouffier et al. 2008; Karlinasari et al. 2017; Gendvilas et al. 2021; Vlad et al. 2022). Few studies have been conducted on the use of drilling resistance for evaluating standing trees in plantation forests (Vlad et al. 2022). The critical issues addressed in the current study include the reliability of the pattern of the basic density variation in testing trees, and the reduction of drilling resistance tool errors in estimating basic wood density.

Therefore, we evaluated wood basic density in eucalypts trees and developed a model for predicting wood basic density in standing trees in a eucalypts plantation forest in North Sumatera, Indonesia, using a drilling resistance tool of Resistograph®. The tree species included in this study comprised *E. grandis*, *E. urophylla*, and the hybrid urograndis.

MATERIALS AND METHODS

Study area and research materials

The study sample included 44-month-old *E. grandis*, *E. urophylla*, and urograndis hybrid trees from a progeny population in Harian Subdistrict, Samosir District, North Sumatera, Indonesia (2°31’12.20” N, 98°32’13.31” E) (Figure 1). Field measurements of trees were carried out using non-destructive drilling resistance commercial equipment (IML Resistograph®), chainsaw, personal protective equipment, and measuring tape. Laboratory equipment at PT. Toba Pulp Lestari. Tbk Wood Laboratory was used to measure basic wood density via destructive sampling.

Non-destructive drilling resistance testing

The diameter at breast height (DBH; 1.3 m) was measured for 312 trees, including 156 *E. grandis*, 138 *E. urophylla*, and 18 hybrid urograndis. Drilling resistance testing was then done radially at DBH in a north to south direction. The area around the point of testing was clear from knots and any other tree defects.

A feed speed of 1500 mm^{-1} and 3500 RPM was used to evaluate drilling resistance as stipulated by the IML Resistograph® manual guide and as recommended by Downes et al. (2018) for eucalypt plantation sampling. The Resistograph® needle was cleaned with 70% alcohol after every use to avoid spreading any infection between trees. Recorded data of drilling resistance value were then transferred from the tool to the computer using the software of PD Tools Pro from IML Company.

Felling trees and collecting samples

After field testing, all the sample trees were felled. The total log length, from the base of the trunk up to the point at which the log diameter was about 5 cm, was defined as the valuable tree length and measured. Each log was then marked and divided into several sections based on the valuable log length. Disk samples of 2- to 3-cm thickness were cut at six points along the tree length: 1.3 m and 0%, 25%, 50%, 75%, and 100% of tree length (Figure 2) (Martins et al. 2020). The samples were then put in a basket and immediately transported to the laboratory.

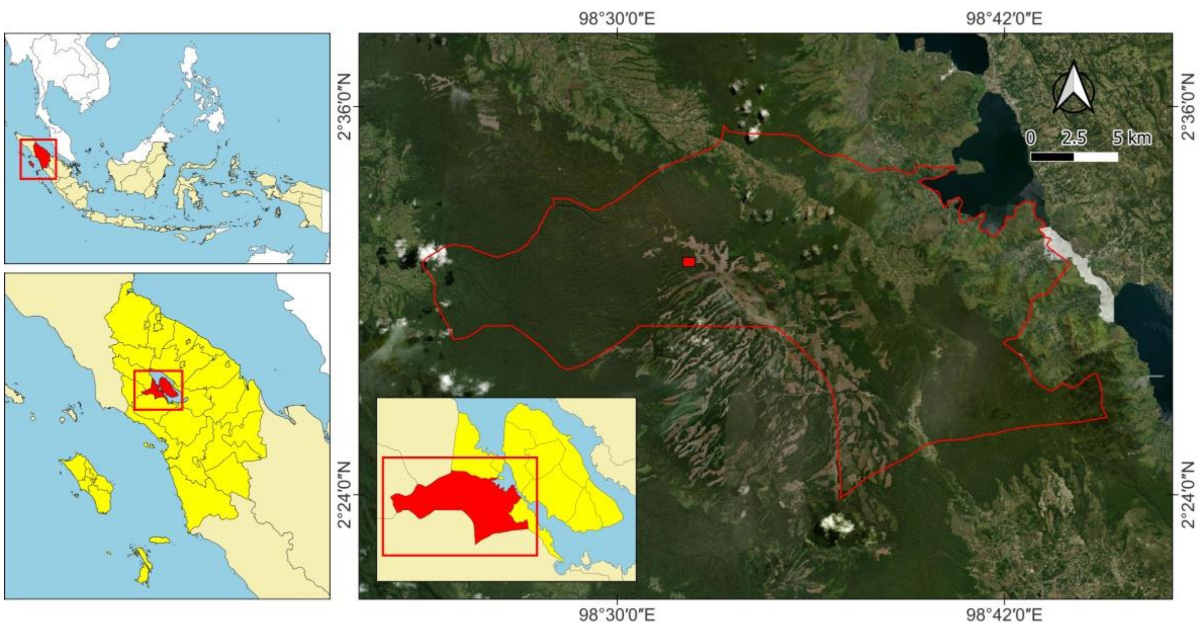

Figure 1. A research site for field testing in Harian Subdistrict, Samosir District, North Sumatera, Indonesia

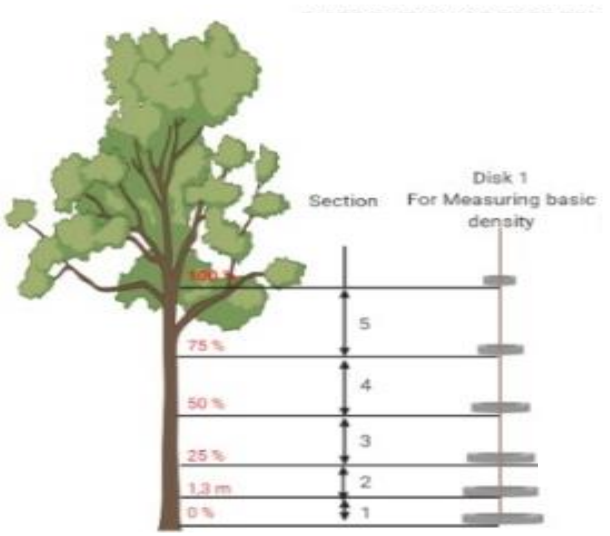

Figure 2. Collection of disk samples from each tree at 1.3 m and 0%, 25%, 50%, 75%, and 100% of tree length

Determination of basic wood density

In the laboratory, the disk samples were immediately cleaned. The volume used was in green condition. The disk samples were then soaked in water for 1 to 4 hours to ensure that the samples were in a green or saturated condition. Volume was calculated based on the green condition. The samples were then dried in an oven at a temperature of 105 ± 3°C until reaching a constant weight. Wood basic density was determined by the ratio of the oven-dry weight to the green volume. The density of pulpwood was determined as stipulated in TAPPI T 258 (2006), using the basic density and moisture content of pulpwood. The average basic wood density at each of the six positions along the valuable tree length was then calculated. The determination of whole tree wood density followed the study by Martins et al. (2020) in which whole tree basic density was calculated by averaging the lower until upper measures weighted by their areas. For that property, the calculation of whole tree basic density was based on frustum volume to average wood basic density within the trees measures weighted by their areas.

Data analysis

Data analysis was carried out to obtain the various values of basic wood density based on tree height through analysis of variance (ANOVA) using 95% confidence intervals. Analysis continued with the Duncan test, which was followed by Pearson's analysis to determine the linear relationship of basic wood density at various tree heights as represented by the disk sections. A simple regression model was developed for predicting the basic wood density at 1.3 m and the whole tree basic density based on data from the drilling resistance tool. The reliability of the model was assessed through a cross-validation analysis using a model of coefficient of determination (R^2) and residual mean square error (RMSE).

RESULTS AND DISCUSSION

Wood basic density distribution

The descriptive statistics for mean, max, min, and standard deviation values for tree basic density and drilling resistance of *E. grandis*, *E. urophylla,* and hybrid urograndis are presented in Table 1. A comparison of the three species for wood basic density shows that *E. grandis* had the lowest basic density, with a mean of 378.8 kg/m^3, followed by hybrid urograndis with a mean of 396.2 kg/m^3. *Eucalyptus urophylla* had the highest wood basic density, with a mean value of 440.2 kg/m^3. Previously, Cremonez et al. (2019) reported that wood density ranged from 381 kg/m^3 to 436 kg/m^3 for eucalyptus tree species. da Silva et al. (2017) found that hybrid urograndis had an average tree basic density of 400 kg/m^3 at 34 months and 420 kg/m^3 at 62 months old. In a study by Couto et al. (2012), the basic wood density of *E. grandis* was lower than that of *E. urophylla*. We found that the average wood basic density was slightly different from the whole tree basic density because the density of each disk sample differed from the whole tree wood basic density.

The variability between species revealed the potential for selection for a hybrid tree improvement program, as shown by the increment of the basic density of hybrid urograndis, which had a mean value between *E. grandis* and *E. urophylla*. Selection based on the basic density of two species could be a potential way to increase the basic wood density of segregation offspring of the hybrid eucalyptus improvement program. Drilling resistance values supported the same distribution of basic wood density as the direct measurements (Table 1).

Figure 3 shows that the wood basic density of *E. grandis* was the lowest of the three species at each position, followed by the hybrid urograndis; *E. urophylla* had the highest wood basic density for each position along the valuable tree length. Based on the ANOVA, wood basic density differed significantly according to disk position, following the vertical position on the tree (Table 2). The differences between the positions were found to affect the total whole tree wood density calculation, which consequently influenced the modeling for drilling resistance and whole tree wood basic density.

Duncan test of basic density based on the position along the tree revealed differences between the values (Table 3). In general, the differences did not show a specific trend based on tree height. The wood basic density value at 0% of length was not significantly different from that at 100%, as shown for *E. urophylla* and hybrid urograndis. Quilhó et al. (2006) previously reported that the wood basic density varied according to the sampling position inside the tree in eucalyptus species.

Table 4 showed a difference in wood basic density between species in each sampling position, whole tree basic density and drilling resistance value inside the tree based on ANOVA with a 95% confidence interval. The differences at each sampling position caused the difference from the whole tree basic density. Based on this information, the best way to average wood basic density for the whole tree was taken by averaging the wood basic density at each position weighted by the areas of the disks.

Eucalyptus urophylla had the highest wood basic density, and the values were significantly different from those of other species from the 25% to the 100% sampling positions based on the Duncan test. *Eucalyptus grandis* had the lowest wood basic density, with values being significantly different from the 25% to the 100% sampling position in comparison with the other species, but it was not significantly different from the hybrid urograndis at the 0% and 100% sampling positions. *Eucalyptus grandis* also had the lowest whole tree basic density and drilling resistance value, while *E. urophylla* had the highest whole tree basic density and drilling resistance value, which were significantly different from those of the other species (Table 5).

Drilling resistance value data followed the same trend as the data for the wood basic density for each species. *Eucalyptus grandis* had the lowest average drilling resistance value (2709.2), followed by hybrid urograndis (3105.9), with *E. urophylla* having the highest average drilling resistance value (3252.8) (Figure 4).

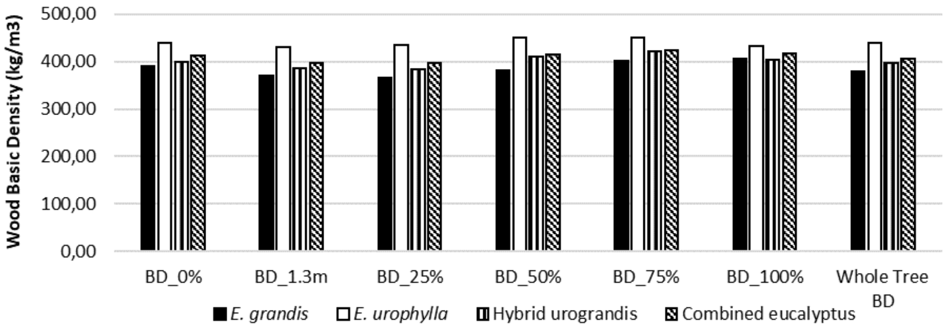

Figure 3. Wood basic density distribution by sampling position from each species

Table 1. Basic wood density and the drilling resistance values of three eucalypt species in North Sumatra, Indonesia

Species	n	Characteristic	Mean	Max	Min	SD	CV %
E. grandis	156	Whole tree basic wood density (kg/m^3)	378.8	447.6	302.4	30.2	8.0
		Drilling resistance value	2709.2	3449.0	1990.0	303.0	11.2
E. urophylla	138	Whole tree basic wood density (kg/m^3)	440.2	507.0	380.2	29.0	6.6
		Drilling resistance value	3252.8	4087.0	2594.0	330.1	10.1
Hybrid urograndis	18	Whole tree basic wood density (kg/m^3)	396.2	451.9	353.6	29.3	7.4
		Drilling resistance value	3105.9	3940.0	2405.0	370.6	11.9
Combined Eucalyptus	312	Whole tree basic wood density (kg/m^3)	407.0	507.0	302.4	42.0	10.3
		Drilling resistance value	2972.5	4087.0	1990.0	414.7	13.9%

Notes: Max: maximum, Min: minimum, SD: standard deviation, CV: coefficient of variance (%)

Table 2. Analysis of variance for wood basic density position along the length of the tree

Source of variance	*E. grandis*		*E. urophylla*		Hybrid urograndis	
	df	MS	df	MS	df	MS
Position	5	41,622***	5	12,059.5***	5	3642.6**
Residuals	930	1215	822	1154.4	102	1052.3

Notes: df: degrees of freedom, MS: mean square, significant at * *p< 0.10, **p < 0.05, ***p < 0.001*

Table 3. Duncan test for wood basic density at six disk positions along the length of the tree for three *Eucalyptus* species

Position	Species		
	E. grandis	*E. urophylla*	Hybrid urograndis
0%	389.4^{b}	439.3^{b}	398.5^{ab}
1.3 m	370^{c}	431.3^{b}	386.4^{b}
25%	366.1^{c}	434^{b}	383.7^{b}
50%	381.9^{b}	451.5^{a}	409.9^{a}
0.75	401.4^{a}	451.7^{a}	421.2^{a}
100%	406.4^{a}	432.6^{b}	403.4^{ab}

Notes: Values followed by the same letter in a column are not significantly different

Table 4. Analysis of variance for wood basic density (BD) between species for each sampling position and the drilling resistance value

Traits	Mean square	
	Species	Residual
BD 0%	92,982***	1141
BD 1.3 m	139,024***	1030
BD 25%	170,235***	1137
BD 50%	177,792***	1159
BD 75%	92,771***	1492
BD 100%	26,970.5***	1117.9
Whole tree BD	138,770***	879
Drilling resistance value	10,991,111***	101,919

Notes: df: degrees of freedom, MS: mean square, significant at * p< 0.10, **p < 0.05, ***p < 0.001

Table 5. Duncan test for wood basic density of three species at six sampling positions, average wood basic density, whole tree basic density, and drilling resistance value

Species	Traits (basic density and drilling resistance value)							
	BD 0%	BD 1.3m	BD 25%	BD 50%	BD 75%	BD 100%	Whole tree BD	DRV
E. urophylla	439.3[a]	431.3[a]	434.0[a]	451.5[a]	451.7[a]	432.6[a]	440.2[a]	3252.8[a]
Hybrid urograndis	398.5[b]	386.4[b]	383.7[b]	409.9[b]	421.2[b]	403.4[b]	396.2[b]	3105.9[b]
E. grandis	389.4[b]	370.0[c]	366.1[c]	381.9[c]	401.4[c]	406.4[b]	378.8[c]	2709.2[c]

Notes: BD: basic density, DRV: drilling resistance value. Values followed by the same letter in a column are not significantly different

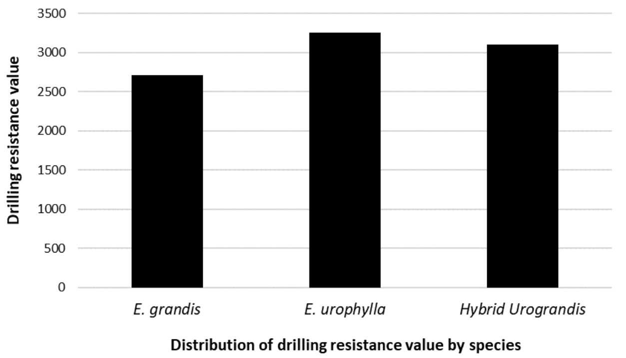

Figure 4. Mean drilling resistance value by species

The correlation analysis presented in Table 6 shows that the wood basic density around DBH at 1.3 m or at 25% of the height and whole tree wood basic density had the greatest correlation, as shown for *E. grandis* (0.91-0.92), *E. urophylla* (0.91-0.94), and the hybrid urograndis (0.92-0.97). The correlation of the wood basic density of the whole tree with that at the DBH position is an important point because the process of data collection for different heights is not possible for non-destructive assessment in the field. The testing point at 1.3 m is considered to be the ideal position for a person in the field. Furthermore, the wood basic density at the DBH point had a good correlation with the tree basic density for the whole tree (r > 0.90). Pádua et al. (2019) discovered a similar trend in eucalyptus species testing.

Modeling of wood basic density using the resistograph

A good correlation was found between the drilling resistance values which tested at DBH-tree (1.3 m) with wood basic density at non-destructive testing (NDT) point (1.3m) in the model calibration. The regression model for predicting the wood basic density at 1.3 m yielded a significant result for a 99% confidence interval for *E. grandis* with $R^2 = 0.67$ and RMSE = 18.75 for calibration, for *E. urophylla* with $R^2 = 0.52$ and RMSE = 21.93, and for combined eucalyptus for all species with $R^2 = 0.76$ and RMSE = 21.76 (Table 7). Based on the ANOVA for basic density in each sampling position, results were significantly different between sampling positions. The regression model to predict the whole tree basic density showed a better quality of calibration than that for the NDT's testing point (1.3 m). The regression model to predict the whole tree basic density yielded the following results: *E. grandis* showed $R^2 = 0.7$ with RMSE = 16.9, *E. urophylla* showed $R^2 = 0.62$ with RMSE = 17.76, and combined eucalyptus species with $R^2 = 0.79$ with RMSE = 19.93 (Table 8).

Table 6 Pearson correlation analysis for wood basic density (BD)

Species	Position	BD 0%	BD 1.3 m	BD 25%	BD 75%	BD 100 %	Whole tree BD
E. grandis	BD 0%	1					
	BD 1.3 m	0.80	1				
	BD 25%	0.73	0.82	1			
	BD 50%	0.63	0.74	0.76			
	BD 75%	0.47	0.58	0.54	1		
	BD 100%	0.44	0.47	0.48	0.54	1	
	Whole tree BD	0.83	0.91	0.92	0.72	0.59	1
E. urophylla	BD 0%	1					
	BD 1.3 m	0.83	1				
	BD 25%	0.75	0.84	1			
	BD 50%	0.57	0.64	0.70			
	BD 75%	0.43	0.54	0.64	1		
	BD 100%	0.40	0.44	0.46	0.62	1	
	Whole tree BD	0.82	0.91	0.94	0.74	0.61	1
Hybrid urograndis	BD 0%	1					
	BD 1.3 m	0.87	1				
	BD 25%	0.72	0.85	1			
	BD 50%	0.58	0.83	0.73			
	BD 75%	0.73	0.86	0.77	1		
	BD 100%	0.89	0.73	0.64	0.71	1	
	Whole tree BD	0.84	0.97	0.92	0.90	0.74	1

Table 7. Wood basic density at 1.3 m prediction model using the resistograph

Model	Calibration					Validation								
						E. grandis			*E. urophylla*			Hybrid urograndis		
	Intercept	Slope	N Cal	R^2 Cal	RMSE Cal	N val	R^2 Val	RMSE Val	N val	R^2 Val	RMSE Val	N val	R^2 Val	RMSE Val
E. grandis	135.10***	0.0861***	117	0.67	18.75	39	0.51	23.0	-	-	-	-	-	-
E. urophylla	196.40***	0.0718***	103	0.52	21.93	-	-	-	35	0.63	18.8	-	-	-
Combined eucalyptus	117.70***	0.0941***	229	0.76	21.76	39	0.50	22.4	35	0.63	23.1	9	0.7	33.3

Notes: N Cal: number of sampling while calibration, R^2 Cal: coefficient of determination while calibration, RMSE Cal: residual mean square error while calibration, N Val: number of sampling for model validation, R^2 Val: coefficient of determination for model validation, RMSE Val: residual mean square error for model validation, significant at * $p< 0.10$, ** $p < 0.05$, *** $p < 0.001$

Table 8. Whole tree wood basic density prediction model using the resistograph

Model	Calibration					Validation								
						E. grandis			*E. urophylla*			Hybrid urograndis		
	Intercept	Slope	N Cal	R^2 Cal	RMSE Cal	N val	R^2 Val	RMSE Val	N val	R^2 Val	RMSE Val	N val	R^2 Val	RMSE Val
E. grandis	150.63***	0.0838***	117	0.7	16.9	39	0.65	17.0	-	-	-	-	-	-
E. urophylla	211.70***	0.0701***	103	0.62	17.76	-	-	-	35	0.72	15.8	-	-	-
Combined eucalyptus	130.90***	0.0928***	229	0.79	19.33	39	0.7	16.8	35	0.72	19.1	9	0.72	30.9

Notes: N Cal: number of sampling while calibration, R^2 Cal: coefficient of determination while calibration, RMSE Cal: residual mean square error while calibration, N Val: number of samplings for model validation, R^2 Val: coefficient of determination for model validation, RMSE Val: residual mean square error for model validation, significant at * $p< 0.10$, ** $p < 0.05$, *** $p < 0.001$

The results from previous studies (Isik and Li 2003; Bouffier et al. 2008; Karlinasari et al. 2017) indicated that wood density was related to NDT drilling resistance under various conditions. The regression model to predict wood basic density using the resistograph for NDT points and whole tree basic density for each species gave significant results for the 99% confidence interval based on the linear R^2 approach (Tables 7 and 8). This correlation shows the potential for predicting basic wood density using the Resistograph®, which is in line with previous studies (Isik and Li 2003; Bouffier et al. 2008; Couto et al. 2012; da Silva et al. 2017; Karlinasari et al. 2017) for various tree species. Couto et al. (2012) tested the Resistograph® to predict wood basic density for clones of *E. grandis* and *E. urophylla* at 42 and 54 months, and the modeling yielded R^2 values of 0.54 to 0.67. The variability of different genotypes could explain the higher R^2 values in our calibration compared with that for clonal sampling used by Couto et al. (2012), which had low variability as well as a restricted range of drilling amplitudes.

For the prediction of wood basic density at 1.3 m, the *E. grandis* model had R^2 validation lower than the calibration (0.51), which showed that the model explained about 0.51 of variation. Meanwhile, the model-predicted wood basic density at 1.3 m in *E. grandis* population compared with the collected data had RMSE of 23.0. The *E. urophylla* model had a higher R^2 than the calibration (0.63), with RMSE of 18.8 for validation.

Predicting the whole tree basic density using the Resistograph® showed less precision compared with the calibration. The *E. grandis* model shows $R^2 = 0.65$ with RMSE of 17.0. Meanwhile, the *E. urophylla* model had a higher R^2 than the calibration, with $R^2 = 0.72$, and a lower RMSE of 15.8 for validation. These numbers showed that the model could be used for other populations as well as the same population.

The combined eucalyptus for all species model showed slight differences for R^2 and RMSE for validation in predicting wood basic density at 1.3 m and whole tree basic density. Based on the R^2 and RMSE, the combined model predicted wood basic density at 1.3 m and whole tree basic density for *E. grandis* slightly differently compared with the use of *E. grandis* model itself (Tables 7 and 8). Predicting wood basic density in *E. urophylla* species using the combined eucalyptus model showed the same R^2 in the validation of the model compared with using the *E. urophylla* model itself. The use of the combined model for predicting wood basic density in *E. urophylla* species had a slight impact on RMSE, with the combined model showing a slightly higher RMSE than the use of the *E. urophylla* model itself (Tables 7 and 8).

In the process of creating the combined eucalyptus model, the hybrid of *E. urophylla* × *E. grandis* was included in the model. The validation of the combined eucalyptus model for the hybrid urograndis was comparable to the validation for *E. grandis* and *E. urophylla*. The validation of the combined model with hybrid urograndis showed R^2 of 0.7 with RMSE of 33.3 for predicting wood basic density at 1.3 m and showed R^2 of 0.71 with RMSE of 30.9 for predicting whole tree basic density (Tables 7 and 8).

Figure 5 shows that all species have a positive linear regression between the drilling resistance value and the wood basic density at 1.3 m, the average wood basic density, and the whole tree wood basic density. Combined eucalypts that come from combined data from three species showed a good relationship in the regression model and indicated the regression models were statistically significant at the 95% confidence level. These results show us that we have the potential to make one wood basic density prediction model that can predict the wood basic density of *E. grandis*, *E. urophylla*, and hybrid urograndis.

Non-destructive sampling based on drilling resistance (resistograph) led to a good model to predict wood basic density. The quality of the models affects their usefulness in rapid tree basic density assessment in a breeding program, such as progeny trials in the field to predict genetic parameters and to make selections based on growth, phenotypic, and wood basic density. Ratcliffe et al. (2014) and Walker et al. (2019) found that resistograph testing for predicting wood basic density yielded results comparable to rapid measurement in progeny trials associated with tree breeding activity. Based on this literature, the prediction model for each species must be selected wisely, considering the linear R2 and RMSE, to reduce the error caused by the model while improving wood density traits in a tree improvement program. Further, Nikolas et al. 2020 found that the drilling resistance technique can be useful for assessing silvicultural, genetics, and ecological studies of forest trees. Not only wood density, and other wood properties can also be explored through NDT drilling resistance techniques, such as the anatomical characteristics of grain direction and features of wood (Sharapov et al. 2021; Arnič et al. 2022). In addition, this technique has reportedly been used to estimate the age of pine, oak, and birch trees (Szewczyk et al. 2018), but it was reported that drilling resistance density technique should not be used to replace dendrochronology in climate-tree growth studies (Orozco-Aguilar et al. 2018).

In conclusion, wood density of *E. grandis*, *E. urophylla*, and hybrid urograndis differed significantly based on the vertical tree height, but there was no specific trend based on height. The wood density of *E. grandis* was lower than those of hybrid urograndis and *E. urophylla*. The 25% section of valuable tree length as well as the DBH section (1.3 m tree height) were ideal testing points for drilling resistance using the resistograph, as shown by the Pearson correlation (r) of about 0.9 in the determination of the whole tree wood basic density. The prediction model of wood basic density developed can be used, based on the statistical regression model calibration and validation. Our study successfully found that the single species model and the combined species model can be used in single and multiple species for rapid assessment of basic wood density from standing eucalyptus tree species, which will be helpful in tree improvement activities and for consideration in wood biomass for pulp production.

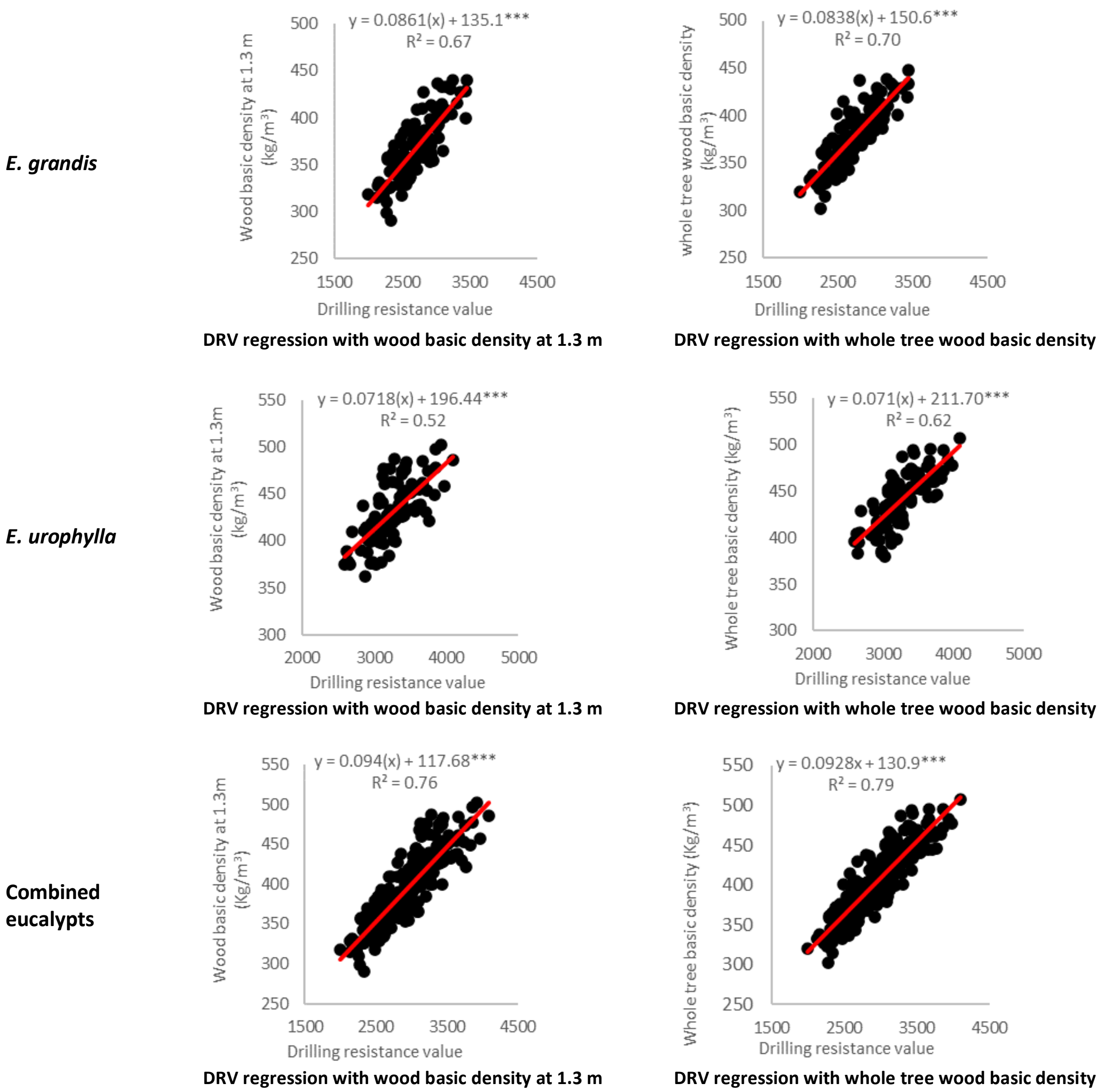

Figure 5. Regression analysis between drilling resistance value (DRV) to wood basic density at 1.3 m, and whole tree-wood basic density

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