

Article

Acclimatisation of White Laran (*Neolamarckia cadamba* Roxb. Bosser) and Binuang (*Octomeles sumatrana* Miq.) Seedlings to Water-Logged and Water-Stress Conditions

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Abstract: Although practices that employ native species in plantation systems are common, the study of *Neolamarckia cadamba* Roxb. Bosser (White Laran) and *Octomeles sumatrana* Miq. (Binuang) in below-ground parameters is limited. The present study was conducted to compare the initial growth performance and below-ground parameters between these two native trees under water-logged and water-stress conditions. The study was conducted near the greenhouse of the Faculty of Tropical Forestry (Universiti Malaysia Sabah, Kota Kinabalu, Sabah, Malaysia) for three months. Fifty seedlings of each species were grown in one-meter rhizotrons under Complete Randomized Design (CRD) with three different treatments: water stress (T1), water-logged (T2), and control (T3). Height and root collar diameter (RCD) increments, leaf area index (LAI), dried shoot biomass (DSB), root depth (RD), root intensity (RI), root biomass (RB), specific root length (SRL), and root length density (RLD) were recorded. The outcome plainly demonstrated that *N. cadamba* seedlings were adaptive to both treatments, but *O. sumatrana* seedlings were more sensitive to water-logged than water-stress conditions. No significant difference was observed between aboveground and below-ground parameters. In conclusion, *N. cadamba* and *O. sumatrana* can potentially survive in these conditions in plantations.

Keywords: root growth; plantation; native species; fast-growing; root interaction



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1. Introduction

Due to the high demand for agricultural activities, many lands were subjected to unattended activities. Land burning with aggressive shifting cultivation resulted in degraded soil, leading governments to maximize land usage in forest plantations [1]. In Sabah, 19,058 ha were used for logging activities and 162,022 m³ for timber harvesting in 2021. Around 370,130 ha of forest plantation area were acknowledged under various Sustainable Forest Management License Agreements (SFMLA) [2].

The importance of forest plantations varied in many ways based on evaluation criteria [3]. Most forest plantations were built on poor soils [4], resulting from logging activity degrading the soil structure and decreasing plant growth [5]. Nevertheless, marginal lands can provide ideal soil conditions with proper management [6]. This is mainly needed to restore ecosystem services and productivity in degraded lands so that all species can perform well [7].

At present, *Neolamarckia cadamba* Roxb. Bosser and *Octomeles sumatrana* Miq. have been introduced as a replacement for light hardwood as both species can grow in optimal environments, as was proved in early plantation trials by Sabah Forestry Department

(SFD). In addition, both species are preferable choices for locations where timber species do not really regenerate [8]. *N. cadamba*, also known as Kelempayan (Peninsular Malaysia and Sarawak), Laran (Sabah), Jabon (Kalimantan), or Kadam (India), is one of the most profit-oriented plantation species in Borneo (Sabah and Sarawak) and in some experimental plantings in Peninsular Malaysia supervised by the Forest Plantation Development Programme [9]. *N. cadamba* belongs to the Rubiaceae family [10]. On the other hand, *O. sumatrana*, also known as Binuang, belongs to the Datticaceae family and has straight boles like *N. cadamba* [11]. *O. sumatrana* can grow at an altitude of 0–600 m above sea level with mineral soils [12]. Moreover, in field planting, root interaction can be very challenging [13] because of methodological restrictions to measuring individual plant roots [14]. Heterogenous soil conditions will affect competition with neighboring roots [15]. Therefore, the present study was conducted on a small scale to measure and compare which species can survive in water-stress and water-logged conditions.

Both species are known as fast-growing species [2]; comparing their root phenotype and growth is essential to assess their performance [16]. *N. cadamba* is planted in different types of locations, wet and dry areas, regardless of the risk of failure because of its suitability to the negative effect of water-stress and water-logging on plant growth [17]. *O. sumatrana* also has high adaptability to dry and moist areas, including two types of soil—clay and sandy clay—along the river banks [18]. Although both are local species, scientific research is lacking regarding their early development in terms of root phenotyping, and water-stress and water-logged treatments. However, the information on this aspect is limited because of the challenges faced in field sampling—especially in root growth [8]. Other root parameters that can be studied to compensate for the absence of data and have a better understanding of the survivability of these species: are root intensity (RI), specific root length (SRL), root length density (RLD) [19], and root depth (RD).

Throughout this research, two indigenous species—*N. cadamba* and *O. sumatrana*—were used to determine if water-stress or water-logging treatments were suitable for their survival ability, mainly in terms of growth rate and root phenotyping. The application of water-stress and water-logging treatments influences the growth performance and root phenotyping of the seedlings of both species. Consequently, the adverse effects on plant growth, development, and seedling survival will restrict the species' potential range. It is essential to understand how they will adapt to the current environment, including water-stress and water-logged conditions [17]. Thus, the study compares the initial growth performance and below-ground parameters between *N. cadamba* (White Laran) and *O. sumatrana* (Binuang) under water-logging and water-stress conditions.

2. Materials and Methods

2.1. Site Description

The study was conducted at the Faculty of Tropical Forestry (Universiti Malaysia Sabah, Kota Kinabalu, Sabah, Malaysia), near the greenhouse ($6^{\circ}02'10.7''$ N $116^{\circ}07'34.9''$). Based on Figure 1, the average rainfall, temperature, and humidity were 14.9–16.1 mm, 27.4–27.1 °C, and 78.6–82.8%, respectively (Malaysia Meteorological Department 2022) (<http://www.met.gov.my>, accessed on 3 December 2022). This semi-controlled experiment was conducted from the third week of July to the end of October 2022.

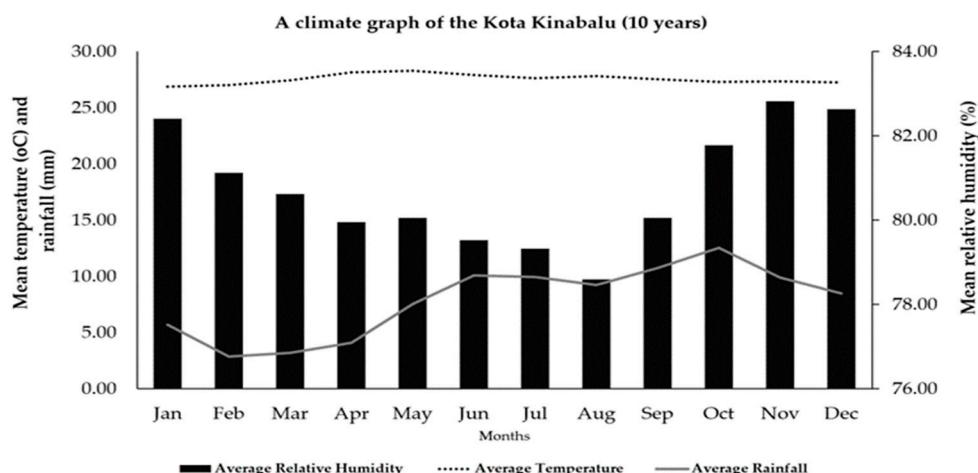


Figure 1. Weather data with the average temperature ($^{\circ}\text{C}$), rainfall (mm), and humidity (%) over a decade (2012–2022).

2.2. Experimental Description

This study utilized 36 rhizotrons (one plant for each rhizotron) in the form of vertical tubes 150 mm in diameter and 1000 mm in length. Eighteen seedlings per species were used throughout the experiment, with six seedlings per treatment involving three treatments; water-stress (T1), water logging (T2), and control (T3), with three replicates for each treatment. For T1, the surface area of the rhizotron was covered using transparent plastic to avoid any water throughout the experiment. Meanwhile, the rhizotron was put into the plastic container with a 30 cm water level from the bottom, making the rhizotron mimic the water-logged treatment for T2. The water was monitored daily so that the level of water was always maintained. For T3, no treatment was applied, and it was exposed to natural rainfall as a control treatment. Samples were arranged using Complete Randomized Design (CRD). The hollow transparent cuboid tube, rhizotron, was made of a 2 mm polycarbonate board. The transparency characteristic makes it easier to observe root interactions with soil, and the tubes were large enough to allow plants to grow to maturity. Four soil depths were utilized to monitor root growth: 0–25, 25–50, 50–75, and 75–100 cm. Before filling the soil, all rhizotrons had their bottoms covered with a plastic net to avoid the soil spilling out from the rhizotron. After filling the topsoil, 5 L of water was slowly passed through the top of the tube for nutrient washing to avoid nutrient content in the tubes. The experiment was harvested two times at 8 Weeks After Transplanting (WAT) during the first harvest and 12 WAT during the second or final harvest. At each harvest time, 18 rhizotrons (9 rhizotrons from *N. cadamba* and 9 rhizotrons from *O. sumatrana*) were harvested.

The rhizotrons were wrapped in non-transparent plastic throughout the study to avoid direct light exposure on the roots and soils. The rhizotrons were only uncovered when the measurement process took place. Before the experiment, the physical properties of the soil were reddish brown (5YR 4/4) to dark yellowish brown (10YR 3/6), sandy clay loam to sandy loam [20], and 1.82% moisture content (MC). The soil was a mixture of topsoil and sand in a 2:1 ratio. It was sieved through a 2 cm plastic gutter guard mesh after being air-dried for seven days in a greenhouse and was then placed into the rhizotron. The soil's chemical properties before the experiment are detailed in Table 1. In this experiment, one-month-old seedlings of *N. cadamba* and *O. sumatrana* were supplied by the Forest Research Centre (FRC, Sandakan, Sabah). The *N. cadamba* seeds were collected from Gum-Gum Forest Reserve, while *O. sumatrana* seeds were from the Tabin Forest Reserve. To mimic natural conditions, no water was added throughout the experiment. NPK fertilizer (15:15:15) was used in this study. Fertilizer was only utilized every other week by transplanting 0.120g per plant for each rhizotron, which is the equivalent of 50 kg per ha.

Table 1. Chemical composition of the soil before the experiment.

| Chemical Composition (Total Content for Each Element). | | | | | | | | | |
|--|----------------|-------|-------|-------|-------|-------|-------|-------|-------|
| pH | Organic Matter | P | K | Ca | Mg | Al | Na | Zn | Fe |
| 4.09–4.15 | 3.22% | 0.11% | 0.28% | 2.18% | 0.35% | 0.91% | 0.62% | 0.02% | 1.41% |

2.3. Data Collection

Root images were collected weekly starting from the seventh week after transplantation (7 WAT) over 12 weeks using the root camera model Nikon Coolpix S6800. The collection of below-ground parameters data involved non-destructive methods for Root Intensity (RI) [21,22] and destructive methods that included the determination of Root Length Density (RLD), Specific Root Length (SRL), Root Depth (RD), and Root Biomass (RB) by root washing [19]. Data were collected every other week starting from 2 WAT. Sampling from the first and second harvesting was performed at 8 WAT and 12 WAT. Each sampling included 18 experimental units and 3 replicates for each treatment for both species. RI was measured with a grid including 14×26 mm squares placed onto the pictures for root counting. RB and RLD (cm cm^{-3}) were determined by washing roots, using low water pressure and a test sieve (2 mm) to wash out all the organic matter. The soil was then weighed and put into an oven to dry at 70°C for 48 h. SRL (cm g^{-1}) was calculated by dividing the root length (cm) by its mass (g), and RLD (cm cm^{-3}) was calculated by dividing the root length (cm) by the soil volume (cm^3). For growth performance, Root Collar Diameter (RCD) (2.5 cm above the base) [23], seedling height, and Leaf Area Index (LAI) were recorded. The leaf area was assessed using an image analyzer with a leaf area meter (LI-3100c). LAI was then calculated by dividing the one-sided leaf area (m^2) and ground surface (m^2). The increment of RCD and height was calculated by subtracting the previously recorded measurement from the current one. For Dried Shoot Biomass (DSB), stems and leaves were dried jointly in a drying oven for 48 h at 70°C and then weighed.

2.4. Statistical Analysis

The data were analyzed using the latest version of the Statistical Package Social Science (IBM SPSS Statistics 28.0) software. Before further analysis, the data were tested using the Shapiro-Wilk test ($p > 0.05$) for testing the normality distribution of the data and the Levene test ($p > 0.05$) for testing the homogeneity of variance. Two-way ANOVA tests were utilized for all variables, such as height, RCD, DRB, LAI, RD, RB, SRL, RLD, and RI, in comparing variances across the means with the standard deviation of different species. Subsequently, Tukey's HSD was employed with $p < 0.05$ to assess the significance of the differences between the measured averages.

3. Results

3.1. Aboveground Parameters

3.1.1. Height Increment

Results from two-way ANOVA indicated that no significant difference ($p > 0.05$) was observed among the three treatments. The highest height increment of *N. cadamba* seedlings was observed in control conditions with no drought stress and an overflow of large quantities of water. In *O. sumatrana*, the highest height increment was observed in water-stress conditions, with a difference of 0.65 cm with seedlings in control conditions. Table 2 shows the means and standard deviations of height increments for each treatment in both species.

Table 2. Mean values of height increment (cm) of *N. cadamba* and *O. sumatrana* seedlings under different treatments ($n = 3$) were not significantly different ($p > 0.05$) using two-way ANOVA followed by Tukey's HSD post hoc.

| Treatments | Height Increment (cm) | | <i>p</i> -Value |
|--------------|-----------------------|---------------------|-----------------|
| | <i>N. cadamba</i> | <i>O. sumatrana</i> | |
| Water stress | 6.72 (1.86) | 4.87 (1.93) | $p > 0.05$ |
| Water-logged | 5.77 (0.96) | 4.53 (0.71) | |
| Control | 7.82 (0.45) | 4.22 (1.99) | |

3.1.2. Root Collar Diameter (RCD) Increment

Table 3 indicates that RCD increments of *N. cadamba* were higher in control conditions, whereas *O. sumatrana* showed a higher RCD increment under water-stress. These results are similar to the ones obtained with height increment. In addition, *O. sumatrana* had its lowest RCD increment under control conditions. From two-way ANOVA, none of the differences observed between treatments and between the two species was significant ($p > 0.05$).

Table 3. Mean values of root collar diameter (mm) of *N. cadamba* and *O. sumatrana* seedlings under different treatments ($n = 3$) were not significantly different ($p > 0.05$) using two-way ANOVA followed by Tukey's HSD post hoc.

| Treatments | Root Collar Diameter (mm) | | <i>p</i> -Value |
|--------------|---------------------------|---------------------|-----------------|
| | <i>N. cadamba</i> | <i>O. sumatrana</i> | |
| Water-stress | 1.18 (0.47) | 1.12 (0.11) | $p > 0.05$ |
| Water-logged | 1.15 (0.36) | 0.98 (0.19) | |
| Control | 1.47 (0.19) | 0.87 (0.35) | |

3.1.3. Leaf Area Index (LAI)

Table 4 indicates that *O. sumatrana* had its lowest LAI under water-logged conditions compared to water-stress conditions for *N. cadamba*. However, *O. sumatrana* showed an increased LAI under water-stress treatment compared to control conditions, in contrast to *N. cadamba*. Indeed, the latter showed its highest LAI value under control conditions. From two-way ANOVA, none of the differences observed between treatments and between the two species was significant ($p > 0.05$, $n = 3$).

Table 4. Mean values of leaf area index ($\text{m}^2 \text{ m}^{-2}$) of *N. cadamba* and *O. sumatrana* seedlings under different treatments ($n = 3$) were not significantly different ($p > 0.05$) using two-way ANOVA followed by Tukey's HSD post hoc.

| Treatments | Leaf Area Index ($\text{m}^2 \text{ m}^{-2}$) | | <i>p</i> -Value |
|--------------|---|---------------------|-----------------|
| | <i>N. cadamba</i> | <i>O. sumatrana</i> | |
| Water-stress | 0.09 (0.06) | 0.18 (0.10) | $p > 0.05$ |
| Water-logged | 0.15 (0.06) | 0.08 (0.03) | |
| Control | 0.18 (0.02) | 0.10 (0.06) | |

3.1.4. Dried Shoot Biomass (DSB)

The DSB of *N. cadamba* and *O. sumatrana* was obtained using a destructive method. As presented in Table 5, the DSB of both *N. cadamba* and *O. sumatrana* seedlings was the

highest under water-logged treatment compared to other conditions. The DSB of both species was the lowest under water-stress conditions. However, the result from two-way ANOVA indicates that none of the differences between treatments was significant ($p > 0.05$).

Table 5. Mean values of dried shoot biomass (g) of *N. cadamba* and *O. sumatrana* seedlings under different treatments ($n = 3$) were not significantly different ($p > 0.05$) using two-way ANOVA followed by Tukey's HSD post hoc.

| Treatments | Dried Shoot Biomass (g) | | <i>p</i> -Value |
|--------------|-------------------------|---------------------|-----------------|
| | <i>N. cadamba</i> | <i>O. sumatrana</i> | |
| Water-stress | 139.67 (42.17) | 116.43 (75.04) | $p > 0.05$ |
| Water-logged | 251.77 (117.52) | 227.33 (128.47) | |
| Control | 145.60 (42.73) | 128.60 (24.46) | |

3.2. Below-Ground Parameters

3.2.1. Root Depth (RD)

Table 6 and Figure 2 indicate that the RD of *N. cadamba* seedlings was highest under control conditions compared to water-stress and water-logged treatments. However, the graph shows that drought stress triggered a more positive root penetration to the deeper soil than water-logged stress. From two-way ANOVA, this difference was shown to be statistically significant ($p < 0.05$). The RD of *O. sumatrana* seedlings was the highest under water-logged treatment, but none of the observed differences was significant.

Table 6. Mean values of root depth (cm) of *N. cadamba* and *O. sumatrana* seedlings under different treatments ($n = 3$) were significantly different ($p < 0.05$) using two-way ANOVA followed by Tukey's HSD post hoc.

| Treatments | Root Depth (cm) | | <i>p</i> -Value |
|--------------|----------------------------|---------------------|-----------------|
| | <i>N. cadamba</i> | <i>O. sumatrana</i> | |
| Water-stress | 74.90 (8.10) ^{ab} | 52.40 (28.25) | $p < 0.05$ |
| Water-logged | 60.13 (2.97) ^b | 60.57 (4.10) | |
| Control | 77.60 (7.16) ^a | 35.10 (13.66) | |

Note: Different letters in superscripts indicate a significant difference at $p < 0.05$.

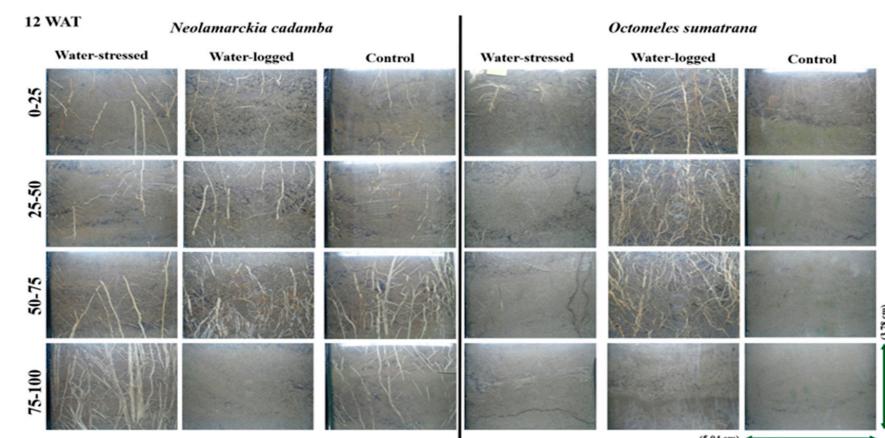


Figure 2. Root images of samples from the second harvesting stage (12 WAT). Roots were directly visualized, and images were measured (each image is 37.8 mm \times 50.4 mm).

3.2.2. Root Intensity (RI)

According to Figures 2 and 3, at 8 WAT *N. cadamba* had a higher RI at the upper soil level, and a significant difference ($p < 0.05$) between the three conditions was observed at that level. On the other hand, a significant difference between the three conditions was observed in *O. sumatrana* at all soil depths except the deepest one. *N. cadamba*'s roots adequately reached the deepest soil compared to *O. sumatrana*, although both species are fast-growing.

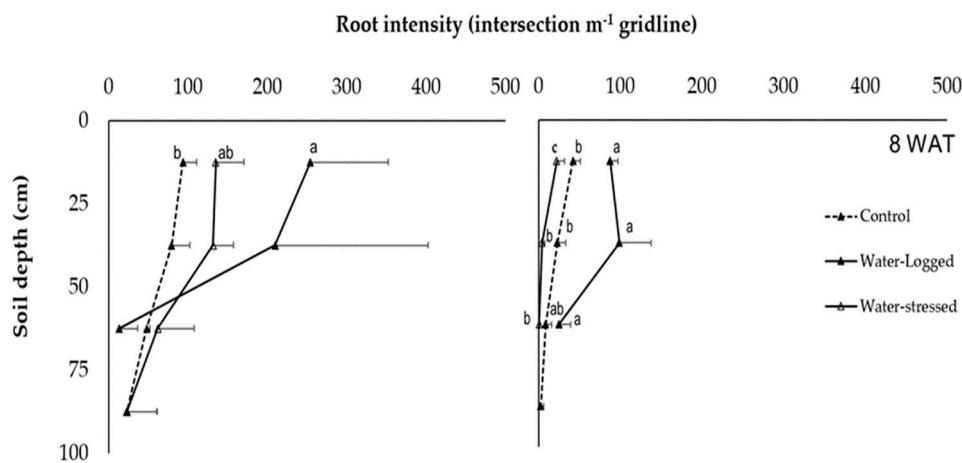


Figure 3. Root intensity (m^{-1} intersection gridline) at 8 WAT under water-stress, water-logged, and control treatment at different soil depths for *N. cadamba* (left) and *O. sumatrana* (right). A two-way ANOVA test was used, followed by Tukey's HSD ($p < 0.05, n = 3$). Error bars indicate standard deviation. Different letters indicate that a significant difference was observed between the various conditions for each depth tested.

At 12 WAT, a significant difference ($p < 0.05$) was observed in *N. cadamba* only at some mid-levels; the difference observed at the upper level at 8 WAT was lost (Figures 3 and 4). *O. sumatrana* showed similar results to those observed at 8 WAT, with significant differences at all soil levels except the deepest one. When comparing the RI of *O. sumatrana* between 8 WAT and 12 WAT, a rapid increase can be observed, especially in water-logged conditions (98.93–201.80 intensity m^{-1} gridline).

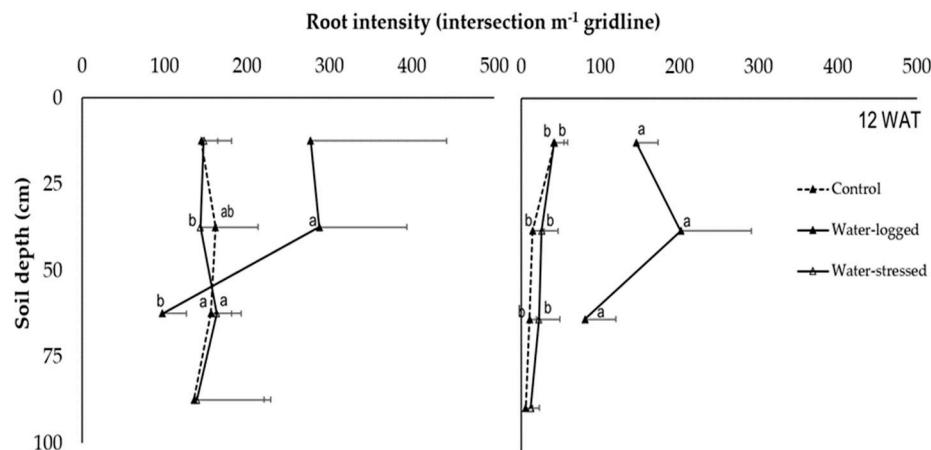


Figure 4. Root intensity (m^{-1} intersection gridline) at 12 WAT under water-stress, water-logged, and control treatment at different soil depths for *N. cadamba* (left) and *O. sumatrana* (right). A two-way ANOVA test was used, followed by Tukey's HSD ($p < 0.05, n = 3$). Error bars indicate standard deviation. Different letters indicate that a significant difference was observed between the various conditions for each depth tested.

3.2.3. Root Biomass (RB)

Root Biomass (RB) was measured at 8 WAT at different soil depths (Figure 5a). *N. cadamba* and *O. sumatrana* present similar results with a significant difference ($p < 0.05$) between treatments and soil depths. Both species have their highest RB value under water-logged conditions, with the RB of *N. cadamba* being twice as high as the RB of *O. sumatrana*. The lowest RB level recorded for *N. cadamba* is at the deepest soil layer under the water-logged treatment. However, at 12 WAT (Figure 5b), no significant difference ($p > 0.05$) was observed between treatments and soil depths for both species.

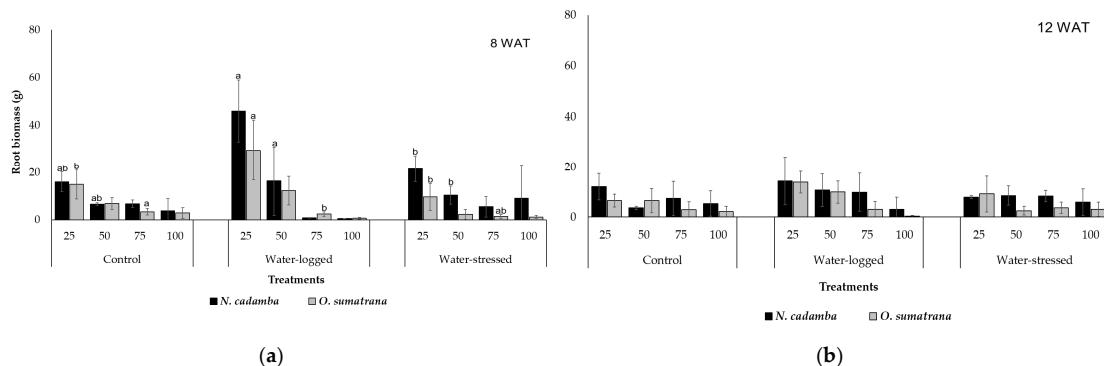


Figure 5. (a) Root biomass (g) at 8 WAT under water-stress, water-logged, and control treatment for *N. cadamba* and *O. sumatrana* at different soil depths. A two-way ANOVA test was used, followed by Tukey's HSD ($p < 0.05, n = 3$). Error bars indicate standard deviation. Different letters indicate a significant difference between the various conditions for each depth tested. (b) Root biomass (g) at 12 WAT under water-stress, water-logged, and control treatment for *N. cadamba* and *O. sumatrana* at different soil depths. A two-way ANOVA test was used, followed by Tukey's HSD ($p > 0.05, n = 3$). Error bars indicate standard deviation.

3.2.4. Specific Root Length (SRL)

The SRL of *O. sumatrana* was significantly higher ($p < 0.05$) at the deepest layer of soil (75–100 cm) compared to other depths. This difference was observed under the three tested conditions. The highest SRL was recorded in the third layer of soil (50–75 cm) under water-stress treatment, and the lowest SRL was recorded in the top layers. However, at 12 WAT, no significant difference ($p > 0.05$) was observed between the treatments and soil depths (Figure 6a). For *N. cadamba*, no significant difference was observed between treatments and soil depths, both at 8 WAT and 12 WAT. The SRL tends to be higher at 8 WAT under water-logged conditions at the deepest layer of soil (75–100 cm) compared to other treatments and soil depths. Despite the large variability observed at 12 WAT (Figure 6b), *N. cadamba* seedlings are about three times longer under the control treatment at the third layer of soil compared to the other treatments and depths.

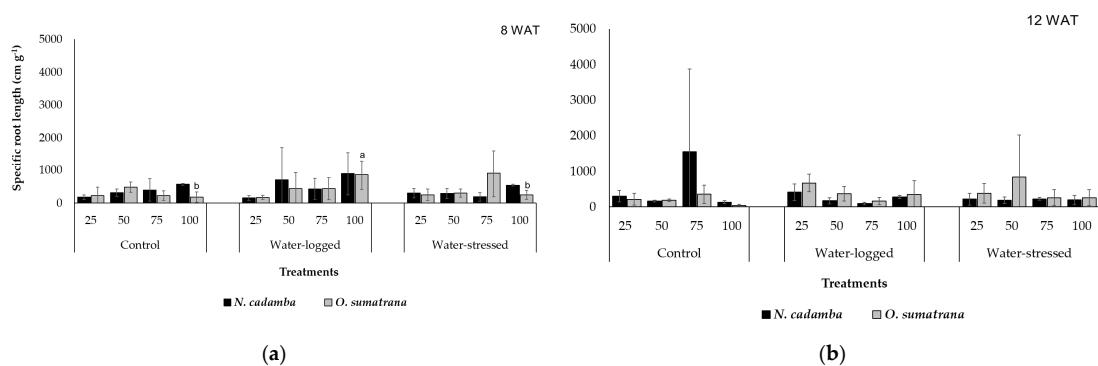


Figure 6. (a) Specific Root Length (cm cm⁻³) at 8 WAT under water-stress, water-logged, and control

treatment for *N. cadamba* and *O. sumatrana* at different soil depths. A two-way ANOVA test was used, followed by Tukey's HSD ($p < 0.05, n = 3$). Error bars indicate standard deviation. Different letters indicate a significant difference between the various conditions for each depth tested. (b) Root length density (cm cm^{-3}) at 12 WAT under water-stress, water-logged, and control treatment for *N. cadamba* and *O. sumatrana* at different soil depths. A two-way ANOVA test was used, followed by Tukey's HSD ($p > 0.05, n = 3$). Error bars indicate standard deviation.

3.2.5. Root Length Density (RLD)

The RLD of *N. cadamba* was found to be significantly different ($p < 0.05$) in the 0–25 cm layer of soil at 8 WAT compared to other soil depths under the water-logged treatment (Figure 7a). No significant difference between water-stress and water-logged treatments was observed at that top layer. At 12 WAT, the highest RLD recorded was under the water-stress treatment at a depth of 75–100 cm compared to other treatments; it was two times higher than the RLD recorded at 8 WAT. However, no significant difference was observed between the three tested conditions at different soil depths. In contrast, the RLD of *O. sumatrana* at 8 WAT showed no significant difference ($p > 0.5$) between treatments at different soil depths (Figure 7a). Nevertheless, the highest RLD recorded was under the water-logged treatment at the upper layer compared to other treatments. At 12 WAT, the RLD increased strongly under water-logged conditions, especially at the second soil depth (25–50 cm) (Figure 7b).

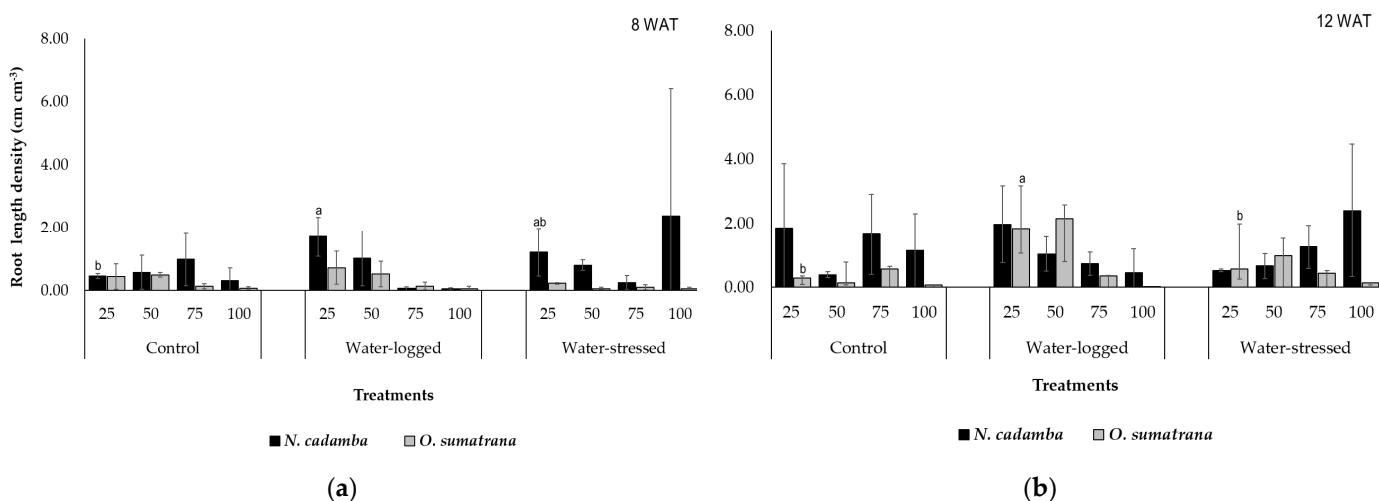


Figure 7. (a) Root length density (cm cm^{-3}) at 8 WAT under water-stress, water-logged, and control treatment for *N. cadamba* and *O. sumatrana* at different soil depths. A two-way ANOVA test was used, followed by Tukey's HSD ($p < 0.05, n = 3$). Error bars indicate standard deviation. Different letters indicate a significant difference between the various conditions for each depth tested. (b) Root length density (cm cm^{-3}) at 12 WAT under water-stress, water-logged, and control treatment for *N. cadamba* and *O. sumatrana* at different soil depths. A two-way ANOVA test was used, followed by Tukey's HSD ($p < 0.05, n = 3$). Error bars indicate standard deviation. Different letters indicate a significant difference between the various conditions for each depth tested.

4. Discussion

The present study demonstrated that the growth of seedlings could be influenced by the different treatments received, including drought pressure, water-logged stress, and control conditions. Previous studies showed that the height and growth ability of trees could be influenced by water-stress [24]. In addition, the average increment of *O. sumatrana*'s height under water-stress conditions was far higher than the one observed in *N. cadamba*, although both species are classified as fast-growing. This may be caused by phenotypic plasticity, defined as individuals' ability to cope when exposed to different environmental conditions in terms of growth, survival, and even transformation [25]. For

N. cadamba, the seedlings were affected by water-stress conditions, which decreased the plant's ability to achieve an ideal height performance. *N. cadamba* was said to be more adaptable in alluvial and moist areas, between periodically flooded areas, or in swamps, as soil moisture can influence the progressive growth of the plant [26]. Besides, the soil media used for the experiments in this study might have influenced the seedlings' growth in both species. A previous study using different media types demonstrated that the second-best medium for *N. cadamba*'s germination was a mix of soil and sand [27]. These conclusions are limited by time and methodology resources, and further experiments are needed to demonstrate that environmental conditions significantly impact the height of those trees.

In this study, *O. sumatrana* showed a positive incline of RCD under water-stress. This result contradicted previous knowledge affirming that RCD can be larger if the plant is exposed to higher soil moisture, as plants can take more water than they need [28]. Water-stress can have different impacts on the plant as it can lead to deleterious or adaptive changes [29]. However, this study was conducted over a short time. A more extended period of water limitation can lead to more significant changes in the structure of plants. Water limitation can restrain cell growth, resulting in a loss of cell turgor, thus decreasing the diameter of newly-formed adventitious roots [30]. Understanding water transport is crucial, as RCD can vary depending on water availability [31]. The RCD of *N. cadamba* rose steadily under the control treatment compared to the water-logged stress, following the knowledge that optimal water availability can increase water-use efficiency [32]. Similarly, the RCD was not significantly reduced by water-logged stress, as previous studies demonstrated that water uptake by the roots is slower under water-logged treatment than under control conditions [33].

No noteworthy difference was observed in the means of the LAI between all three conditions. The leaf area indicates drought tolerance and is essential in metabolic activities [17]. Water-stress allows adaptive action for immediate survival and structural plants' ability to alter their gene expression, thus allowing improved functioning [29]. *O. sumatrana* had an apparent increase of LAI under water-stress due to a reduction in the number of leaves produced but not in the total leaf surface. The capability to increase leaf area and the development of the leaf area itself were seemingly under genetic control [34]. The highest mean of LAI in *N. cadamba* was recorded under control treatment, probably due to seedlings producing leaves quickly because there was no water restriction [35]. Water-stress treatment in *N. cadamba* led to slightly lower mean values than in *O. sumatrana* because small leaves endure turgor pressure better than larger leaves and can significantly contribute to turgor maintenance under stress conditions [17]. The leaf growth changes caused by the deficiency of nutrients were well-demonstrated throughout these findings. Nutrient leaching occurs by the loss of water-soluble plain nutrients from the soil because of rainfall, except for water-stress treatment since samples were covered by transparent plastic. The observed positive effect could be sustained as the growth in all live individuals was stagnant [36]. Therefore, the results observed for LAI do not necessarily mean that the growth is not optimal, as other parameters also influence growth performance.

Results obtained from the analysis of dried shoot biomass showed that the mean value at 8 WAT and 12 WAT was impacted by water-logged treatment. The shoot biomass is closely related to roots. The shoots' dry weight reflects the roots' capability to support the DSB in maintaining plant structure and form and absorbing nutrients and water [37]. This is because roots play a significant role in the uptake of nutrients and water while providing support and anchorage to plants [38]. Soil water availability is one of the features that restrict the production of plants [39]. Water and nutrients can be absorbed efficiently when the root density is greater, which increases shoot biomass [19]. The higher the moisture content in soil due to water availability, the more root growth can be improved, thus improving plant growth [39]. Both species recorded their lowest reading at both harvest stages when submitted to a water-stress treatment. Water restriction leads to a deficit in the number of leaves per plant and green leaves present and a decrease in leaf longevity

depending on the soil's water potential [17]. A stressful environment can be the principal reason that prevents maximal growth and biomass production [25].

As for RD and RI, the data were presented according to roots visible at the rhizotron interface (Table 6, Figures 2–4). Genetic and environmental conditions generally influence root depth. Root depth could be a significant feature in species in addition to their root biomass, as roots play an essential role in water uptake and nutrient absorption and can accommodate the shape of plants by hydraulic lift (HL). Additionally, the soil-water relationship is interconnected with the rooting condition, as the existing variation of optimal rooting depths depends on the species and its capability to adapt to various soil conditions [40]. Based on the results, different root depths can be seen, with both species thriving excellently in particular conditions. *N. cadamba* root depth generally approached 80 cm, demonstrating that this species' root system is adaptive to water restriction pressure. A root system capable of penetrating deeper into the soil to extract water from deeper layers is an indispensable criterion for drought resistance. Its impact on the survival ability of the plant is significant as it allows efficient water use under drought stress [30]. *O. sumatrana* prefers to penetrate high moisture of soil, approaching 65 cm of depth, which is almost 80% of *N. cadamba*'s root depth. Under the water-stress condition, as root length is reduced due to hypoxia [33], roots approach the third layer of soil (50–75 cm). Besides, it is believed that *N. cadamba* and *O. sumatrana* could not have more root extensions when approaching the deepest soil layer (75–100 cm) due to water clogging. This observation was supported by a previous study demonstrating that constant flooding leads to unsuitable conditions for *O. sumatrana* to grow [2]. Another study also stated that some trees of *N. cadamba* in forest plantation areas, which have continuous access to excessive water, resulted in aboveground disadvantages and poor root systems [9].

The rhizotron is one of the methods used to calculate the RI through two-dimensional root imaging (captured image), also known as a non-destructive method [41]. The mean value for RI for both species at 75–100 cm was the lowest under water-logged treatment. The same condition applied to different species also showed that root development was severely restricted under complete water-logged treatment. The finding showed that roots could have different functions and growth if the plant survives under water-logged treatment as the roots go into hypoxia [42]. That is why the RI mean value gap between water-logged treatment and control treatment is slightly different; both species can survive in an environment with high soil moisture content but not in a fully clogged environment in the long term [17]. Usually, the growth rate of roots is gravely decreased when plants undergo water-logged treatment [43]. Therefore, root traits significantly improve the relationship between below-ground activities and plant growth [41].

In each treatment, root biomass production was affected to a different extent. Through the analysis of both species in the first and second harvests under water-stress, water-logged, and control treatment, the RB in the upper layer (0–25 cm) and the second layer of soil (25–50 cm) presented the highest average of RB. On the other hand, in soil depths of 50–75 cm and 75–100 cm, only a low amount of root biomass was produced—about one-third of the root mass growing in the upper layer. In the third and fourth depths of the soil, a root biomass reduction is expected at the end of the harvesting stage. Indeed, root respiration decreases as water-logging produces delayed effects and can damage the root biomass [43]. The higher the depth of the soil and, thus, the water content, the lower the root biomass production [44]. Low root biomass production is a primary element that significantly impacts growth patterns and water relations [33]. Hypoxic or anoxic conditions inhibit root growth, making their primary purpose difficult [45]. On the other hand, roots need to absorb more water in the first and second layers of soil; soil moisture must be maintained to support the distribution of roots. In addition, higher root biomass in upper soil layers is caused by a lower soil water content at the surface than in subsurface layers [44].

Generally, the SRL observed in *N. cadamba* was higher than that of *O. sumatrana*. SRL is the root length ratio to fine roots' dry mass [19]. SRL increases simultaneously with

RI [46]. SRL is a complex parameter that includes variations in root diameter and root tissue density [47]. At 8 WAT, *N. cadamba* and *O. sumatrana* presented their highest SRL under water-logged treatment, which increases the root diameter [43]. *N. cadamba*, at the second harvest stage, presented its highest SRL under the control treatment. It was argued that roots in normal conditions are more productive in deeper soils since roots often occupy shallow layers [48]. A different situation was observed with *O. sumatrana* at 12 WAT, with a steady increase under water-stress treatment. Root elongation is necessary when plants are grown in conditions with restricted supplies of water in the soil [49]. A greater SRL is obtained by having a smaller diameter of roots, and reaching water under water-stress requires an increase in root length or root hair density and a decrease in plant carbon investment [50]. Thus, the analysis must be emphasized by a better understanding of drought adaptation mechanisms, as roots are the least affected compared to vegetative, reproductive, and aerial organs [30].

RLD is essential as it was used to evaluate the root system by exploring the soil in search of nutrients and water [51]. A low RLD was observed in *O. sumatrana* in the fourth layer of soil (75–100 cm) under the water-logged treatment because compacted soil is more prone to a complete water-logged condition where hypoxia is likely to impede root growth [49]. Indeed the lowest RLD was observed in the third and fourth layers of soil (50–100 cm). A previous study demonstrated that if the root system is exposed to flooding, the mortality rate of the plant increases [52]. However, *O. sumatrana* recorded its highest RLD at the second layer of soil under the water-logged treatment compared to other treatments. Water from rainfall is usually kept deep in the soil, and the rapid growth of roots penetrating through the soil increases the capture of water and nitrogen [53]. Roots can change based on different soil depths depending on the availability of nutrients and water [54]. RLD can drastically increase, and roots can spread in the upper layer of soil that is not water-logged [42]. The higher RLD of *N. cadamba* observed under the water-stress treatment at 12 WAT in the third layer of soil (50–75 cm) is assumed to be a potential adaptation feature [55]. Roots are more present in drought conditions where plants try to survive, showing their capability to adapt to marginal lands. Exploring root increase has considerable potential in genetic research to optimize root system architecture (RSA) in water-stress conditions [56]. Besides, the mean value was slightly higher at a soil depth of 50–75 cm compared to the upper layers. Nevertheless, a previous study suggested that the reallocation of carbon under water-stress impacts root growth, decreasing RLD in upper layers [51]. Roots tend to penetrate deep soil because of the limited water availability in top soil layers [57]. This phenomenon is part of xerotropism, where the root gravity response is enhanced in response to desiccation [58].

5. Conclusions

In conclusion, *N. cadamba* is a commercial native species that can tolerate limited water conditions and survive in slightly damp areas. On the other hand, *O. sumatrana* survives better in slightly wet areas compared to dry ones. Even though some of the parameters studied were not significantly different, at least the present study may provide some information and estimation on how both species interact and survive in those areas. The lack of significant difference in the findings could be influenced not only by the heterogenous of the soil but also the genetic factor of the plant. The scope of the present study is limited to a few aspects, and many gaps remain. It is recommended that such a study could be validated in real planting by considering the suitable methodology, especially working with the roots aspect. However, these data could contribute to tree selection for future candidate species in tree plantations and be a guideline to improve crop trees' performance under water restriction.

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References

1. Lintangah, W.; Mojiol, A.R.; Kodoh, J.; Solimun, M. An Assessment of Tree Plantation Activity among Smallholders in the District of Ranau, Sabah. *Mod. Appl. Sci.* **2010**, *4*, 58. [[CrossRef](#)]
2. Sabah Forestry Department. Sabah Forestry Department Annual Report 2021. Available online: <https://forest.sabah.gov.my/> (accessed on 26 November 2022).
3. Szulecka, J.; Pretzsch, J.; Secco, L. Paradigms in tropical forest plantations: A critical reflection on historical shifts in plantation approaches. *Int. Forest. Rev.* **2014**, *16*, 128–143. [[CrossRef](#)]
4. Hamid, H.A.; Abiri, R. The way forward of Forest Plantation in Malaysia. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *959*, 012001. [[CrossRef](#)]
5. Ilstedt, U.; Nordgren, A.; Malmer, A. Soil chemical and microbial properties after disturbance by crawler tractors in a Malaysian forest plantation. *For. Ecol. Manag.* **2006**, *225*, 313–319. [[CrossRef](#)]
6. Csikós, N.; Tóth, G. Concepts of agricultural marginal lands and their utilisation: A review. *Agric. Syst.* **2022**, *204*, 11. [[CrossRef](#)]
7. Bijalwan, A. A Potential Fast Growing Tree for Agroforestry and Carbon Sequestration in India: *Anthocephalus cadamba* (Roxb.) Miq. *Am. J. Agric. For.* **2014**, *2*, 296. [[CrossRef](#)]
8. Lee', Y.F.; Chia, F.R.; Anuar, M.; Ong, R.C.; Ajik, M. The Use of Laran and Binuang for Forest Plantations And Intercropping with Oil Palm in Sabah. *Sepilok Bull.* **2005**, *4*, 1–13.
9. Yahya, A.Z. A Quarterly of the Forest Research Institute Malaysia. 2015. Available online: https://www.frim.gov.my/v1/fif/pdf_file/FIF-September2015-weboptimized.pdf (accessed on 26 November 2022).
10. Krisnawati, H.; Kanninen, M.; Kallio, M. *Anthocephalus Cadamba Miq.: Ecology, Silviculture and Productivity*; Center for International Forestry Research: Bogor, Indonesia, 2011; pp. 1–10.
11. Nordahlia, A.; Husain, H.; Lim, S.C.; Uyup, M.K.A. Wood Properties of Selected Plantation Species: *Tectona Grandis* (Teak), *Neolamarchea Cadamba* (Kelempayan/Laran), *Octomeles Sumatrana* (Binuang) and *Paraserianthes Falcataria* (Batai). *Timber Technol. Bull.* **2014**, *54*, 1–7.
12. Kailola, J.; Mardiatmoko, G.; Simanjuntak, R.; Kastanya, A. The Moisture Content and Absorption Levels of Carbon Dioxide in Binuang Bini (*Octomeles Sumatrana* Miq.) Trees For Climate Change Management. *J. Manaj. Hutan Trop.* **2021**, *27*, 143–151. [[CrossRef](#)]
13. Zhao, J.; Bodner, G.; Rewald, B.; Leitner, D.; Nagel, K.A.; Nakhforoosh, A. Root Architecture Simulation Improves the Inference from Seedling Root Phenotyping towards Mature Root Systems. *J. Exp. Bot.* **2017**, *68*, 965–982. [[CrossRef](#)]
14. Hassan, A.; Kodoh, J.; Kamu, A.; Majius, R.; Yunus, N.M. Root Interactions on Sole Crop and Intercrop Give Different Effects of Competition. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *449*, 012012. [[CrossRef](#)]
15. Schenk, H.J. Root Competition: Beyond Resource Depletion: Root Competition: Beyond Resource Depletion. *J. Ecol.* **2006**, *94*, 725–739. [[CrossRef](#)]
16. Barber, N.A.; Milano, N.J.; Kiers, E.T.; Theis, N.; Bartolo, V.; Hazzard, R.V.; Adler, L.S. Root Herbivory Indirectly Affects Above-and below-Ground Community Members and Directly Reduces Plant Performance. *J. Ecol.* **2015**, *103*, 1509–1518. [[CrossRef](#)]
17. Sudrajat, D.J.; Siregar, I.Z.; Khumaida, N.; Siregar, U.J.; Mansur, I. Adaptability of White Jabon (*Anthocephalus Cadamba* Miq.) Seedling From 12 Populations to Drought and Waterlogging. *J. Agric. Sci.* **2015**, *37*, 130–143. [[CrossRef](#)]
18. Bogidarmanti, R.; Darwo. Application of Silviculture Techniques to Improve Productivity of Binuang Bini Plant (*Octomeles Sumatrana* Miq.) as an Alternative Plant in Community Forest. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *394*, 012022. [[CrossRef](#)]
19. Hassan, A.; Balachandran, P.; Khamis, K.R. Early Root Development of *Eucalyptus Pellita* F. Muell. Seedlings from Seed and Stem Cutting Propagation Methods at Nursery Stage. *Int. J. For. Res.* **2021**, *2021*, 1–10. [[CrossRef](#)]
20. Anonymous; Munsell Color (Firm). *Munsell Soil Color Charts: With Genuine Munsell Color Chips*, 1954 ed.; Munsell: Baltimore, MD, USA, 1954; Volume 1.

21. Hassan, A.; Dresbøll, D.B.; Rasmussen, C.R.; Lyhne-Kjærbye, A.; Nicolaisen, M.H.; Stokholm, M.S.; Lund, O.S.; Thorup-Kristensen, K. Root Distribution in Intercropping Systems—A Comparison of DNA Based Methods and Visual Distinction of Roots. *Arch. Agron. Soil Sci.* **2021**, *67*, 15–28. [[CrossRef](#)]
22. Thorup-Kristensen, K. Are Differences in Root Growth of Nitrogen Catch Crops Important for Their Ability to Reduce Soil Nitrate-N Content, and How Can This Be Measured? *Plant Soil* **2001**, *230*, 185–195. [[CrossRef](#)]
23. Chhetri, D.B.K.; Fowler, G.W. Estimating Diameter at Breast Height and Basal Diameter of Trees from Stump Measurements in Nepal’s Lower Temperate Broad-Leaved Forests. *For. Ecol. Manag.* **1996**, *81*, 75–84. [[CrossRef](#)]
24. Trouvé, R.; Bontemps, J.-D.; Seynave, I.; Collet, C.; Lebourgeois, F. Stand Density, Tree Social Status and Water Stress Influence Allocation in Height and Diameter Growth of *Quercus Petraea* (Liebl.). *Tree Physiol.* **2015**, *35*, 1035–1046. [[CrossRef](#)]
25. Li, F.-L.; Bao, W.-K.; Wu, N. Morphological, Anatomical and Physiological Responses of *Campylotropis Polyantha* (Franch.) Schindl. Seedlings to Progressive Water Stress. *Sci. Hortic.* **2011**, *127*, 436–443. [[CrossRef](#)]
26. Rahman, I.A.; Suratman, M.N. Assessments of Growth, Volume and Above Ground Biomass of Four Forest Plantation Species In Sarawak, Malaysia. In Proceedings of the Second International Conference on Science, Engineering & Environment, Osaka, Japan, 21–23 November 2016; pp. 1–6.
27. Irawan, U.S.; Purwanto, E. White Jabon (*Anthocephalus Cadamba*) and Red Jabon (*Anthocephalus Macrophyllus*) for Community Land Rehabilitation: Improving Local Propagation Efforts. *Agric. Sci.* **2014**, *2*, 36–45. [[CrossRef](#)]
28. Mei, T.-T.; Zhao, P.; Wang, Q.; Cai, X.; Yu, M.; Zhu, L.; Zou, L.; Zeng, X. Effects of Tree Diameter at Breast Height and Soil Moisture on Transpiration of *Schima Superba* Based on Sap Flow Pattern and Normalization. *J. Appl. Ecol.* **2010**, *21*, 2457–2464.
29. Chaves, M.M.; Pereira, J.S.; Maroco, J.; Rodrigues, M.L.; Ricardo, C.P.P.; Osorio, M.L.; Carvalho, I.; Faria, T.; Pinheiro, C. How Plants Cope with Water Stress in the Field? Photosynthesis and Growth. *Ann. Bot.* **2002**, *89*, 907–916. [[CrossRef](#)]
30. Labdelli, A.; Adda, A.; Halis, Y.; Soualem, S. Effects of Water Regime on the Structure of Roots and Stems of Durum Wheat (*Triticum Durum* Desf.). *J. Bot.* **2014**, *2014*, 703874. [[CrossRef](#)]
31. Rahman, M.S.; Rahman, M.; Amin, M.; Raihan, A. Effect of Water Stress on The Shoot Morphology and Root Architecture of *Azadirachta Indica* A. Juss. Seedling Under Nursery Condition. *J. Sci. Technol.* **2017**, *15*, 25–33.
32. Driesen, E.; De Proft, M.; Saeyns, W. Soil Moisture Levels Affect the Anatomy and Mechanical Properties of Basil Stems (*Ocimum Basilicum* L.). *Plants* **2021**, *10*, 1320. [[CrossRef](#)]
33. Schmull, M.; Thomas, F.M. Morphological and Physiological Reactions of Young Deciduous Trees (*Quercus Robur* L., *Q. Petraea* [Matt.] Liebl., *Fagus Sylvatica* L.) to Waterlogging. *Plant and Soil* **2000**, *225*, 227–242. [[CrossRef](#)]
34. Gomez-del-Campo, M.; Ruiz, C.; Lissarrague, J.R. Effect of Water Stress on Leaf Area Development, Photosynthesis, and Productivity in Chardonnay and Airén Grapevines. *Am. J. Enol. Vitic.* **2002**, *53*, 138–143. [[CrossRef](#)]
35. Liu, Z.; Hikosaka, K.; Li, F.; Jin, G. Variations in Leaf Economics Spectrum Traits for an Evergreen Coniferous Species: Tree Size Dominates over Environment Factors. *Funct. Ecol.* **2020**, *34*, 458–467. [[CrossRef](#)]
36. Junaedi, A.; Mindawati, N.; Rochmayanto, Y. Early Growth of Jabon (*Anthocephalus Cadamba* Miq.) In A Drained Peatland of Pelalawan, Riau. *J. For. Res.* **2021**, *8*, 59–72. [[CrossRef](#)]
37. Budiman, B.; Sudrajat, D.J.; Lee, D.K.; Kim, Y.S. Effect of Initial Morphology on Field Performance in White Jabon Seedlings at Bogor, Indonesia. *J. Appl. Sci. Technol.* **2015**, *11*, 206–211. [[CrossRef](#)]
38. Pandey, R.; Chinnusamy, V.; Rathod, G.; Paul, V.; Jain, N. Evaluation of Root Growth and Architecture. *Div. Plant Physiol. Indian Agric. Res. Inst.* **2017**, 95–102. [[CrossRef](#)]
39. He, Y.Q.; Zhu, Y.G.; Smith, S.E.; Smith, F.A. Interactions Between Soil Moisture Content and Phosphorus Supply in Spring Wheat Plants Grown In Pot Culture. *J. Plant Nutr.* **2002**, *25*, 913–925. [[CrossRef](#)]
40. Maeght, J.-L.; Rewald, B.; Pierret, A. How to Study Deep Roots—And Why It Matters. *J. Plant Nutr.* **2013**, *4*, 1–14. [[CrossRef](#)]
41. Takahashi, H.; Pradal, C. Root Phenotyping: Important and Minimum Information Required for Root Modeling in Crop Plants. *Breed. Sci.* **2021**, *71*, 109–116. [[CrossRef](#)]
42. Fujita, S.; Noguchi, K.; Tange, T. Different Waterlogging Depths Affect Spatial Distribution of Fine Root Growth for *Pinus Thunbergii* Seedlings. *J. Plant Nutr.* **2021**, *12*, 614764. [[CrossRef](#)]
43. De San Celedonio, R.P.; Abeledo, L.G.; Mantese, A.I.; Miralles, D.J. Differential Root and Shoot Biomass Recovery in Wheat and Barley with Transient Waterlogging during Preflowering. *Plant Soil* **2017**, *417*, 481–498. [[CrossRef](#)]
44. Sainju, U.M. Root Biomass, Root/Shoot Ratio, and Soil Water Content under Perennial Grasses with Different Nitrogen Rates. *Field Crops Res.* **2017**, *210*, 183–191. [[CrossRef](#)]
45. Sauter, M. Root Responses to Flooding. *Curr. Opin. Plant Biol.* **2013**, *16*, 282–286. [[CrossRef](#)]
46. Kramer-Walter, K.R.; Bellingham, P.J.; Millar, T.R.; Smissen, R.D.; Richardson, S.J.; Laughlin, D.C. Root Traits Are Multidimensional: Specific Root Length Is Independent from Root Tissue Density and the Plant Economic Spectrum. *J. Ecol.* **2016**, *104*, 1299–1310. [[CrossRef](#)]
47. Ostonen, I.; Püttsepp, Ü.; Biel, C.; Alberton, O.; Bakker, M.R.; Löhmus, K.; Majdi, H.; Metcalfe, D.; Olsthoorn, A.F.M.; Pronk, A.; et al. Specific Root Length as an Indicator of Environmental Change. *Plant Biosyst.-Int. J. Deal. All Asp. Plant Biol.* **2007**, *141*, 426–442. [[CrossRef](#)]
48. Alam, M.; Jiang, Y.-J.; Umar, M.; Su, L.; Rahman, M.; Ullah, F. Influence of Drainage and Root Biomass on Soil Mechanical Behavior in Triaxial Tests. *Acta Geotech.* **2022**, *17*, 2875–2893. [[CrossRef](#)]

49. Bengough, A.G.; McKenzie, B.M.; Hallett, P.D.; Valentine, T.A. Root Elongation, Water Stress, and Mechanical Impedance: A Review of Limiting Stresses and Beneficial Root Tip Traits. *J. Exp. Bot.* **2011**, *62*, 59–68. [[CrossRef](#)] [[PubMed](#)]
50. Comas, L.H.; Becker, S.R.; Cruz, V.M.V.; Byrne, P.F.; Dierig, D.A. Root Traits Contributing to Plant Productivity under Drought. *J. Plant Nutr.* **2013**, *4*, 1–16. [[CrossRef](#)]
51. Faye, A.; Sine, B.; Chopart, J.-L.; Grondin, A.; Lucas, M.; Diedhiou, A.G.; Gantet, P.; Cournac, L.; Min, D.; Audebert, A.; et al. Development of a Model Estimating Root Length Density from Root Impacts on a Soil Profile in Pearl Millet (*Pennisetum glaucum* (L.) R. Br). Application to Measure Root System Response to Water Stress in Field Conditions. *PLoS ONE* **2019**, *14*, e0214182. [[CrossRef](#)] [[PubMed](#)]
52. Coutts, M.P.; Philipson, J.J. Tolerance of Tree Roots To Waterlogging. I. Survival of Sitka Spruce and Lodgepole Pine. *New Phytol.* **1978**, *80*, 63–69. [[CrossRef](#)]
53. Wasson, A.P.; Richards, R.A.; Chatrath, R.; Misra, S.C.; Prasad, S.V.S.; Rebetzke, G.J.; Kirkegaard, J.A.; Christopher, J.; Watt, M. Traits and Selection Strategies to Improve Root Systems and Water Uptake in Water-Limited Wheat Crops. *J. Exp. Bot.* **2012**, *63*, 3485–3498. [[CrossRef](#)]
54. Feddes, R.; Raats, P.A.C. *Unsaturated-Zone Modeling Progress, Challenges and Applications*; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2004; pp. 95–131.
55. Fang, Y.; Du, Y.; Wang, J.; Wu, A.; Qiao, S.; Xu, B.; Zhang, S.; Siddique, K.H.M.; Chen, Y. Moderate Drought Stress Affected Root Growth and Grain Yield in Old, Modern and Newly Released Cultivars of Winter Wheat. *Front. Plant Sci.* **2017**, *8*, 672. [[CrossRef](#)]
56. Rogers, E.D.; Benfey, P.N. Regulation of Plant Root System Architecture: Implications for Crop Advancement. *Curr. Opin. Biotechnol.* **2015**, *32*, 93–98. [[CrossRef](#)]
57. Kou, X.; Han, W.; Kang, J. Responses of Root System Architecture to Water Stress at Multiple Levels: A Meta-Analysis of Trials under Controlled Conditions. *J. Plant Nutr.* **2022**, *13*, 1085409. [[CrossRef](#)] [[PubMed](#)]
58. Fromm, H. Root Plasticity in the Pursuit of Water. *Plants* **2019**, *8*, 236. [[CrossRef](#)] [[PubMed](#)]

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