Root architecture and its relation with the growth characteristics of three planted *Shorea* species (Dipterocarpaceae)

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Abstract. Root and its architecture are important for trees to support their growth and development. However, there have been still few reports on tree roots architecture of important tropical forest tree species such as *Shorea* species. In this study, the differences of root architecture formation and the relation of root architecture and phenotype (growth) characteristics, including Index of Roots Anchoring (IRA) and Index of Roots Binding (IRB) of *S. stenoptera*, *S. palembanica*, and *S. leprosula* in Gunung Walat Education Forest were examined through root growth patterns, root morphology, and root growth variables. The results showed that the root growth patterns and the root morphology of three species were similar, which were classified into Champagnat group model with monopodial typical growth and tended to form orthotrophic branching. The total of root length significantly influenced tree height and trunk volume, while the depth root significantly influenced tree height and the crown diameter. The IRA values of *S. stenoptera* dan *S. palembanica* were categorized into medium group, while *S. leprosula* belonged to high group, suggesting that *S. leprosula* has a strong root anchorage compared to other two species. The IRB values of three *Shorea* species were categorized into low group, indicating low root binding ability in soil.

1. Introduction

*Shorea* spp. (meranti) is an important timber tree species that has a high economic and ecological value [1]. As the largest members of the Dipterocarpaceae family, meranti dominates the lowland mixed dipterocarp forest of West Malesia [2, 3]. However, *Shorea* population in Indonesia are decreasing due to the exploitation of the valuable timber and land conversion of the forest, where this species exists, from forests to other uses including forest plantation and shifting cultivation activity [1, 4]. A total of 147 species of meranti are included in the International Union for Conservation of Nature (IUCN) Red List of Threatened Species with 94 species are classified as critical endangered, 35 species are endangered, 9 species are vulnerable, 3 species are in low risk, 3 species are near threatened, 1 species is least concern and 1 species is extinct [5]. Based on these data, conservation efforts of these species either in-situ or ex-situ are needed. One of the successful effort of meranti ex-situ genetic conservation areas in West Java, Indonesia, is located in Gunung Walat Educational Forest.
In order to support the conservation of genetic resources of meranti in GWEF, an understanding of the biological aspects of the species such as root architecture is necessary [6].

Root and its architecture are important for trees to support their growth and development, such as for anchoring, air and nutrition absorption, and their distribution [7]. However, there have been still few reported research on tree roots architecture especially in forest tree species such as Shorea species. Therefore, the objectives of the study were (i) to determine the difference in the shape of root architecture on three meranti species (Shorea stenoptera, Shorea palembanica, and Shorea leprosula) in GWEF and (ii) to analyze the relationship of root architecture with growth characteristics (phenotypes), including Index of Roots Anchoring and Index of Roots Binding (IRB), of the three Meranti species (Shorea stenoptera, Shorea palembanica, and Shorea leprosula) in GWEF. This report provided a description of the root architecture of the three meranti species (Shorea stenoptera, Shorea palembanica, and Shorea leprosula) in the ex-situ conservation area of GWEF, as well as its relationship to plant growth characteristics.

2. Material and method

2.1. Study site

The study was conducted from August to October 2013 in the 0.6 ha of meranti (Shorea spp) ex-situ conservation Demonstration Plot No. 1 in Gunung Walat Education Forest (GWEF) (figure 1). The demonstration plot was established in 2004 with an area of ± 1.2 ha and meranti species were planted under moderate density of Agathis loranthifolia stands [6]. The GWEF itself is a 359 ha mature plantation forest managed by the Faculty of Forestry, Bogor Agricultural University (IPB), Indonesia, since 1968 [6]. The forest is located at Cicantayan and Cibadak sub-district, Sukabumi district, West Java province, which is around 60 km away from IPB Darmaga Campus, Bogor (figure 1).

Figure 1. Map of 0.6 ha Demonstration Plot in 2014 with a scale of 1:1000. Red: S. palembanica, blue: S. mecistopteryx, yellow: S. stenoptera, green: S. leprosula, grey: S. pinanga. Source: http://aunp.forst.uni-goettingen.de/outputs/papers/progress.pdf.
2.2. Research procedure

2.2.1 Sample selection. Selection of Shorea tree used for root sampling was based on purposive sampling method at meranti ex-situ conservation area. Root samples were taken from 9 individuals of 10-year-old live trees, which had the best phenotype (straight rod, stem diameter, and tree height) in each species. Furthermore, three Shorea species i.e. Shorea stenoptera, S. leprosula, and S. palembanica were selected for this study (figure 2).

![Leaf images](image)

**Figure 2.** Adult tree and leaf morphology of three Shorea studied. (a) Shorea leprosula, (b) Shorea stenoptera, and (c) Shorea palembanica.

2.2.2 Measurement of Shorea tree growth variables. Tree growth of each Shorea was indicated by tree height, stem diameter, crown diameter and stem volume variables.

- Tree height. The total of tree height was measured from ground line to top of terminal bud using Haga Hypsometer.
- Stem diameter. The data was obtained by initially measuring the tree’s circumference using measuring tape. The tree circumference was measured at 1.3 m above the ground (diameter breast height/dbh) for the trees that have a height of more than 4 m, whereas the calculation was conducted at 30 cm above the ground for the trees that have a height of less than 4 m. Afterwards, stem diameter was calculated by dividing the circumference measurement by 3.14.
- Crown diameter. The data was obtained by measuring the canopy length from north to south, and canopy length from west to east was measured on each individual tree using measuring tape. Furthermore, the crown diameter was calculated by dividing the sum of the canopy length from north to south and canopy length from west to east by 2.
- Stem volume. Calculation of stem volume for each individual tree was performed using the formula as in equation (1).

\[
V = \frac{1}{4} \pi D^2 H f
\]

where \(V\) is volume (m\(^3\)), \(\pi\) is 3.14, \(D\) is diameter (m), \(H\) is height (m) and \(f\) is form factor (0.7).

2.2.3 Roots excavation. Root excavation was firsthand performed on the western side of the roots, then continued on the eastern side to prevent the fall of the tree. First, root excavation was carried out by digging the soil at a distance of 50 cm from the outermost canopy. Furthermore, the excavation was continued at a distance of every 10 cm using a small shovel to brush up to the open root (figure 3).
2.2.4. Root architecture. Roots that have been excavated were further divided into 4 quadrants and determined its north, east, south, and west direction. The division of the quadrant was undertaken by drawing a straight line with a rope from north to south, and from west to east. Furthermore, each root type (primary root, secondary root, and tertiary root) was classified using different colored ropes. Each root that has been roped was then marked by using black markers as measurement points. The measurement points were made at the place, where the root direction changes (figure 4). The more measurement points were made, the closer fabrication of 3D root diagrams to the original. In addition, root length (cm), root diameter (mm), root depth (cm), and root orientation [8] were also measured.

2.2.5. Index of Roots Anchoring (IRA) and Index of Roots Binding (IRB). The diameter of the vertical root and horizontal root data on each root were required in order to calculate Index of Roots Anchoring (IRA) and Index of Roots Binding (IRB) through the equation (2).

\[
\text{IRA} = \frac{\sum dv^2}{\sum db^2} \quad \text{and} \quad \text{IRB} = \frac{\sum dh^2}{\sum db^2}
\]

(2)

where,

IRA : Index Root Anchoring
IRB : Index Root Binding
dv : vertical root diameter
dh : horizontal root diameter
db : stem diameter

Therewith, the value of IRA and IRB were classified based on Hairiah et al [8] as shown in table 1.
Table 1. Classification of Index Root Anchoring (IRA) and Index Root Binding (IRB) [9].

| Class  | IRA     | IRB     |
|--------|---------|---------|
| Low    | < 0.1   | < 1.5   |
| Moderate | 0.1 - 1.0  | 1.5 - 3.5 |
| High   | > 1.0    | > 3.5   |

2.3. Data analysis

Root data taken from the field were analysed using 3D Virtual Branch 1.0.3 software and Photoscape. While, root photos taken from the field were analysed using Ms. Office Picture Manager. Furthermore, the 3D root diagram and root photos of each Shorea species were analysed to determine root growth pattern, root morphology, and root characteristics.

The relationship between root architecture and growth characteristics were analysed using correlation model, while the effects of relationship between root architecture and growth characteristics were analysed using regression model. Root data and growth characteristics were analysed using Ms. Excel 2007 and SPSS 20.0 software.

Analysis on soil samples was undertaken at the Forest Influence Laboratory of the Faculty of Forestry, Bogor Agriculture University (IPB). The analysis of soil chemical properties included pH, C-organic, CEC, and soil texture.

3. Result and discussion

3.1. Tree growth characteristics of Shorea spp.

In this study, characteristics of Shorea species was revealed by measuring the tree growth variables (table 2). The results showed that the highest average value of tree height was in S. stenoptera (T=12.33 m), followed by S. leprosula (T=9.33 m) and S. palembanica (T=9.17 m) (table 2). The highest average value of stem diameter was in S. leprosula (θ=10.36 cm), followed by S. stenoptera (θ=9.24 cm) and S. palembanica (θ=8.81 cm). The highest average of crown diameter was in S. palembanica (θ=651.67 cm), followed by S. stenoptera (θ=642.50 cm) and S. leprosula (θ=450.00 cm). While, the highest average value of stem volume (V=0.06 m³) were in S. stenoptera and S. leprosula and the lowest was in S. palembanica (V=0.04 m³).

Shorea leprosula is a meranti species that undergoes the fastest growth when compared with other meranti in Borneo [10] such as S. platyclados, S. parvifolia, S. virescens and S. johorensis [4]. However, based on the measurement results, S. stenoptera has the highest average of tree height and S. leprosula has the highest stem diameter. These results occurred because the stand density in the plot of S. stenoptera was higher than the stand density in S. leprosula plot. The high density indicates the upper stratum of the forest canopy is closed and prevent most radiation [11,12], resulting in high competition in obtaining light between the tree communities. This light competition has a strong impact on the height growth over diameter growth in the tree community [13,14], so that individual trees under this pressure typically appear more slender than their dominant counterparts [15,16,17].

Table 2. Average growth variables in each Shorea spp.

| Variable | Species Name |
|----------|--------------|
| H (m)    | S. stenoptera | S. palembanica | S. leprosula |
|          | 12.33 a± 1.30 | 9.17 b± 0.67   | 9.33 b± 0.88 |
| θ (cm)   | 9.24 ab± 1.10 | 8.81 b± 0.65   | 10.36 a± 0.87 |
| θ j (cm) | 642.50 a± 68.25 | 651.67 a± 41.67 | 450.00 b± 51.07 |
| V (m³)   | 0.06 a± 0.02  | 0.04 a± 0.01   | 0.06 a± 0.01 |

(H) Height, (θ) Diameter, (θ j) Crown Diameter, (V) Stem Volume, ababc Duncan multiple range test at a 5 %
3.2. *Shorea* spp. root growth pattern

Root growth patterns of *Shorea* spp. were revealed by observing the typical root growth, axis branching pattern and orientation of the axis. The results showed that there was no difference on root growth pattern between the three *Shorea* spp. The typical root growths were monopodial, axis branching patterns were lateral and the orientations of the axis were orthotropic (table 3). This pattern suggested that the root architecture model of the three species was Champagnat’s. The Champagnat’s model is an architectural model that has pseudo-monopodial growth properties composed by a mixture of axes that are mostly oriented orthotropic. The branching occurs in the distal part, and some axes grow in plagiotropic [18].

Table 3. *Shorea* spp. root growth pattern.

| Species          | Typical growth | Axis branching pattern | Orientation of the axis |
|------------------|----------------|------------------------|-------------------------|
| *S. stenoptera*  | Monopodial     | Lateral                | Ortotrop                |
| *S. leprosula*   | Monopodial     | Lateral                | Ortotrop                |
| *S. palembanica* | Monopodial     | Lateral                | Ortotrop                |

3.3. Root morphology of *Shorea* spp.

Root morphology refers to the surface and branching of roots as an organ, including the characteristics of the root epidermis. The results showed that the root morphological characters of *S. stenoptera* were relatively hard and slippery surface, and less root hair (figure 5). Root color was 7.5 YR 8/2 (Munsell color standards), with clear-cut branching. The root system developed vertically, with the size of the primary proximal root diameter was quite large.

Figure 5. The root architecture of *S. stenoptera*. (a) root photo, (b) 3D diagram of root from side view, and (c) 3D diagram of root from the top view.

The morphological characters of *S. palembanica* root were relatively hard and slippery surface, and have root hair on its surface (figure 6). Root color was 7.5 YR 7/2 (Munsell color standards), with more complicated branching. Root system developed vertically and the diameter of the root was the lowest when compared to other species. Furthermore, the morphological characters of the *S. leprosula* root were relatively hard and slippery surface and have a root hair on the distal part (figure 7). Root color was 7.5 YR 7/2 (Munsell color standards), with clear branching and the root system developed vertically.
This study investigated that the root growth pattern and root morphology of *Shorea* spp. were relatively the same. This pattern was supported by Tomlison [19], which reported that the shape characterizes the appearance of a biological group, meaning that the roots of the same biological group tend to have similarities in architectural form and pattern in this case.

![Figure 6](image1.png)  
**Figure 6.** The root architecture of *S. palembanica*. (a) root photo, (b) 3D diagram of root from side view, and (c) 3D diagram of root from the top view.

![Figure 7](image2.png)  
**Figure 7.** The root architecture of *Shorea leprosula*. (a) root photo, (b) 3D diagram of root from side view, and (c) 3D diagram of root from the top view.

### 3.4 Relationship between root architecture and growth characteristics

The relationship between root architecture and growth characteristics of *Shorea* spp. were analyzed using Pearson correlation model (table 4) and regression model at significance level of 5% (figure 9). The results showed that the total length of primary root, the total length of the secondary
root, and the overall root length significantly affected tree height and volume. The highest correlation value was found in the relationship between the total length of primary root and tree height (77.8%), followed by the relationship between root depth and tree height (75.3%), and crown diameter (67.1%). Table 4 also evidenced that the total length of the root significantly affected tree height (67%), and tree volume (66.1%). Positive correlation values indicated that the increasing of total root length led to the increasing tree height as well as tree volume.

**Table 4.** Correlation between tree growth variables and root variables.

| Root variables | Tree Growth Variables |
|---------------|-----------------------|
|               | H (m)  | θ (cm) | θj (cm) | V (m³) |
| ∑ AP          | 0.016  | -0.438 | -0.011  | -0.27  |
| ∑ AS          | -0.534 | 0.077  | 0.207   | -0.235 |
| ∑ AT          | -0.513 | 0.082  | 0.312   | -0.19  |
| Tp.AP (cm)    | 0.778* | 0.199  | 0.473   | 0.661* |
| Tp. AS (cm)   | 0.608* | 0.333  | 0.589   | 0.642* |
| Total Root Length | 0.670* | 0.301  | 0.568   | 0.661* |
| θ AP (cm)     | -0.23  | 0.362  | 0.378   | 0.076  |
| θ AS (cm)     | 0.258  | 0.305  | 0.432   | 0.314  |
| Root Depth (cm) | 0.753* | 0.026  | 0.671*  | 0.456  |

(H) Height, (θ) Diameter, (θ j) Crown Diameter, (V) Stem Volume, (∑ AP) Number of Primary Roots, (∑ AS) Number of Secondary Roots, (∑ AT) Number of Tertiary Roots, (Tp.AP) Total Primary Roots, (Tp. AS) Total Secondary Roots, (θ AP) Diameter of Primary Roots, (θ AS) Diameter of Secondary Roots, and (*) significance level of 5%.

The coefficient of determination between total root length and tree height was 44.8%, while the coefficient of determination between the total root length and volume was 45.2%. Those coefficient of determination value showed that the relationship between each variable was low. However, the results of regression model at significant level of 5% (figure 8) denoted that there was a relationship between the total root length and height ($r^2 = 44.8\%$) (figure 8a) and there was a relationship between the total root length and volume ($r^2 = 45.2\%$) (figure 8b). The regression model at significant level of 5% (figure 9) also displayed that there was a relationship between the root depth and height ($r^2 = 56.6\%$) (figure 9a) and there was a relationship between the root depth and volume ($r^2 = 44.9\%$) (figure 9b).

**Figure 8.** Regression model. (a) between total root length and height, and (b) between total root length and volume.
3.5. Roots Anchoring (IRA) and Index of Roots Binding (IRB)

Index of Root Anchoring (IRA) is a comparison of the diameter of vertical roots and stem diameter, while Index of Root Binding (IRB) is the ratio between the diameter of horizontal roots with stem diameter [20]. The results showed that *S. stenoptera* and *S. palembanica* possessed a moderate level of IRA and low level of IRB pointed that the roots of the two species were quite capable of supporting the tree trunks to remain upright, but were not good enough to grab the soil (table 5). While, *S. leprosula* held a high level of IRA value and a low level of IRB value, which described that this species had strong root anchoring, but the roots were not good enough to grab the soil (table 5).

**Table 5.** IRA and IRB value of *Shorea* spp.

| Species        | IRA Average | Category | IRB Average | Category | Tree Robustness |
|----------------|-------------|----------|-------------|----------|-----------------|
| *S. stenoptera*| 0.35        | Moderate | 1.46        | Low      | 133.44          |
| *S. palembanica*| 0.66       | Moderate | 0.76        | Low      | 104.09          |
| *S. leprosula*  | 1.36        | High     | 0.77        | Low      | 90.06           |

This work revealed that the three *Shorea* species studied did not have roots that were strong enough, so the trees were prone to collapse when the tree faced an interference. The study of Abe and Ziemer [20] reported that the horizontal roots that spread in the surface layer of the soil would grip the soil and vertical roots as anchors would support the uptake of the tree so that the tree would not easily collapse by the mass movement of land.

The robustness of tree is one of the factors influencing the survival of a tree species. The level of robustness of the tree can be examined by dividing the tree height with tree diameter [21]. A high level of tree robustness value shows a low life capability because of the unbalanced ratio between height and diameter. The present study showed that *S. stenoptera* had the highest level of robustness (133.44), followed by *S. palembanica* (104.09) and *S. leprosula* (90.06). This pattern indicated that the trees, which had moderate level of IRA value and low level of IRB value would also have a low robustness level.

4. Conclusions

The root growth patterns on three meranti species (*Shorea stenoptera*, *Shorea palembanica*, and *Shorea leprosula*) were similar, which were classified into Champagnat group model with monopodial typical growth and tended to form orthotropic branching. The root morphology was also similar, and the variance of root characteristic variables was not significant between species. The total of root length significantly influenced tree height and trunk volume, while the depth root significantly influenced tree height and the crown diameter. The IRA values of *S. stenoptera* dan *S. palembanica* were categorized into medium group, while *S. leprosula* was categorized into high group, suggesting
that *S. leprosula* had a strong root anchorage compared to other two species. Furthermore, the IRB value of three *Shorea* species was categorized into low group, indicating low root binding ability in soil.

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**References**

[1] Cao C P Gailing O Siregar I Z Siregar U J and Finkeldey R 2009 Genetic variation in nine *Shorea* species (Dipterocarpaceae) in Indonesia revealed by AFLPs *Tree Genet Genomes* **5**:407–420

[2] Ashton P S 1982 *Flora Malesiana Series I-Spermatophyta. Flowering Plants Vol. 9, part 2, Dipterocarpaceae* (The Netherlands: Martinun Nijhoff Publishers)

[3] Ashton P S 1991 Toward a regional classification of the humid tropics of Asia *Tropics* **1**:1–12

[4] Widiyatno Purnomo S Soekotjo Na’iem M Hardwinoto S and Kasmujiono 2013 The growth of selected *Shorea* spp in secondary tropical rain forest: the effect of silviculture treatment to improve growth quality of *Shorea* spp *Procedia Environ Sci* **17**(2013):160–166

[5] The IUCN Red List of Threatened Species Version 2017-3 (www.iucnredlist.org (Accessed 09 February 2018)

[6] Faculty of Forestry, Bogor Agricultural University 2005 Establishment of an ex situ conservation area and domestication of *Shorea* spp. and *Calamus* spp. *Final Report ASEAN-EU University Network Programme, Conservation and Sustainable Utilization of Plant Genetic Resources in SE-Asia* (Bogor: Bogor Agricultural University)

[7] Lynch J 1995 Root architecture and plant productivity *Plant Physiol* **109**(1):7–13

[8] Soethe N Lehmann J and Engels C 2006 Root morphology and anchorage of six native tree species from a tropical montane forest and an elfin forest in Ecuador *Plant and Soil* **279**:173–185

[9] Hairiah K Widianto and Suprayogo D 2008 Adaptasi dan mitigasi pemanasan global : bisakah agroforestri mengurangi resiko longsor dan emisi gas rumah kaca *Kumpulan makalah INAFE* (Surakarta: UNS)

[10] Pamoengkas P and Prasetya R 2014 The Growth of Red Meranti (*Shorea leprosula* Miq.) with Selective Cutting and Line Planting in areas IUPHHK-HA PT. Sarpamit Central Kalimantan *Jurnal Silvikultur Tropika* **5**(3):174–180

[11] Weiner J 1990 Asymmetric competition in plant populations *Trends Ecol. Evol.* **5**(11):360–364 doi: 10.1016/0169-5347(90)90095-U

[12] Pacala S W Canham C D Saponara J Silander J A Jr, Kobe R K and Ribbens E 1996 Forest models defined by field measurements: estimation, error analysis and dynamics *Ecol Monogr* **66**(1):1–43

[13] King D A 1990 The adaptive significance of tree height *Am Nat* **135**:809–828

[14] Falster D S and Westoby M 2003 Plant height and evolutionary games *Trends Ecol Evol* **18**:337–343

[15] Sumida A Ito H and Isagi Y 1997 Trade-off between height growth and stem diameter growth for an evergreen Oak, *Quercus glauca*, in a mixed hardwood forest *Funct. Ecol* **11**:300–309

[16] Sumida A Miyaura T and Torii H 2013 Relationships of tree height and diameter at breast height revisited: analyses of stem growth using 20-year data of an even-aged *Chamaecyparis obtusa* stand *Tree Physiol* **33**:106–118

[17] Seki T Ohta S Fujiwara T and Nakashizuka T 2013 Growth allocation between height and stem diameter in nonsuppressed reproducing *Abies mariesii* trees *Plant Species Biol* **28**:146–155

[18] Hallé F Oldeman R A A and Tomlinson P B 1978 *Tropical trees and forests: an architectural analysis* (Berlin, Heidelberg, New York: Springer-Verlag)
[19] Tomlinson P B 1986 *The botany of mangroves* (Cambridge: Cambridge University Press)
[20] Setiawan O and Narendra B H 2012 *Strychnos lucida* R.Br. root system for landslide control
    *Jurnal Penelitian Kehutanan Wallacea* 1(1): 50–61 (In Indonesian)
[21] Jayusman 2005 *Evaluasi keragaman genetik bibit surian di perseaian* (Yogyakarta: Pusat
    Penelitian dan Pengembangan Hutan Tanaman) (In Indonesian)