Assessing intraspecific wood density variations of *Syzgium* sp. in tropical forest of Southwest Sabah

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Abstract. Wood density (WD) is a critical determinant of estimating forest above-ground biomass (AGB) and carbon stock. Thus, heterogeneity in WD on individuals within species trees needs to be scrutinized, and acquisition of fixed WD value is essential to estimate carbon stock with confidence. This study investigated intraspecific variation in WD of *Syzgium* sp., also known as “Jambu” or “Kelat”. It is the most occurring species in study areas, and is regarded as an economically important species. Firstly, one half-diameter drilling from bark-to-pith measurement was taken per tree using Rinntech Resistograph R650-ED at breast height. Meanwhile, 5.15 mm-diameter core was sampled at 1.30 m above-ground, with DeWalt DCF899HP2 20V impact wrench 950 Nm and Haglöf increment borer. WD was estimated for each core sample using a dimensional method. Drilling resistance (DR) profiles were processed using DECOM 2.38m Scientific (c), and several independent variables were extracted from the resistogram. All resistogram-derived variables were positively correlated with field WD (R: 0.2 – 0.70). In addition, variability on WD in *Syzgium* sp. population is predominantly explained by the Resistograph amplitude, expressed as mean raw scale of adjusted DR (DR\text{adj.RawSC}) in a regression model. Given that intraspecific variation in WD is a crucial conjecture in forest AGB estimation, it is recommended to analyze with larger samples, and in-depth exploration on Resistograph-based variables is deemed to improve the accuracy of WD prediction models.

Keywords: Wood density; resistograph; Syzgium; variation; resistance drilling.

1. Introduction
Wood density (WD) is an important trait that is generally associated with wood strength. As a result, density prediction of wood has gained attention among researchers, making it a current research topic. To better understand variation in wood, WD should be studied further, primarily at the within-species level. Acquiring a fixed value of WD would be advantageous for improving forest AGB estimation as WD is required to convert data on wood volume to biomass. This is supported by a previous applied remote sensing LiDAR data study, which stated that WD must be integrated into allometry equations in LiDAR applications [1]. Nonetheless, variation in WD caused by various factors such as tree species, moisture, site, temperature, and elevation has posed challenges to recent research efforts to obtain an accurate WD value. As WD data is critical for explaining WD heterogeneity, various tools have been developed to acquire WD in standing trees without sacrificing excessive energy or costs. Numerous studies used destructive methods to obtain an accurate estimated value of WD. In contrast, other studies chose a faster and more accessible alternative to assess WD variability as obtaining infield WD measurement could be difficult [2-6]. Analysis of Syzgium sp. in this study can allow inferences about…
its use as a keystone species in Long Mio, as it is the most abundant species in study sites. Given the preceding, it is perplexing that the WD of the vast majority of tropical trees remains unknown. Considering some species are not available in the database, a heavy reliance on global wood databases to obtain WD value at the species level could be problematic.

This study estimated field WD using variables extracted from drilling resistance (DR) using a micro-drilling device, Resistograph, and developed optimal predictive WD estimates to understand intraspecific WD at the species level better. The results of this study could help provide a simple approach analysis of resistographic profiles obtained from live trees and the extraction of valuable variables from the profiles.

2. Methodology

2.1. Study area
The study was conducted in the district of Sipitang, Sabah, Malaysia (Figure 1). The study area is located adjacent to the border between Sabah, Sarawak and Kalimantan. It consists of state lands and forest reserves, previously licensed to Sabah Forest Industries Sdn. Bhd, and was relinquished to Sabah Forestry Department in September 2021.

2.2. Field measurement
Ninety-two individuals of Syzgium sp. were sampled to develop predictive WD regression models. The main selection criterion is employed: species relative abundance, which was obtained from previous inventory data. Tree drilling resistance measurement and tree coring were conducted in 30 m x 30 m size re-measured plots from 2011 until the present. Data collection was carried out from April to October 2021. The diameter of the sampling trees was measured at breast height (DBH) by a diameter tape.

2.3. Drilling resistance measurement and processing
One bark-to-pith DR was measured using the Rinntech Resistograph® R650-ED (Heidelberg, Germany) from each tree at breast height about 1.30 m above ground level. The drilling speed was set to 20 mm/sec during all measurements. The resistograph uses a micro-drilling device with a needle of 3 mm diameter, 50 cm length, and has drill torque mechanism, corresponding to a magnitude of drill difficulty in penetrating the wood. Each profile was checked immediately after drilling, printed by a Bluetooth wireless thermal printer and the measurement was repeated when necessary. The resistograph chart was recorded electronically for each drilling measurement and the data were downloaded to a computer. In this study, we used two types of DR profiles; unadjusted (with bark) and adjusted (debarked). Both were processed using DECOM Scientific 2.38m1 version. Next, the profiles were imported to the Microsoft Excel program, and for each tree, the mean amplitude was determined. Several independent variables were defined from both DR profiles and statistically analyzed.

2.4. Wood cores extraction and processing
5.15 mm bark-to-pith increment cores were extracted from each tree in the same manner as Resistograph using power drill-borer, DeWalt DCF899HP2 20V impact wrench 950 Nm and Haglöf increment bore. Core dimensions consist of diameter and length were determined by a Mitutoyo 150 mm digital caliper with accuracy of 0.01 mm. Next, cores were placed in plastic straws with both tips sealed with masking tapes in a cooler containing dry ice packs in the field to keep them fresh during the cores collection phase.
2.5 Wood density determination

Core fresh weight was weighted using CAS MWP-H 600 digital micro weighing scale with accuracy of 0.01 g after returning from the inventory plots. Then, cores were wrapped in aluminium foil, placed into plastic zip-locks, kept in a cooler and transported to the Hydrology Laboratory at the Faculty of Tropical Forestry. Next, core samples were oven-dried in Memmert 100-800 at 105°C to constant mass for 72 hours. After oven-drying, samples were weighed immediately using the same digital balance. Lastly, WD (g cm⁻³) was calculated as dry mass divided by its fresh volume by using the following equation (1) [7];

\[
WD = \frac{M}{\frac{L}{4} \times d^2 \times L}
\]

where, \( L \) = total length (cm), \( d \) = mean diameter of core sample (cm) and \( M \) = dry mass (g) of core sample

2.6 Statistical analyses

Correlations between field wood density and each DR variable were inspected using Pearson’s correlation. Stepwise multiple linear regression analysis was used to regress field wood density with the DR variables. All statistical analyses were run using statistical software R version 4.0.3. Outliers were inspected by using Grubbs test and eight outliers were removed. The optimal performance of the WD estimation model was selected based on adjusted coefficient of determination (R²adj), Akaike information criterion (AIC), root-mean-square error (RMSE) and relative RMSE. RMSE was calculated from leave-one-out cross-validation (RMSELOOCV) for model evaluations.

3. Results and discussion

This study investigated the intraspecific variation of WD in Syzgium sp. to develop a reliable and accurate WD estimation model for Syzgium sp. in the tropical forest. All fitted linear models were significant (<.01). Table 1 shows DR-derived variables were moderately positive correlated with field WD. The best model fit given R²adj = 74% of the variability of the dependent variable WD (g cm⁻³) is explained by the six explanatory variables: DRadj,RawSC, DRRawSC, DRSD, DRBT, DRVar,and DRMEd. It can be said that DR-derived variables were satisfactorily capable to explain the intra-specific WD variation of Syzgium sp appreciably.
Surprisingly, Model 4 is improved by incorporating bark thickness as one of the explanatory predictors for WD variability. The presence of bark is usually associated with low resistance or density in the DR profiles. It is displayed as an abrupt ‘dropout’ at the profile's beginning and end [8]. It is presumably due to each tree having different bark thickness due to their diameter, thus creating a considerable portion of the drilling profile and subsequently contributing to increasing drilling density. On the contrary, previous studies reported that profile debarking during DR processing in their research could improve the accuracy of predictive Resistograph WD estimates model [9-10]. This is in agreement with our findings that the mean raw scale of adjusted or debarked DR (DRadj.RawSC) is one of the main predictors for all the fitted models. Nevertheless, single radial Resistograph measurement is sufficient for WD estimation in preference to more than one measurement which is congruent to our Resistograph-measurement practice [11]. In addition, the inclusion of standard deviation of unadjusted DR in all fitted models indicates that it sufficiently represents the variability of the energy consumed in the perforation of the sample. As standard deviation means the ‘dispersion’ of the sample, it can indicate heterogeneity in WD of Syzygium sp, making it as one of the best explanatory variables in WD estimates modeling. The inclusion of various independent variables in Model 4 suggests that more potential variables could be explored and extracted from the drilling resistance using Resistograph to improve the WD estimates modeling. Model 4 is chosen as the best model based on its higher R2adj = 74%, revealing that 74% of the data fit the regression model. Even though it has a slightly higher RMSE % than the other models, it has a high predictive value and the lowest AIC.

Several possible factors may have caused moderate linear within our study's species-level relationship between WD and DR derived variables. As WD was determined from oven-dried increment cores, whereas the DR readings were obtained from live trees, it could have been affected by different tree moisture contents. Application of partial drilling in this study that only assesses bark-to-pith might lead to the inability to capture a considerable amount of WD variability across the tree bole. Nonetheless, first half drilling from bark-to-pith was highly favorable for Resistograph WD prediction of live trees to avoid accumulated friction on the drill’s shaft, subsequently to improve WD estimates [12]. Our findings are in agreement with similar moderate positive results for WD estimates using Resistograph through multiple regression as reported in previous studies [13-14].

**Table 1.** The correlations between the field estimated WD (g cm⁻³) and selected variables extracted from drilling resistance for regression analyses.

| Wood Density (g cm⁻³) | Drilling Resistance (DR) | Description | Pearson’s Correlation |
|-----------------------|--------------------------|-------------|-----------------------|
| Field WD              | DRadj.RawSC              | Mean raw scale of adjusted DR | .691**               |
|                       | DRRawSC                  | Mean raw scale of unadjusted DR | .637**               |
|                       | DRSD                     | Standard deviation of unadjusted DR | .671**               |
|                       | DRMed                    | Median of unadjusted DR | .645**               |
|                       | DRvar                    | Variance of unadjusted DR | .529**               |

*Correlation is significant at the 0.01 level.

**Table 2.** WD estimation models.

| Model | Variables          | Regression equation              | R2adj | RMSE (g cm⁻³) | RMSE (%) | AIC  |
|-------|--------------------|----------------------------------|-------|---------------|----------|------|
| 1     | DRadj.RawSC, DRRawSC, DRvar | WD = 0.324 - 2.63DRRawSC + 4.51E-06DRvar | .5476 | .06377         | 11.084   | -180.51 |
| 2     | DRadj.RawSC, DRRawSC, DRvar | WD = 0.2207DRRawSC + 1.587DRadj.RawSC | .6983 | .06376         | 11.082   | -211.00 |
| Model  | Equation                                                                 | R²   | RMSE (g cm⁻³) | MAE (g cm⁻³) | MBE (g cm⁻³) |
|--------|--------------------------------------------------------------------------|------|---------------|--------------|--------------|
| 1      | DRadj.RawSC + DRRawSC + DRSD + DRMed + DRvariance - 1.68E-05DRvariance   | 0.7319 | 0.06375      | 11.080       | -216.61      |
| 2      | DRadj.RawSC + DRRawSC + DRSD + DRMed + DRvariance + 1.68E-05DRvariance   | 0.7319 | 0.06375      | 11.080       | -216.61      |
| 3      | DRadj.RawSC + DRRawSC + DRSD + DRMed + DRvariance + 1.70E-05DRvariance   | 0.7319 | 0.06375      | 11.080       | -216.61      |
| 4      | DRadj.RawSC + DRRawSC + DRSD + DRMed + DRvariance - 1.70E-05DRvariance   | 0.7319 | 0.06375      | 11.080       | -216.61      |

**Figure 2.** Field WD (g cm⁻³) versus estimated WD (g cm⁻³) using field WD derived from (a) Model 4, (b) Model 3, (c) Model 2 and (d) Model 1.
4. Conclusion

The correlations between WD and DR-derived variables were moderate. The fitted models that used the regression variables extracted from DR can be used for predicting WD. While our regressions only link the DR-variables to WD, further studies are needed to establish the accuracy of prediction for species-specific WD, thus are capable of explaining the variation on individuals within species trees. Our research and discovery envisage more predictive WD models for tropical tree species soon, and continuous improvement is deemed crucial on existing WD estimate models derived from Resistograph variables.

5. References

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