Growth Stress and Wood Property Assessment of Different Provenances of Big-Leaf Mahogany *(Swietenia macrophylla* King*)* Landrace in the Philippines

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Abstract

The scarcity of timber to supply the wood-based industries is one of the prevailing problems worldwide. Tree plantations are the remaining solutions to subdue the shortage of raw materials, at the same time sequester atmospheric CO_2 in its biomass to reduce global warming. Planting Big-Leaf mahogany (*Swietenia macrophylla* King) contributes valuable economic inputs to small tree farmers in the Philippines. However, the occurrence of lumber defects during processing due to growth stresses reduces the potential value of timber. The first part of this study was aimed at examining the differences of surface growth stresses and wood properties of 8-year old BL mahogany from six landrace provenances in two progeny trial sites, Butuan and Cagayan de Oro in the Philippines. The longitudinal released strains of the surface growth stress (SRS) were not significantly different among six landrace provenances and between two trial sites. The SRS were not significantly related to diameter at breast height (DBH) in both trial sites. The high level of negative SRS was observed in some tested trees with small diameter in both trial sites, which was attributed to the tension wood formation in an irregular shaped stem. The xylem density (XD), average microfibril angle in the secondary cell wall (MFA), vessel element length (VL) and vessel element width (VW) have no significant differences among six landrace provenances. In terms of trial sites, Butuan trial site gave high lateral growth (DBH), high XD, longer FL with a narrow FW and smaller MFA as compared to the Cagayan de Oro trial site. It was observed that an 8-year old BL mahogany plantation with small diameter trees exhibited high SRS, low XD, small FL, wide FW and large MFA, which are passively considered as properties of juvenile wood.

The increasing global population with a commensurate increase in demand for forest products such as timber becomes a worldwide challenge on how to balance forest regulations in response to environmental concerns and utilization of timber resources. Sustainable tree plantations of fast-growing species are the best option to meet the increasing demand for timber. However, planting of the fast growing trees has an issue in the utilization of juvenile wood. This is a concern that is also partly addressed in this study.

The area of juvenile wood zone of an 8-year old planted BL mahogany *(Swietenia macrophylla* King*)* was uniform regardless of diameter, hence, assumed that xylem maturation is dependent on diameter.

The radial distribution patterns of FL, VL, VW and XD exhibit shorter FL and VL, narrow VW and low-density XD from the pith, then suddenly increases outward and become more or less stable near the bark. However, the radial distribution pattern of FW and MOE overlaps and becomes scattered regardless of tree diameter sizes. The Juvenile wood zone of FL is significantly different from the transition wood zone and to the mature wood zone, and vice versa. The Juvenile wood zone of VL, VW and XD is significantly different in transition wood zone and mature wood zone, but there is no difference between transition wood zone and mature wood zone. Same trends were observed in FL, VL, VW and XD in terms of its relationship between DBH and the *b*-value, and the diameter boundaries of three wood zones. Using selected xylem maturation properties e.g. FL, VL, VW and XD, BL mahogany starts to mature when it reached the diameter of 18.08cm , 17.36cm,16.23cm and 17.87cm, respectively.

Tree girdling is one of the convenient methods to disrupt translocation of water and nutrients in the trunk from the soil that causes death of trees in certain period of time depending on the species, site and size of trunk. Part of the study aimed to determine the effect of girdling in different periods (0, 1 year, and 2 years) on the growth stress reduction and basic wood properties of 8-year old planted Big leaf Mahogany (*Swietenia macrophylla* King*)*. Result shows that after 2 years of girdling, all test trees with small sizes in two trial sites did not survive. However, test trees with large sizes have 100% and 83% survival, and medium sizes have 83% and 50% survival in Butuan and Cagayan de Oro trial sites, respectively. Longitudinal released strain of surface growth stresses (SRS) of test trees with large size and medium size have highly significant differences between the non-girdled and 2-year girdled, but no significant variation between the non-girdled and 1-year girdled test trees. The small size test trees have the same SRS in three treatment periods. Using the difference of residual released strain of growth stresses (RRS), the diameter class and treatment periods revealed no significant differences both in longitudinal and tangential releases. Moisture content (MC) of test trees showed significant differences between girdled and non-girdled treatment. Small size test trees that died after 2 years of girdling have almost the same MC that ranges from 11.93% to 14.87% from pith to the bark, as compared to the non girdled test trees that gradually increases from 37.39% to 64.68% from pith to the bark. The lightness, redness and yellowish parameters have high significant differences between non-girdled and girdled test trees. The wood color of non-girdled test trees averages are; 70.95 in L* (lightness), 10.64 in a* (redness) and 22.14 in b*(yellowness) and the wood color of girdled test trees averages are; 67.80, 13.60 and 24.57, respectively. A significant correlation were found between a* and L*, b* and L*, and a* and b* parameters. These results showed that the variation in wood color of non-girdled and the girdled test trees of BL mahogany produced an inverse variation between a* and L*, b* and L*, but not with a^* and b^*. The color difference (ΔE^*_{ab}) of small, medium and large diameter class between girdled and non girdled test trees were 1.06, 10.47 and 18.72, respectively. This color variation is detectable by the human eye, except the color difference of wood samples from small diameter class.

Heat water treatment has been proven to reduce the residual release strain inside the log in some other tree species. In BL mahogany, heat water treatment drastically reduced the average residual release strains in three diameter classes: small, medium and large tree sizes to 47.98%, 53.57% and 53.19%, respectively. Significant reduction in residual released strain was observed in small and medium size trees, but not with the large size trees. The effect of heat water treatment on wood color averages as: 55.38 in (lightness), 16.79 in a* (redness) and 26.30 in (yellowness) while the control wood color averages: 62.83, 15.80 and 28.78, respectively. The effect of heat water treatment in L*(lightness) and b*(yellowish) parameters have high significant differences between control and water heated wood samples, but not with the a* (redness). A significant correlation was found only between a* and L*, and not with b* and L*, and a* and b* parameters. The color difference (ΔE^*_{ab}) of small, medium and large diameter class between between control and water heated wood samples were 8.48, 9.18 and 8.33, respectively. This color variation is detectable by the human eye. Therefore, BL mahogany lumber applied with heat water treatment will reduce the residual release strain and enhances the wood color.

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5.3 Results and Discussion

Chapter 1 Introduction

1.1 General introduction

The Philippines is teeming with different types of tree species that grow naturally in different forest types scattered all over the country. Many of these tree species possess superior wood characteristics that are known in the local as well as in the international markets as the “Philippine Mahogany”. Unfortunately, the supply of these tree species has dwindled considerably because of excessive extraction of these resources in 1960’s to 1980’s known to be the “Logging Era” in the Philippines. In the recent year, the country experiences the scarcity of raw materials like timber.

Developing industrial tree plantations is the best way to increase the supply of timber and revive the wood-based industries in the country. Industrial tree plantation species (ITPS) like big-leaf (BL) mahogany *(Swietenia macrophylla* King) is one of the promising ITPS that grows well within the different soil conditions of the Philippines. BL mahogany sawn wood is one of the high valued in the international market. In the Philippines, this tree species is one of the high valued lumbers because of its wood durability and workability. However, low recovery during wood processing was observed due to distortion of lumber; this phenomenon occur inside the log is the release of strain (growth stress) during saw milling. Growth stress was known as the accumulated strain (stress) inside the stem accumulated during wood cell development and maturation. It was considered a serious problem in wood processing because this undesirable lumber shape deformation that resulted to low recovery thereby degrading the market value of timber. In line with this, it is very necessary to understand the process, occurrence and possible solution to reduce the impact of growth stress in BL mahogany.

1.2 Background

Philippines produced wood from natural forest during the 1960's and 1970's and became major player in the international market. In the past 50 years, wood productions from the natural forest have been exhausted that the country shifted to tree plantations. As early as 1980's the government and private timber companies started to introduce different kind of industrial tree plantation species for reforestation and tree plantation projects. And one of the promising tree species introduced in the Philippines is the BL mahogany.

1.2.2 Industrial tree plantation in the Philippines

The increasing population of the Philippines expectedly will increase the demand on wood products for building infrastructures for fast growing economy. These rising demands are now just relying on tree plantations that considerably not able to cater the current needs of the local market.

In 1967, simply *"tree farming"* was introduced in the Philippines. The idea was to encourage local people to plant a portion of their farms with trees, in addition to their traditional agri-livestock activities, in order to supplement their livelihood (Jurvélius, 1997). In 1999, the government issue a policy declaring portion of Region 13 to be the "CARAGA Forest Plantation Corridor" (DENR administrative order no. 99-13) allocating 684,503 hectares of forestland located in the provinces of Agusan del Sur, Agusan del Norte, Surigao del Norte and Surigao del Sur. This policy invites private investors to developed industrial tree plantation sufficing the current wood requirements of wood-based industries in the country. In support to the concurrent policy, Executive Order no. 23 was promulgated declaring a "moratorium on the cutting and harvesting of timber in the natural and residual forests". This policy aims to protect and preserve the remaining natural forest of the country. Recently, most of the industrial tree plantations and tree farms were planted with *Falcataria moluccana*, *Gmelina arborea, Swietenia macrophylla, Acacia* species and *Eucalyptus* species.

1.2.3. About Big-leaf mahogany *(Swietenia macrophylla* King)

Big-leaf Mahogany (*Swietenia macrophylla* King) is a large deciduous tree with an umbrella-shaped crown (Figure 1), frequently reaching heights of over 30 m and diameter at breast height (DBH) of more than 1.5 m. However, heights of 40–60 m and diameters of 2.5–3.5 m were reported before the population was extensively logged (Lamb 1966). The trunk is straight and cylindrical, slightly grooved, with well-developed spurs. The crown of young trees is narrow, but old trees have a broad, dense and highly branched crown. The open, rounded crown has thick, rising branches and thick, dense foliage. The outer bark of older trees is scaly, shaggy, deeply longitudinally furrowed and brownish-grey to reddish-brown, and the inner bark is red-brown or pinkish-red (Krisnawati et al. 2011). The leaves are usually paripinnate, sometimes imparipinnate, 12–45 cm long, and are made up of 3–6 pairs of lanceolate orovate leaflets. The leaflets are asymmetrical, 5–12 cm long and 2–5 cm wide, with a whole margin and an acute or acuminate apex (Soerianegara and Lemmens 1993; Schmidt and Jøker 2000).

BL mahogany grows naturally in Belize, Bolivia, Brazil, Colombia, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Peru, and Venezuela. However, it is nearly extinct in Ecuador, Colombia, Panama, and Costa Rica; close to commercial extinction in Bolivia; declining in Mexico, Belize, and Brazil; and in severe decline in Guatemala, Peru, Nicaragua, and Honduras (Lugo, et al 2003).

The largest plantations of BL mahogany have been reported in South and Southeast Asia and the Pacific regions. BL mahogany has since become a promising tree species for industrial plantations as well as for reforestation and afforestation in Indonesia. BL mahogany is suitable for large-scale timber production plantations because of its excellent timber quality. Generally, the wood can be used for construction materials, plywood (veneer), high-grade furniture and cabinet making. It is also suitable for paneling, framing, flooring, automobile bodies, interior trim of boats, radio and phonograph cabinets, bodies of musical instruments, moldings and other ornaments (Krisnawati et al. 2011).

In the Philippines BL mahogany was introduced from unknown origins in 1907 as park trees in Manila (Ponce 1933). In 1913, the Forestry School at the University of the Philippines in Los Baños received 1012 seeds of mahogany from an unknown number of parent trees from the Royal Botanic Gardens at Sibpur, Calcutta, India. Three subsequent introductions of unknown quantities and number of parent trees from the same source in India followed through till 1916. Seedlings produced during these introductions were mostly planted at Los Baños, with only a few seedlings trial-planted in Baguio, Benguet province. There was no other documented report on mahogany importation into the country until the 1960s when tree planters in north-eastern Mindanao imported an unspecified quantity of seeds directly from an unknown source in Central America (Abarquez et al , 2015).

Chapter 2

Surface growth stress and wood properties of 8-year old planted Big-leaf Mahogany *(Swietenia macrophylla* King*)* from different landrace provenances and trial sites in the Philippines

2.1 Introduction

The Big-Leaf (BL) mahogany *(Swietenia macrophylla* King) is one of the world's most high valued timber species. For many decades, some countries and/or some private bodies have invested in plantations in order to ensure a sustained production of high-value timber (Mead and Odoom, 2001; Lugo et al. 2003). Such cases exist in Asia (Indonesia, Philippines, Sri Lanka and Fiji), where the species find good growing conditions (Hammond, 2002) as well as, to a lesser extent, in some countries of Central America (Costa Rica) and South America (Brazil, Peru, Bolivia). In 2011 international market, the average price ($)/m^3 of BL Mahogany sawnwood from Brazil and Guatemala were $1,195.00/m^3 to $1,884.00/ m^3, respectively (ITTO, 2014)

In the Philippines, BL mahogany is one of industrial tree plantation species. It was introduced from unknown origins in 1907 as park trees in Manila (Ponce, 1933). In 1913, the Forestry School at the University of the Philippines Los Baños (UPLB) received 1012 seeds of BL mahogany from an unknown number of parent trees from the Royal Botanic Gardens at Sibpur, Calcutta, India. Since then, there were no other documented reports on mahogany importation into the country until the 1960s when tree planters in northeastern Mindanao imported an unspecified quantity of seeds directly from an unknown source in Central America (Abarquez et al, 2015). The landrace of BL mahogany in the Philippines has been developed by generations in different provenances.

The increasing deforestation in the country is mainly due to lack of timber supply to augment the existing needs of the growing population. The development of tree plantation is the most efficient way to supply alternative resources while recovering the degraded natural forest. This is also effective in reducing atmospheric CO_2 and mitigating climate change. Recently, BL Mahogany tree plantation is one of the major sources of lumber and considered as high-value lumber in the local market in the Philippines. One of the prevailing problems in the locally produced lumber is its distorted form after milling and so forth; which in cracks at the edge of the logs decreases the product market value. Only few researchers have investigated that distortion in the lumber form could be attributed to species-specific growth stress inside a log which is generated during the tree growth (Kubler,1987). The presence of growth stress in tree stems often cause problems when using processing the logs into timber products. Examples are radial cracks at the edge of cut logs, crooked sawn lumber, and so forth (Gril, et al., 2017)

However, some wood properties (xylem density, tangential and radial shrinkage, modulus of elasticity(MOE), and modulus of rupture(MOR) of BL mahogany differ between natural forest and plantation forest (Langbour et al. 2011); these findings may influence the specific wood utilization of planted BL mahogany.

Several studies suggests that the distinctive anatomical characteristics and chemical composition of tension wood directly cause the changes in physical and mechanical properties which lead to technological problems, such as distortion of solid wood during sawing due to the release of high longitudinal growth stresses (Boyd,1977, Kubler,1987, Okuyama, et al 1990, Washusen et al. 2003), defects during drying due to its high longitudinal shrinkage (Arganbright et al. 1970, Dadswell et al.1955, Jourez et al,2001, Onaka,1949] and severe woolly surface during sawing and rotary cutting (Panshin et al. 1980) due to G-fibres, as well as bad quality of paper made of G-fibres (Parham et al. 1977).

However, there is very limited data on the growth stresses and wood qualities as well as the possibility of tension wood formation of planted BL mahogany in the Philippines. Thus, this study aimed to examine the differences of surface growth stresses and wood properties of 8-year old planted BL mahogany from six landrace provenances and two trial sites and, described the occurrence of tension wood formation in trees. The information generated in this study is very essential for the plantation management of BL mahogany in the Philippines to enhance its uses and productivity.

2.2 Materials and Methods

2.2.1 Study area and sample trial sites

Experimental samples were randomly selected from two established field trial sites of BL mahogany (*Swietenia macrophylla* King) located in Butuan City and Cagayan de Oro City representing contrasting growing conditions within the target plantation region in northern Mindanao, Philippines (Figure 2-1) (Table 2-1).

The field trials were established in September of 2009 by the Department of Environment and Natural Resources (DENR Philippines) with support from the Commonwealth Scientific and Industrial Research Organization (CSIRO Australia) and the Australian Government (AusAID Public Sector Linkages Program) [9]. The seeds consisted of six landrace provenances in Philippines: Makiling (Laguna), Minglanilla (Cebu), Maasin (Leyte) and Tacloban (Leyte), and Lianga (Surigao del Sur) as shown in Figure 2-1.

2.2.2 Plant Material

In each trial site, three tested tree samples were randomly selected in each of the six landrace provenances. A total of 36 tested trees in two trial sites were used in the study. Table 2-2 summarizes the growth data (diameter and height) of the tested trees collected prior to the measurement of various material parameters.

2.2.3 Lateral growth rate - Diameter at Breast Height (DBH)

The lateral growth rate of diameter at breast height was measured using 1,460 planted trees in each trial. These planted trees were composed of 73 individual families of BL mahogany collected from six provenances in the Philippines. In every individual family, five test trees were used which was replicated 4 times in every trial site.

2.2.4 Longitudinal released strain of surface growth stresses (SRS)

Growth data (diameter and height) were collected prior to the measurement of various material parameters measured at four cardinal points at the breast height of every tree. Then, the longitudinal released strain (SRS) of the surface growth stresses was measured. A rectangular specimen was then collected at the point where the SRS was measured and used to measure xylem density (XD), fiber length (FL), fiber width (FW), vessel element length (VL), vessel element width (VW), and the average microfibril angle in the cell wall (MFA)(Figure 2-1.a). The values measured at the four cardinal points were averaged for each test tree (Kojima et al. 2009). In addition to above tested trees, two trees with inclined stem were selected in Butuan trial site.

For each standing tree, measurement was conducted at four cardinal points (North, South, East, and West) at diameter breast height (DBH) (1.3 meters from the ground). A strain gauge (electric-wire-strain gauge, 10 mm length, KFG-10-120-C1-11L3M3R, Kyowa Co., Tokyo, Japan) was glued to the exposed secondary xylem surface along the longitudinal direction and was connected to a strain meter (UCAM-1A, Kyowa Co., Tokyo, Japan). After measuring the initial strain on the tree sample, the surface stress was released using a handsaw, and the strain was then recorded. The amount of the longitudinal released strain of growth stress was calculated by subtracting the initial measurement from the second reading (Okuyama et al.,1981; Yamamoto et al., 1989; Kojima et al. 2009; Yoshida and Okuyama, 2002).

2.2.5 Xylem density (XD)

Wood samples (1cm x 1cm x 1cm) were prepared from the rectangular specimen taken from the points where the RS was measured. These samples were seasoned at room temperature inside desiccators containing a saturated aqueous solution of NaCl for 1 week until equilibrium for “air-dried density” measurement denoted as xylem density (XD). The density was determined using the mercury displacement method (Kollmann and Cote,1968; Kojima et al. 2009).

2.2.6 Fiber length (FL), width (FW), Vessel element length (VL) and Vessel element width (VW)

After the measurement of XD, part of each cubic specimen was treated in a compound liquid of water, potassium chlorate, and 60% nitric acid (Saiki et al., 1989), followed by 10% NaOH (aq) treatment and then defiberized (Cheng et al., 2000), and dispersed in an aqueous suspension. A drop of defiberized wood suspension was placed on a glass slide and then covered with a cover slip. Using a digital microscope (Olympus BX60), digital images of all 90 fiber samples were randomly selected and captured. All vessel elements were also captured. The captured images were processed using an image processor software (Image J ver.1.51K) to measure the fiber length (FL), fiber width (FW), vessel length (VL) and vessel width (VW).

2.2.7 Average microfibril angle in the secondary cell wall (MFA)

From another part of the rectangular wood specimen for XD measurement, a small specimen [0.1(R)x1(T)x1(L) cm] were derived for MFA determination using the X-ray diffractometry (Ultima IV, Rigaku Corporation) following the method of Cave (1966) , Meylan (1967) and Kojima et al. (2009). The data generated from the X-ray diffractometry were the average MFA of the secondary cell wall (S^2 and G).

2.2.8 Statistical Analysis

Three trees were selected from each of the six landrace provenances per trial site by complete random design. A total of thirty-six test trees were tested in two trial sites. In every tested tree, there were four measuring points (cardinal directions) assigned for the measurement of SRS, XD, FL, FW, VL, VW and MFA. A total of 144 sampling points were derived from 36 randomly selected test trees from six different landrace provenances of two trial sites. Simple linear regression models were used to test the correlation between the lateral growth rate and wood properties; SRS, XD, FL, FW, VL, VW and MFA. The comparison in wood properties: SRS, XD, FL, FW, VL, VW and MFA, among provenances and between trial sites were tested using a two-way ANOVA and Scheffe's method for multiple comparison tests using SPSS v20 software.

2.3 Results and discussion

2.3.1 Lateral growth rate - Diameter at Breast Height (DBH)

Upon comparing the lateral growth (DBH) of all planted trees among six landrace provenances and between two trial sites (Figure 2-2), the result showed that the lateral growth (DBH) among six landrace provenances has no significant difference (Table 2-3), while the difference between two trial sites was highly significant. The average DBH of two trials sites were 23.25cm and 14.17cm for Butuan and Cagayan de Oro, respectively. Regardless of provenances, Butuan trial site produced bigger diameter trees than the Cagayan de Oro trial site.

2.3.2 Longitudinal released strain of surface growth stresses (SRS)

The SRS in each tested tree is shown in Figure 3. Six landrace provenances (Makiling, Minglanilla, Maasin, Tacloban, Lianga, and Bislig) in two trial sites (Butuan City and Cagayan de Oro City) gave similar longitudinal released strain of surface growth stress (SRS). The differences in the average SRS among six landrace provenances and between trial sites were analyzed using a two-way ANOVA and Scheffe’s post-hoc multiple comparison method. Results showed no significant differences among landrace provenances and between trial sites, as well as no significant interaction between provenance and trial site (Tables 2-3 and 2-4). It has been reported that the longitudinal released strain of surface growth stress (SRS) has been found similar to the studies on tropical species e.g. *Tectona grandis* (Wahyudi et al.,2001) and *Eucalyptus grandis* in different latitudes (Kojima et al., 2009), regardless of the lateral growth.

The relationship between DBH and averaged SRS is shown in Figure 2-4 and Table 2-5. It reveals that no significant correlations were observed in both trial sites.

2.3.3 Xylem density (XD)

The differences in the average XD among six landrace provenances and between two trial sites were analyzed using a two-way ANOVA and Scheffe's multiple-comparison (post-hoc) method. Result showed no significant differences among six landrace provenances and high significant differences between two trial sites, as well as a highly significant interaction between provenance and trial site (Table 2-3).

The relationship between DBH and XD is shown in Figure 2-5 and Table 2-4. There were no correlations between Butuan and Cagayan de Oro trial site. These results were the same as with the findings of Kojima, et al., 2009 (*G. Arborea)* an*d* Zobel and Jett, 1995 (*Populus tremuloides, Eucalyptus grandis*) who found out that a diffuse-porous hardwood species usually showed little or no relationship between growth rate and xylem density.

2.3.4 Fiber length (FL), Fiber width (FW), Vessel element length (VL) and Vessel element width (VW)

Tables 2-3 and 2-4 show that FL and FW averaged at each measuring point have significant differences among six landrace provenances and trial sites. Landrace provenances from Makiling and Tacloban gave the highest average FL of 1.172mm and 1.176mm, respectively. The highest average FW was in the landrace provenances of Lianga (0.027mm), Maasin (0.027mm), Makiling (0.027mm) and Tacloban (0.026mm). High significant differences were found between two trial sites; those in Butuan trial site which have larger FL (1.175mm) with thinner FW (0.023mm) as compared with those in Cagayan de Oro trial site which have shorter FL (1.082mm) and wider FW (0.029mm). The high growth rate condition in Butuan trial site promotes longer but thinner fiber. This result partly coincides with the findings that higher growth rate in the tropical plantation promotes longer FL (Kojima et al.2009). Previous studies also reported that shorter fiber and vessel element are characteristic of juvenile wood (Zobel and Jett, 1995; Kojima et al.2009). It is considered that some trees of 8- year old BL mahogany could still produce juvenile wood. The VL and VW have no significant difference among six landrace provenances and two trial sites.

The FL, FW and VL in Butuan and Cagayan de Oro trial sites were not correlated in terms of DBH. However, VW was positively correlated with DBH in Butuan trial site but not in Cagayan de Oro trial site. The relationship between VL and FL was positive only in Cagayan de Oro trial site which exhibited smaller average DBH as compared with the Butuan trial site (Figure 2-6 and Table 2-4). The FL, VL and VW have no significant interaction between landrace provenances and trial sites, as compared to FW with high significant interaction between landraces provenances and trial sites.

It was also considered that the formation of tension wood was related with shorter fiber and vessel element. Some studies revealed that the tension wood contained a lower vessel proportion than normal wood (Chow, 1946, Jourez et al .2001, Onaka., 1949, Ruelle et al. 2006).

2.3.5 Average microfibril angle in the secondary cell wall (MFA)

The MFA is considered to have a major role in controlling certain fiber qualities, including fiber stiffness and dimensional stability (Barnett and Bonham, 2004).

The differences of average MFA on each tested tree among six landrace provenances and between two trial sites were also analysed by a two-way ANOVA and Scheffe's multiple-comparison (post-hoc) method. This analysis indicated no significant difference among six landrace provenances and a high significant difference between two trial sites with an average MFA of 19.82° in Butuan and 24.94° in Cagayan de Oro trial sites (Tables 2-3 and 2-4).

The effect of the DBH on MFA averaged in each tree is shown in Figure 8 and Table 5. DBH has no significant correlation with averaged MFA in both trial sites. Same results were observed in *Acacia mangium, A. auriculiformis, hybrid Acacia (Acacia mangium × A. auriculiformis), Eucalyptus grandis, E. globulus, and Falcataria molucanna*, indicating that in these cases, acceleration of secondary growth does not affect the MFA at the outermost surface of the xylem (Kojima et al.2009).

The effects of MFA on SRS showed no correlation in Butuan trial site, but a positive correlation was observed in Cagayan de Oro trial site (Figure 2-9 and Table 2-5). MFA has no significant interaction between landrace provenances and trial sites (Table 2-3). It is reported that there might be a causal relationship between both qualities in a small-diameter tree, e.g., formation of the tension wood fiber with a thick G- layer and low MFA in several hardwood species (Okuyama et al., 1990; Washusen et al. 2003; Kojima et al. 2012). MFA values smaller than 10 degrees are often correlated with high tensile stress generation in tension wood compared with normal wood (Baba et al., 1996; Okuyama et al., 1990; 1994; Yamamoto et al., 1992, Kojima et al.,2009). In tension wood, the tensile growth stress increases with the amount of gelatinous fibers, increasing cellulose content, and decreasing MFA (Baba et al., 1996; Okuyama et al., 1990; 1994; Yamamoto et al., 1992; Wardrop and Dadswell, 1955) findings were confirmed also in 8 years old BL mahogany based on a separate experiment using two inclined mature stems as shown in Figures 2-10 and 2-11. In tension wood, the longitudinal growth stress possesses a very large tensile value. The presence of growth stress in tree stems often causes problems when using logs as raw material for timber products. Examples are radial cracks at the edge of cut logs, crooked sawn lumber, and so forth (Kubler, 1987). Processing of BL mahogany timber with tension wood should be avoided until desired practical solution will be applied to solve this problem.

2.4 . Conclusion

The results indicated that the SRS was invariable regardless of landrace provenances and trial sites. The XD, VL, VW and MFA have no significant differences among six landrace provenances. And FL and FW have high significant differences among six landrace provenances. It was found in this study that Butuan trial site has a high lateral growth (DBH), high XD, longer FL with a narrow FW and a smaller MFA compared with Cagayan de Oro trial site. However, in terms of VL and VW, no significant differences between the two trial sites were observed. In both trial sites, DBH does not affect SRS, MFA, XD, VL, FL and FW. However, VW was positively correlated only in Butuan trial site.

A small diameter tree exhibits high SRS, small FL, wide FW and large MFA. A high level of SRS was observed in some tested trees with a small diameter growth, which was attributed to tension wood formation. These suggest that the current cambium age is still producing juvenile wood especially in a smaller diameter tree. It is recommended to conduct further investigations on the xylem maturation properties of BL mahogany in relation to diameter growth and cambial ages. In order to avoid leaning trees with tension wood in tree plantation for timber production, it is necessary therefore to avoid planting trees in sloping areas and employ required spacing in silvicultural management.

TABLES

Table 2-1. Location and description of sampling sites (Abarquez et al., 2015; PAGASA, 2010)

Trial Site	Location		Elevation (m.a.s.l)	Annual Rainfall (mm)	Soil			
	Latitude	Longitude			pH	Organic Matter (%)	Phosphorus (ppm)	Potassium (ppm)
Butuan	8° 56' N	125° 35' E	13–15	2057	6.8	1.2	4.5	144
Cagayan de Oro	8° 23' N	124° 42' E	413–415	1703	5.8	4.5	1.3	48

Table 2-2. Summary of growth data of sampled trees at each trial sites and landrace provenances: averages and standard deviations of diameter at breast height (DBH) and tree height (Ht)

Trial Sites	Provenances	*n*		Average DBH (SD) cm		Average Ht (SD) m	
Butuan	Bislig	3		33.00	(9.61)	21.00	(4.58)
	Cebu	3		36.60	(10.62)	21.00	(2.65)
	Lianga	3		37.70	(7.91)	22.00	(2.52)
	Maasin	3		22.00	(2.60)	18.00	(0.58)
	Makiling	3		30.00	(7.65)	20.00	(2.00)
	Tacloban	3		24.00	(4.69)	19.00	(1.53)
	Total	**18**	Average	**30.55**	**(7.18)**	**20.17**	**(2.31)**
Cagayan de Oro	Bislig	3		22.40	(8.13)	9.00	(2.00)
	Cebu	3		22.30	(8.25)	10.00	(2.08)
	Lianga	3		26.30	(10.65)	9.00	(0.58)
	Maasin	3		21.00	(6.47)	12.00	(3.61)
	Makiling	3		23.50	(8.59)	14.00	(4.73)
	Tacloban	3		22.00	(7.54)	11.00	(3.06)
	Total	**18**	Average	**22.92**	**(8.27)**	**10.83**	**(2.67)**

Table 2-3. Two-way analysis of variance (ANOVA) for the effects of six landrace provenances and two trial sites on lateral growth, surface released strain and wood properties averaged in each tested trees.

Parameters	Source of variance	df	SS	MS	Sig. (p-value)
Lateral Growth (DBH) cm.	Trial site	1	2966.62	63.15	0.000
	Provenance	5	413.62	82.72	0.125
	Provenance x trial site	5	425.37	85.07	0.115
Surface release strain (%)	Trial site	1	0.00	0.00	0.622
	Provenance	5	0.00	0.00	0.436
	Provenance x trial site	5	0.00	0.00	0.715
Xylem density (g/cm³)	Trial site	1	0.15	0.15	0.000
	Provenance	5	0.03	0.01	0.182
	Provenance x trial site	5	0.08	0.02	0.004
Fiber length (mm)	Trial site	1	0.31	0.31	0.000
	Provenance	5	0.24	0.05	0.000
	Provenance x trial site	5	0.09	0.02	0.043
Fiber width (mm)	Trial site	1	0.00	0.00	0.000
	Provenance	5	0.00	0.00	0.000
	Provenance x trial site	5	0.00	0.00	0.000
Vessel length (mm)	Trial site	1	0.00	0.00	0.899
	Provenance	5	0.04	0.01	0.073
	Provenance x trial site	5	0.01	0.00	0.736
Vessel width (mm)	Trial site	1	0.00	0.00	0.688
	Provenance	5	0.02	0.00	0.479
	Provenance x trial site	5	0.01	0.00	0.580
Microfiber angle (°)	Trial site	1	589.18	589.18	0.000
	Provenance	5	260.06	52.01	0.062
	Provenance x trial site	5	162.80	32.56	0.245

Table 2-4. Scheffe's multiple-comparison test for the effect of six landrace provenances on lateral growth and wood properties in tested trees.

Parameters	Provenances											
	Bislig		**Cebu**		**Lianga**		**Maasin**		**Makiling**		**Tacloban**	
Lateral Growth (DBH) cm.	18.07	*a*	19.22	*a*	21.93	*a*	16.50	*a*	18.95	*a*	17.60	*a*
	(8.79)		(10.12)		(10.82)		(5.09)		(7.68)		(5.90)	
Surface release strain (%)	-0.04	*a*	-0.03	*a*	-0.04	*a*	-0.03	*a*	-0.03	*a*	-0.03	*a*
	(0.02)		(0.02)		(0.02)		(0.02)		(0.02)		(0.02)	
Xylem density (g/cm³)	0.58	*a*	0.60	*a*	0.59	*a*	0.61	*a*	0.63	*a*	0.59	*a*
	(0.07)		(0.09)		(0.04)		(0.10)		(0.08)		(0.05)	
Fiber length (mm)	1.08	*a*	1.08	*a*	1.14	*ab*	1.13	*ab*	1.17	*b*	1.18	*b*
	(0.06)		(0.12)		(0.13)		(0.09)		(0.10)		(0.08)	
Fiber width (mm)	0.03	*ab*	0.02	*a*	0.03	*b*	0.03	*b*	0.03	*b*	0.03	*b*
	0.00		0.00		0.00		0.00		0.00		0.00	
Vessel length (mm)	0.43	*a*	0.39	*a*	0.44	*a*	0.42	*a*	0.42	*a*	0.41	*a*
	(0.04)		(0.06)		(0.06)		(0.09)		(0.04)		(0.04)	
Vessel width (mm)	0.21	*a*	0.19	*a*	0.22	*a*	0.20	*a*	0.21	*a*	0.19	*a*
	(0.06)		(0.04)		(0.05)		(0.09)		(0.04)		(0.04)	
Microfiber angle (°)	21.06	*a*	22.42	*a*	20.01	*a*	24.30	*a*	21.08	*a*	22.42	*a*
	(3.67)		(5.37)		(5.11)		(4.40)		(7.06)		(5.84)	

Means followed by the same letters (*a,b*) in the same row are not significantly different at $p \leq 0.05$ according to Scheffe's method

Values in parenthesis are standard deviation

Table 2-5. Correlation matrices of lateral growth and wood properties in tested trees in two trial sites

Variables	Trial site		SRS	MFA	XD	FL	FW	VL	VW
DBH	Butuan	Pearson Correlation	-0.102	0.112	-0.420	0.116	-0.194	0.215	0.505*
		N	18	18	18	18	18	18	18
	Cagayan de Oro	Pearson Correlation	-0.415	-0.435	-0.205	0.206	0.157	0.092	0.442
		N	18	18	18	18	18	18	18
SRS	Butuan	Pearson Correlation		-0.016	0.385**	-0.007	0.187	0.057	-0.025
		N		67	67	67	66	66	66
	Cagayan de Oro	Pearson Correlation		0.380**	-0.005	0.027	-0.057	0.201	-0.162
		N		62	65	65	65	65	65
MFA	Butuan	Pearson Correlation			0.217	-0.108	-0.123	-0.284*	-0.248*
		N			72	71	71	71	71
	Cagayan de Oro	Pearson Correlation			-0.012	0.061	0.078	0.082	-0.204
		N			67	67	67	67	67
XD	Butuan	Pearson Correlation				0.066	0.114	-0.085	-0.209
		N				71	71	71	71
	Cagayan de Oro	Pearson Correlation				-0.085	-0.046	-0.132	-0.040
		N				72	72	72	72
FL	Butuan	Pearson Correlation					-0.252*	-0.025	0.086
		N					70	70	70
	Cagayan de Oro	Pearson Correlation					0.287*	0.529**	-0.037
		N					72	72	72
FW	Butuan	Pearson Correlation						0.270*	0.353**
		N						71	71
	Cagayan de Oro	Pearson Correlation						0.154	0.158
		N						72	72
VL	Butuan	Pearson Correlation							0.141
		N							71
	Cagayan de Oro	Pearson Correlation							-0.304*
		N							72

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

FIGURES

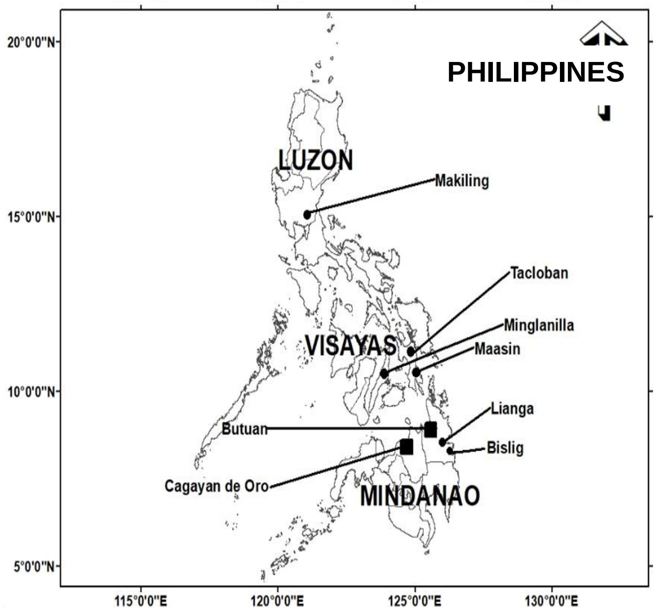


Figure 2- 1. Location of six provenances (●) and two trial sites (■) of BL Mahogany (*Sweitenia macrophylla* King) in the Philippines

(a) *(b)*

Figure 2-1.a Field Data Collection: measurement of surface release strain*(a)* and Wood sample collection*(b)*

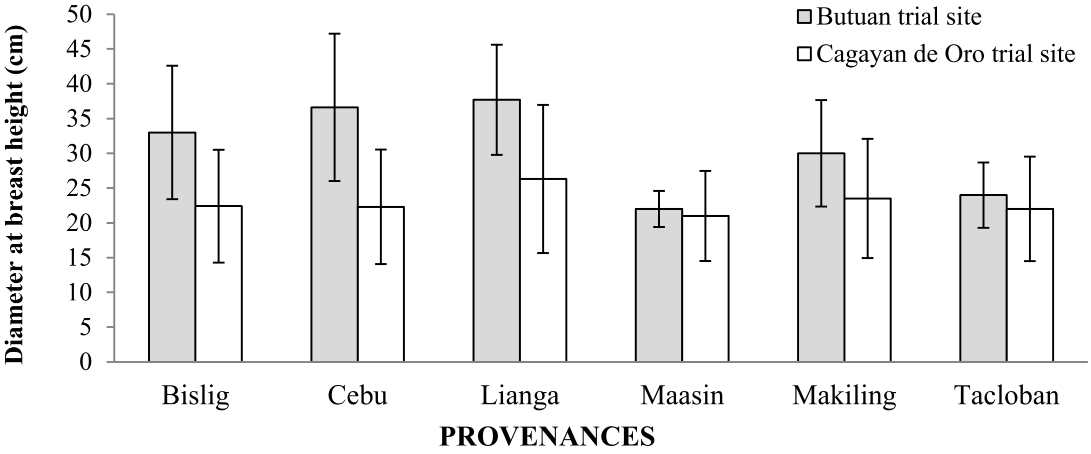


Figure 2-2. The distribution of averaged DBH of all planted trees of BL mahogany from six landrace provenances in two trial sites: Butuan trial Site and Cagayan de Oro trial site. Number of samples = 2,920 trees (1,460 trees in every trial site); bar stands for ± 1 standard deviation.

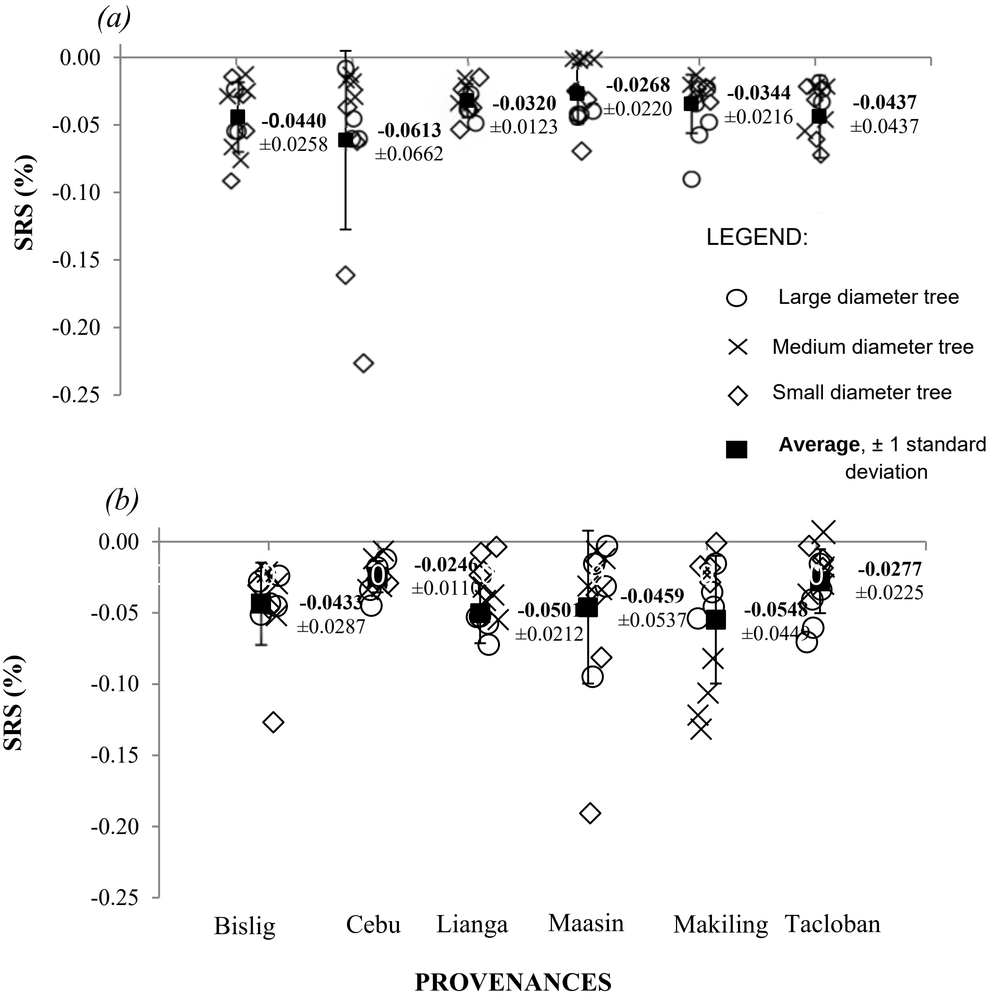
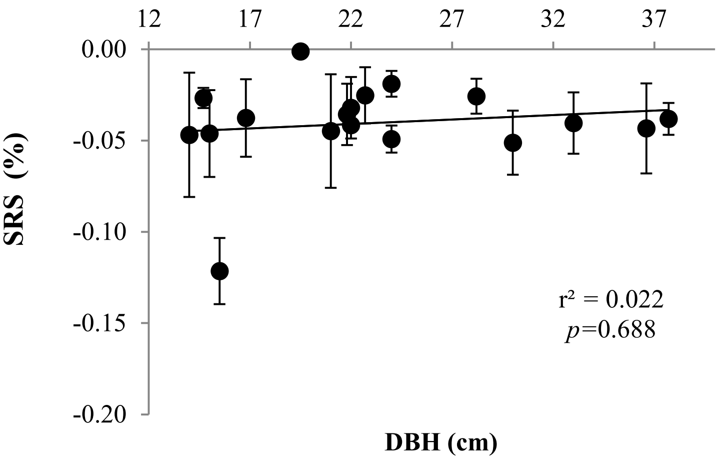


Figure 2- 3. The longitudinal released strain of surface growth stress (SRS) in tested trees in six landrace provenances at two trial sites (a) SRS (%) at Butuan trial site, (b) SRS (%) at Cagayan de Oro trial site. All the values are the averaged (■), with ± 1 standard deviation in each provenance

(a)



(b)

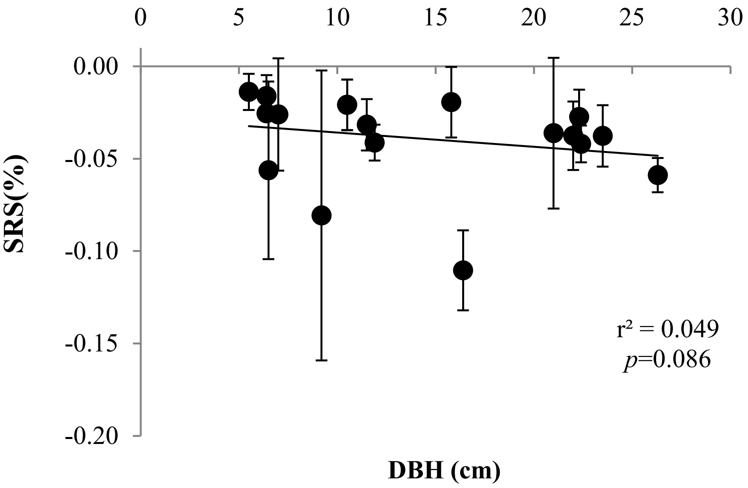


Figure 2-4. The relationship between DBH and SRS averaged in each tested tree with ± 1 standard deviation in two trial sites (a) Butuan trial Site, (b) Cagayan de Oro trial site

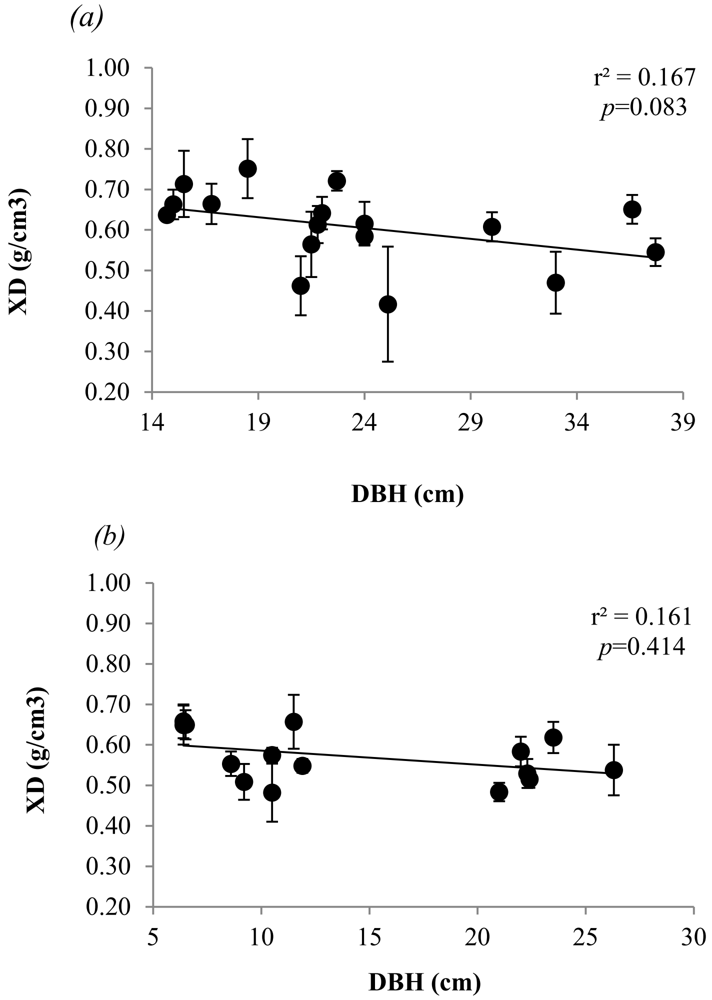


Figure 2- 5. The relationship between DBH and XD averaged in each tested tree with ± 1 standard deviation in two trial sites (a) Butuan trial Site, (b) Cagayan de Oro trial site

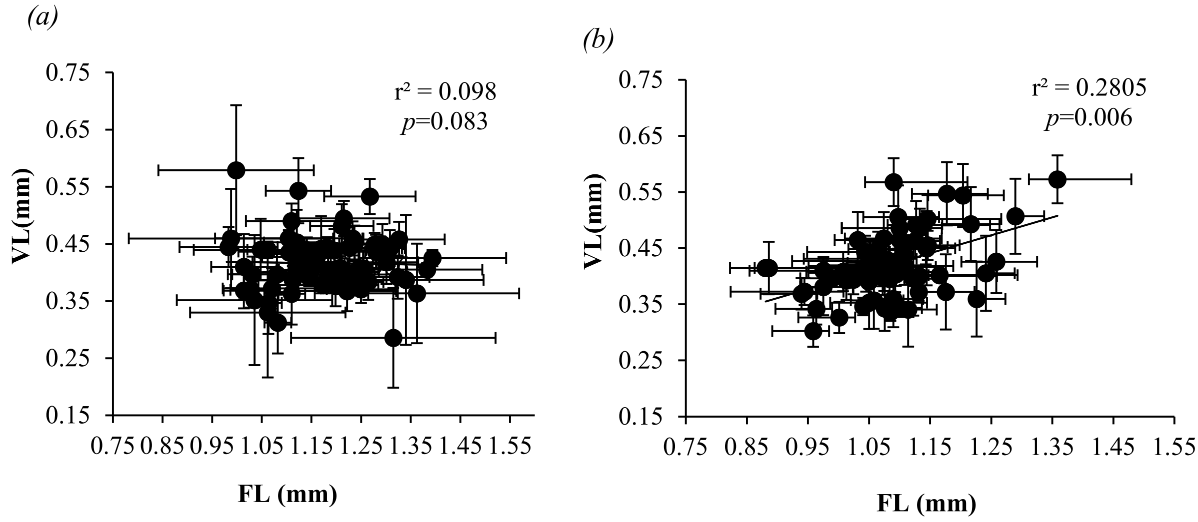


Figure 2-6. The relationship between FL and VL averaged at each measuring point in each tested tree in two trial sites (a) Butuan trial site, (b) Cagayan de Oro trial site. Each bar is ± 1 standard deviation

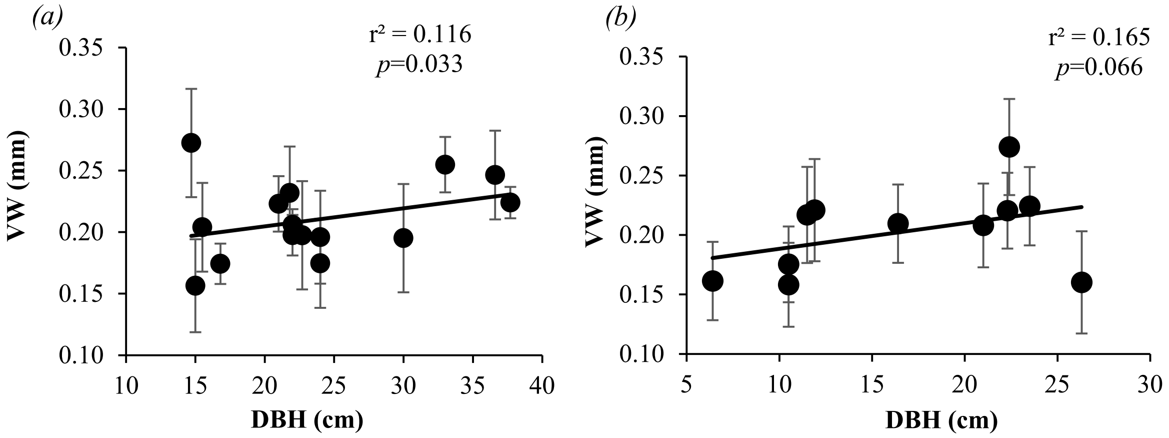


Figure 2-7. The relationship between DBH and VW averaged in each tested tree with ± 1 standard deviation in two trial sites (a) Butuan trial site, (b) Cagayan de Oro trial site

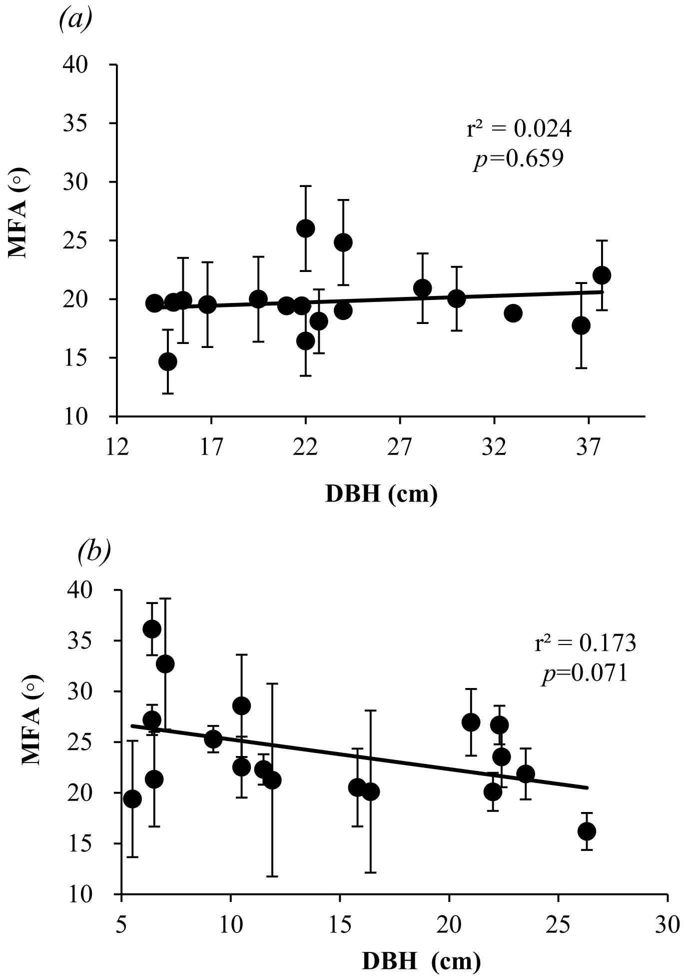


Figure 2- 8. The relationship between DBH and MFA averaged in each tested tree with ± 1 standard deviation in two trial sites (a) Butuan trial site, (b) Cagayan de Oro trial site

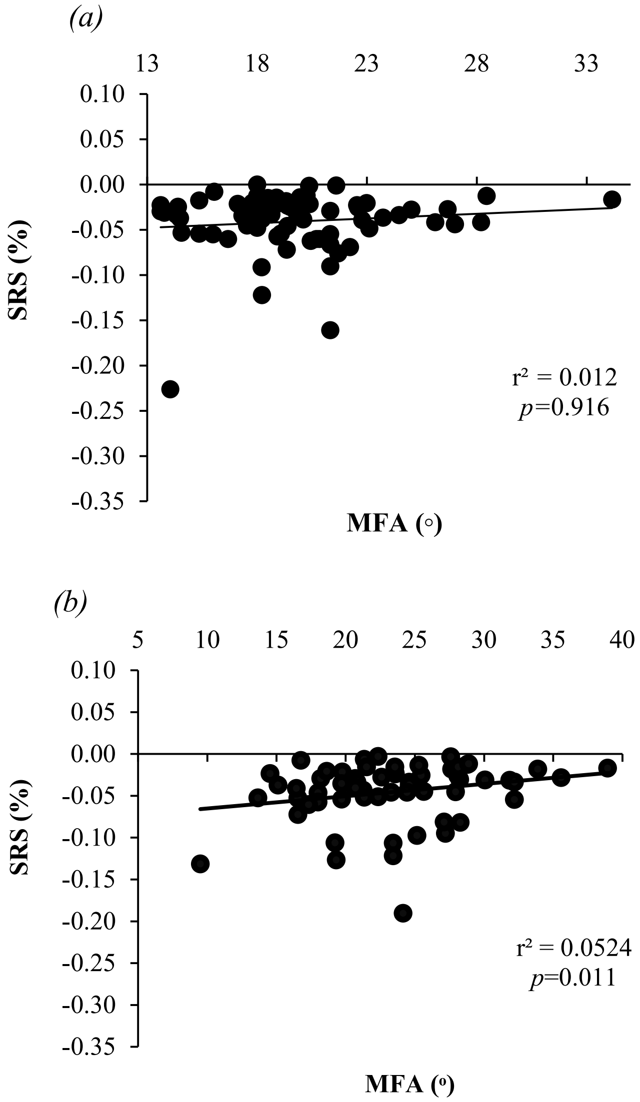


Figure 2- 9. The relationship between MFA and SRS at each measurement point in each tested tree in two trial sites (a) Butuan trial site, (b) Cagayan de Oro trial site

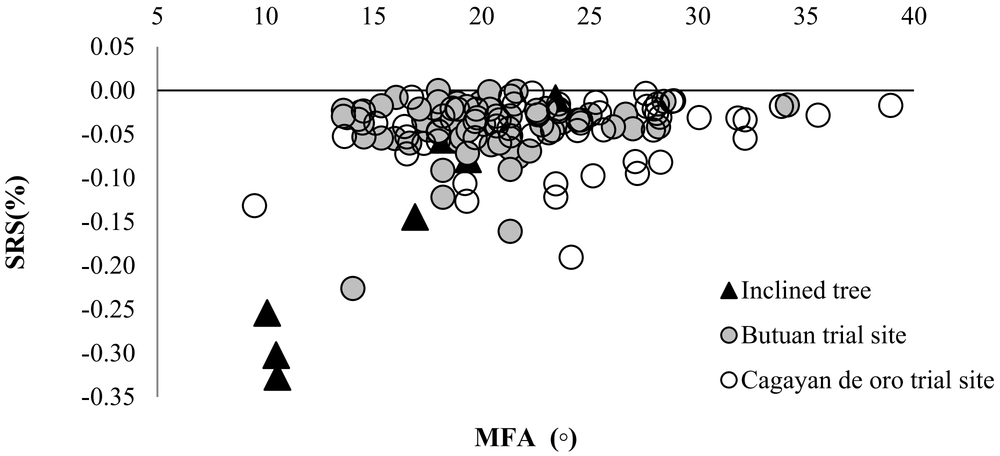
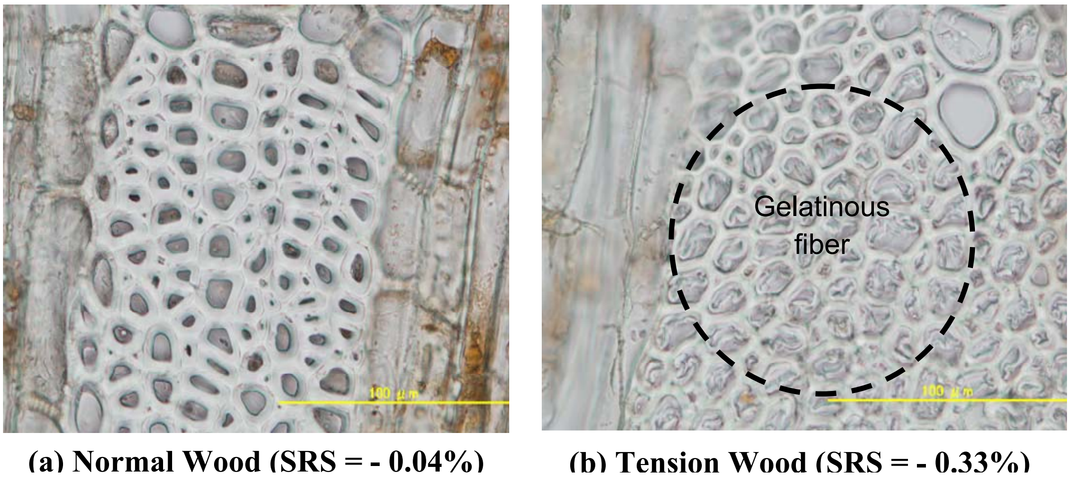


Figure 2-10. The relationship between MFA and SRS at each measurement point in each tested tree in two trial sites and in two tested trees containing tension wood on the upper side along the inclined stems



(a) Normal Wood (SRS = - 0.04%) **(b) Tension Wood (SRS = - 0.33%)**

Figure 2- 11. Microscopic image of a transverse section of (a) Normal wood and (b) Tension wood (tree with inclined stem in Butuan trial site) of a 8-year-old BL Mahogany. Tension wood G-fiber contains a thick G-layer (circled). Scale:100μm

Chapter 3

Radial distribution of growth stress and Xylem maturation properties of 8-year old Planted Big-leaf Mahogany *(Swietenia macrophylla* King*)* in the Philippines

3.1 Introduction

The increasing global population with a commensurate increase in demand for forest products such as timber becomes a worldwide challenge on how to balance forest regulations in response to environmental concerns and utilization of timber resources. Sustainable tree plantations of fast-growing species are the best option to meet the increasing demand for timber. However, planting of fast growing trees has an issue in the utilization of juvenile wood. This is a concern that is partly addressed in this study.

In the Philippine local market, the current demand of timber is increasing due to the rapid infrastructure development program. In order to meet this demand, the major source of timber is coming from tree plantations of fast growing species. It is for this reason that some of the small-scale tree farmers are encouraged to bargain early-age planted trees because of high demand and price. The younger age plantation usually contains timber with large proportion of developing juvenile wood. According to Maeglin 1987, wood near the pith of a tree, i.e. juvenile wood is different from wood near the bark, i.e. mature wood. The presence of juvenile wood can reduce mechanical properties as well as cause warping, excessive shrinking and swelling, fuzzy grain, and general instability in the manufacture and use of the wood. These problems may show up in the wood when sawing, veneering, drying and machining.

Wood maturity is one of the important factors to consider in terms of wood properties stability when used as raw materials for building and furniture. Using Big-Leaf (BL) mahogany *(Swietenia macrophylla* King) as tree plantation species, it is very important to know the wood maturation properties, whether it is dependent on cambium age or tree diameter. Having knowledge on the significant features of wood maturation is important to the silvicultural management of tree plantations.

Studies on the effect of juvenile wood on soft wood have been extensively explored as compared to hardwood. Some specific researches have been done concerning juvenile wood effects in hardwoods. Bendtsen and Senft,1986 examined plantation-grown cottonwood for juvenile wood effects. Foster and Thor, 1979 recorded juvenile wood variation for specific gravity (SG) and fiber length in American sycamore. Harrington and DeBell, 1980 explored SG variation from the pith to the bark in red alder. Quanci, 1988 on the other hand examined juvenile wood effects on the MOE, MOR, SG, microfibril angle, cell length, ring number, and average ring width in white ash. Roos et al., 1990 researched juvenile wood effects on MOE, MOR, and SG in quaking aspen. While Taylor and Wooten, 1973 looked at variation from pith to bark for SG, fiber length, fiber dimensions, and volumetric composition in black willow, willow oak, sycamore, pecan, and sugarberry. Taylor, 1979 also investigated juvenile wood effects on SG and fiber length in blackgum, mockernut hickory, post oak, shagbark hickory, and southern red oak.

A number of studies have focused on the transition from juvenile to mature wood zones were conducted by the following; Zobel and Sprague, 1998; Bendtsen, 1978; Taaissa and Burkhart, 1998; Bao et al., 2001; Pramod and Rao, 2012; Rahayu et al., 2014. In the case of Japanese Red Pine (*Pinus densiflora*), xylem maturation depends on cambium age (Sudo, 1973). Several studies have been carried out on the structural changes during transition from juvenile to adult wood in conifers (Shiokura, 1982; Bendtsen, 1978; Lee & Wang, 1996). This means that the faster a specimen grows at the early growing stage, the higher is the diameter of juvenile wood when its harvested.

Yang et al. (1986) noted that the formation of juvenile wood is related to the age of the formation of the cambial initials; therefore the distribution of juvenile wood in trunks of *Larix laricina* is conical, tapering toward the tree top. Clark and Saucier (1989) concluded that planting density does not significantly affect the age of transition from juvenile to mature wood, but it does affect the diameter of the juvenile core. In the case of *Picea mariana*, Alteyrac et al. (2006) concluded that the transition age varies significantly with sampling height, but there were no significant differences with stand density. In *Cryptomeria japonica* (Kitahara et al., 2000) and in *Populus simonii* (Huang and Furukawa, 2000), higher growth rates promote the earlier formation of mature wood.

Honjo et al. (2005) reported that the radial variation of fiber length was related to the growth rate rather than the age of the cambium in hardwood, eg., *Acacia mangium*. Acacia spp. and *Paraserianthes* spp., thus, they concluded that xylem maturation was dependent on diameter growth. In *Eucalyptus* spp., xylem maturation was controlled by cambium age (Kojima et al., 2009). Fibre length and microfibril angle appeared to be the best anatomical indicators in delineating the demarcation point between juvenile and mature wood (Rahayu et al 2014).

To improve the dearth of knowledge on this aspects, the radial distribution of growth strain and xylem maturation properties of an 8-year old Planted Big-leaf Mahogany was investigated. This is with the aims determining the factors that affect xylem maturation.

3.3 Materials and Methods

3.2.1 Study area and sample trial sites

Experimental samples were randomly selected from two established field trial sites of BL mahogany located in Butuan City and Cagayan de Oro City representing contrasting growing conditions within the target plantation region in northern Mindanao, Philippines (Figure 3-1)(Table 3-1).

The field trials were established in September 2009 by the Department of Environment and Natural Resources (DENR Philippines) with support from the Commonwealth Scientific and Industrial Research Organization (CSIRO Australia) and the Australian Government (AusAID Public Sector Linkages Program) (Abarquez et al., 2015).

3.2.2 Plant Material

Sample trees were randomly selected from 8-year old progeny trial sites of BL mahogany in Mindanao, Philippines. Twelve four test tree samples of different diameter classes were randomly selected in two trial sites. Table 3-2 summarizes the lateral growth data (diameter at breast height) collected prior to the measurement of various material parameters.

3.2.3 Radial distribution pattern

In every trial sites, there were 12 test trees or four (4) per diameter classes (large, medium and small) that were used in the study. From the diameter at breast height (DBH), a quarter-sawn board were prepared measuring 5cm thickness (center: pith and length that is 2.6 times the DBH were taken from the pith to the north and the south side of the stem, excluding the bark. Sampling points were set up at the center of the length of the board the intervals of which is every 2cm from the pith to the bark (Figure 2). Wood samples from the sampling points were prepared for the measurement of Fiber length (FL), width (FW), Vessel element length (VL), Vessel element width (VW), Xylem density (XD), Microfibril angle (MFA) and Modulus of Elasticity (MOE).

3.2.4 Fiber length (FL), width (FW), Vessel element length (VL) and Vessel element width (VW)

After the measurement of XD, part of was extracted and treated with a mixture of water, potassium chlorate, and 60% nitric acid (Saiki et al., 1989), followed by 10% NaOH (aq) treatment, then fiberized (Cheng et al., 2000), and dispersed in an aqueous suspension. A small drop of the suspension was mounted on a clean glass slide, which was then temporarily cover with a glass cover. At least 90 whole fibers were randomly selected and pictures of all the vessel elements in every wood block specimen were captured using a digital microscope. The captured images of fiber and vessel elements were processed using image processor software (Image J) in order to measure the fiber length (FL), fiber width (FW), vessel length (VL) and vessel width (VW).

3.2.5 Xylem density (XD)

Wood samples (1cm x 1cm x 1cm) were prepared from the rectangular specimen taken from every points where the RS was measured. These samples were seasoned at room temperature inside a desiccators containing saturated aqueous solution of NaCl for 1 week until equilibrium was met in order to achieve air dried state. This was used in the “air-dried density” measurement denoted as xylem density in this paper. The density was determined using the mercury displacement method (Kollmann and Cote,1968; Kojima et al. 2009).

3.2.6 Modulus of Elasticity (MOE)

Segmented wood sample specimen (0.5cm(R)x 1cm(T)x10cm(L)) were taken at centimeter interval from the quarter-sawn lumber (1 inch thick) cut in the diameter line or from pith to bark on each side. The strain of each segmented wood samples was measured using the 500N Horizontal - Universal Testing Machine, connected to a strain meter (EDX-10B, Kyowa Co., Tokyo, Japan) and to laptop computer.

3.2.6 Analysis of data

The analysis on wood maturity assumed that fiber length is shortest at the pith, increases abruptly outward, and then stabilizes at a certain point (Ohbayashi and Shiokura, 1990), Kojima et al, 2009). To assess the results objectively, the relationship between fiber length (y mm) and the distance from the pith (x cm) can be approximated by the following exponential function: (Kojima et al, 2009)

$$y(x;b) = -(y_\infty - y_0)\exp^{-\mathrm{b}(|x|-1)} + y_\infty; \qquad (1)$$

where y_∞ is the fiber length in the mature wood region, and y_0 is the length 1 cm from the pith. On the basis of DBH, the test trees were arbitrarily divided into small, medium, and large diameter classes for each species. y_∞ was determined to be the averaged value at the outermost point in the tested tree of the large diameter class, whereas y_0 was determined to be the averaged value 1 cm from the pith in all trees tested. The ''b-value (cm^{-1})'' was found from the radial distribution of fiber length in each tested tree by the least squares method using Eq. (1).

The three zones (juvenile, transition and mature wood zones) were determined in the north and south sides of each tree (Figure 2).

[1] Juvenile wood zone ($0 < x < x_j$)

x_j is the boundary distance of juvenile wood from the pith, where x_j is given as a solution of the equation:

$$\frac{1000(y(x_j+1)-y(x_j))}{y\,(x_j)} = 1(\%)$$

from Eq. (1) x_j can be solved as

$$\therefore x_j = \frac{\ln(\ 100(y_\infty - y_0)\left(1.01-\exp^{-b}\right)/y_\infty\ )}{b} + 1 \qquad (2)$$

x_j is the distance from the pith at the 1% expansion point, where the expansion rate of fiber length from x to x + 1 (cm) in radius becomes 1%. Boundary diameter, *Dj*, is x_j (in the north side) plus x_j (in the south side).

[2] Mature wood zone ($x_m < x$)

$$\frac{100(y(x_m + 1) - y(x_m))}{y\ (x_m)} = 0.1\%$$

from Eq. (1) x_m can be solved as;

$$\therefore x_m = \frac{\ln(\ 1000(y_\infty - y_0)\left(1.001 - \exp^{-b}\right)/y_\infty\ )}{b} + 1 \qquad (3)$$

x_m is the distance from the pith at the 0.1% expansion point, where the expansion rate of fiber length from x to x + 1 (cm) in radius becomes 0.1%. From this definition, xylem maturation starts at the time when tree radius becomes larger than x_m. Boundary diameter, D_m, is x_m (north side) plus x_m (south side).

[3] Transition wood zone ($x_j < x < x_m$)

Changing wood qualities from the juvenile to the mature wood zone.

The juvenile zone can be defined as the distance from the pith to the radius at the 0.3% expansion point, where the expansion rate of fiber length from x to x + 1 (cm) in radius becomes 0.3%.

$$\frac{100(y(x_t + 1) - y(x_t))}{y\ (x_t)} = 0.3(\%)$$

from Eq. (1) x_t can be solved as

$$\therefore x_t = \frac{\ln(\ 1000(y_\infty - y_0)\left(1.003 - \exp^{-b}\right)/3y_\infty\ )}{b} + 1 \qquad (4)$$

The boundary diameter, D_t, is the sum of x_t (north side) and x_t (south side).

Comparing the wood maturation properties, simple linear regression models were used to test the correlation between the lateral growth rate and fiber length b-value and tree wood zones. The comparison in wood properties: FL, FW, VL, VW, XD, MFA and MOE, among diameter classes were tested using simple comparison methods: one-way ANOVA and scheffe's method to test the multiple mean comparison using SPSS version 20.

3.3 Result and Discussion

3.3.3 Fiber length (FL), width (FW), Vessel element length (VL) and Vessel element width (VW)

The use of fiber length to examine the xylem maturation property that may depends on on either cambium age or diameter age of a tree has been studied in different hardwood species (Kojima et al., 2009, Honjo et al., 2005, Huang et al., 2000). Other relevant xylem properties: FW, VL, VW, XD and MOE were considered in this study. It assumes that the above mention xylem properties may also have the potential to identify the boundary distance between juvenile and mature wood.

The radial distribution patterns of xylem maturation properties: FL, FW, VL and VW in various diameter classes were shown in Figure 3-3. FL, VL and VW exhibit shorter FL and VL and narrow VW from the pith, and suddenly increase outward and become more or less stable near the bark. Similar results were observed in the study of *Leucaena leucocephala* where FL and VW showed significant variation from pith to near the bark (Pramod and Rao, 2012). Same findings were recorded in *Falcataria moluccana* (Kojima et al., 2009) and *Antocephalus cadamba* (Rahayu et al., 2014) with the increasing pattern of FL from pith to near the bark. However, the radial distribution pattern of FW overlaps and are scattered regardless of diameter.

In Table 3-3, the relationships between the xylem maturation properties were described. FL was positively correlated with VL and VW. However, no correlation was detected between the relation of FL to FW and

MOE. This is similar findings of Quanci (1988) where in there was no statistical evidence that cell length contributed to MOR and MOE variation in white ash were noted.

This indicated the potential of VL and VW to identify boundary distance between juvenile and mature wood. To confirm this theory, the relationship between *b*-value as affected by DBH shows no significant relationship to FL, VL and VW (Figure 3-4). In this case, the area of juvenile wood zone is uniform, regardless of diameter, showing that xylem maturation depends on diameter, suggesting that maturation starts after a certain diameter is reached as described by Kojima et al., 2009.

The relationship between DBH and the boundary diameters of selected xylem maturation properties (FL, VL and VW) were shown in Figure 3-5 and the calculated ANOVA was in Table 3-4. Using One-way ANOVA, the diameter boundaries of three wood zones (juvenile wood, transition wood and mature wood) were highly significant in FL, VL and VW. Table 3-5 showed the comparison among the means using Scheffe's test. The FL of the uvenile wood zone is significantly different with the transition wood zone and the mature wood zone. The Juvenile wood zone of VL and VW is significantly different in both transition wood zone and mature wood zone, but there is no difference between transition wood zone and mature wood zone. Using selected xylem maturation properties, BL mahogany starts to mature when it reached the diameter of 18.08cm for FL, 17.36cm for VL and 16.23cm for VW. Same trends were observed in FL, VL and VW in terms of its relationship between DBH and the *b*-value and diameter boundaries of three wood zones.

3.3.2 Xylem density (XD)

The radial distribution of XD in various diameter classes is shown in Figure 3-3. XD exhibits low density from the pith, and suddenly increased the density outward and become more or less stable near the bark. This is similar with the study of Rahayu et al., 2014, that the density of *Antocephalus cadamba* nears the pith for the 5-year-old was 234 kg m-3 and 6-year-old, 297 kg m-3, and the density near the bark was 573 kg m-3 and 606 kg m-3 respectively. The XD of *Falcataria moluccana* at 5-year-old near the pith was 237 kg m-3 and 6-year-old, 259 kg m-3, and the density near the bark was 393 kg m-3 (5 years old) and 456 kg m-3(6 years old). And the study of Barrios, et al 2017 for *Pinus radiata* that exhibited an increasing XD from pith to bark pattern that tended toward an asymptotic value.

The relationship between FL and XD gave a positive correlation as shown in Table 3-3. Like FL, it indicated the potential of XD to indentify the boundary distance between juvenile and mature wood. To confirm this theory, the relationship between *b*-value as affected by DBH showed no significant results to XD, this result was similar to FL (Figure 3-4). Using One-way ANOVA, the diameter boundaries of the three wood zones (juvenile wood, transition wood and mature wood) were highly significant in XD (Table 3-4). Table 5 showed the comparison among the means using Scheffe’s test. Juvenile wood zone of XD was significantly different in both transition wood zone and mature wood zone, but no differences between transition wood zone and mature wood zone were obsrved. XD has the same trends with FL, VL and VW in terms of its relationship between DBH and the *b*-value and diameter boundaries of three wood zones.

3.3.3 Modulus of Elasticity (MOE)

The radial distribution patterns of MOE overlapped with each others and were scattered regardless of diameter as shown in Figure 3-3. This result contradicted to the study of *Pinus radiata* that exhibited an increasing MOE value from pith to bark that tended toward an asymptotic value (Barrios, et al 2017).

The relationship between FL and MOE has no correlation as shown in Table 3-3. The above mentioned results confer almost similar MOE value (Average: 5.45GPa) from the pith to the bark regardless of diameter.

3.4 Conclusion

The radial distribution patterns of FL, VL, VW and XD exhibited shorter FL and VL, narrow VW and low density XD from the pith, and suddenly increased outward and became more or less stable near the bark. However, the radial distribution patterns of FW and MOE overlapped each other and scattered regardless of tree diameter sizes. The juvenile wood zone of FL was significantly different to the transition wood zone and to the mature wood zone, vice versa. The juvenile wood zone of VL, VW and XD was significantly different in both transition wood zone and mature wood zone, but no difference between transition wood zone and mature wood zone was observed. Same trends were observed in FL, VL, VW and XD in terms of their relationship between DBH and the *b*-value, and the diameter boundaries of the three wood zones. Therefore, it is important to enhance tree plantation by selecting quality planting materials, have a good planting site and apply appropriate silvicultural practices to promote high lateral growth rate to produce large diameter trees at shorter period of time in order to promote xylem maturation. Using selected xylem maturation properties e.g. FL, VL, VW and XD, BL mahogany starts to mature when it reached the diameter of 18.08cm , 17.36cm,16.23cm and 17.87cm, respectively.

TABLES

Table 3-1. Location and description of sampling sites (Abarquez et al., 2015; PAGASA, 2010)

Trial Site	Location		Elevation (m.a.s.l)	Annual Rainfall (mm)	Soil			
	Latitude	Longitude			pH	Organic Matter (%)	Phosphorus (ppm)	Potassium (ppm)
Butuan	8° 56' N	125° 35' E	13–15	2057	6.8	1.2	4.5	144
Cagayan de Oro	8° 23' N	124° 42' E	413–415	1703	5.8	4.5	1.3	48

Table 3-2. Average lateral growth data (DBH) of test tree samples in different diameter classes: averages and standard deviations of diameter.

Diameter Class	No. of test trees	Average DBH (SD) cm
Large	4	22.88 (1.75)
Medium	4	18.30 (0.89)
Small	4	14.18 (0.39)
Total	12	

Table 3-3. Correlation coefficients between xylem maturation properties of 8 year old planted Big leaf Mahogany *(Swietenia macrophylla* King*)*

Variables		**VL**	**FW**	**VW**	**MOE**	**XD**
FL	Correlation	.565**	.076	.420**	-.025	.469**
	N	115	115	115	115	114
VL	Correlation		.087	.483**	.066	.290**
	N		115	115	115	114
FW	Correlation			.556**	.176	-.149
	N			115	115	114
VW	Correlation				.106	.163
	N				115	114
MOE	Correlation					.020
	N					114
**. Correlation is significant at the 0.01 level (2-tailed).						

Table 3-4. One-way analysis of variance (ANOVA) for the effects in diameter boundaries of three wood zones (juvenile wood, transition wood and mature wood) in selected xylem maturation properties.

Source of Variation	***df***	***SS***	***MS***	***P-value***
FL	2	1516.65	758.32	0.0000
VL	2	775.41	387.70	0.0020
VW	2	1086.17	543.08	0.0000
XD	2	1241.96	620.98	0.0000

Table 3-5. The average diameter boundaries of three wood zones (juvenile wood, transition wood and mature wood) of selected xylem maturation properties.

Xylem maturation properties	Dsitance from the Pith(cm)		
	Juvenile wood	Transition wood	Mature wood
FL	6.60^{a}	12.51^{b}	18.08^{c}
VL	7.81^{a}	12.71^{b}	17.36^{b}
VW	5.54^{a}	10.89^{b}	16.23^{b}
XD	5.41^{a}	11.83^{b}	17.87^{b}

Means followed by the same letters (a,b & c) in the same row are not significantly different at $p \leq 0.05$ according to Scheffe's method

FIGURES

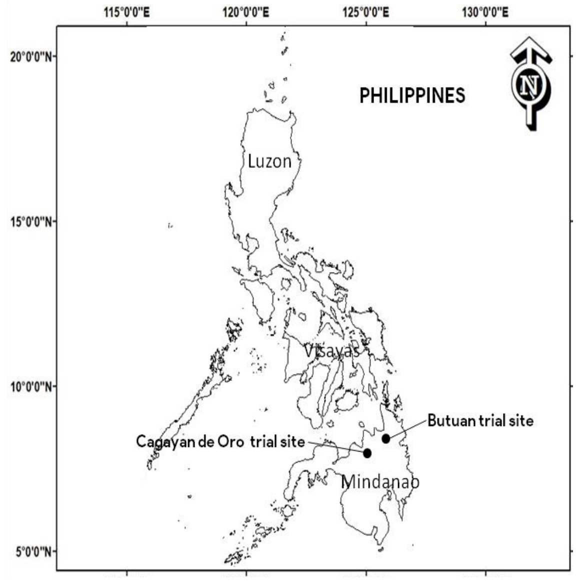


Figure 3-1. Location of the (●) two trial sites of BL Mahogany (*Sweitenia macrophylla* King) in the Philippines.

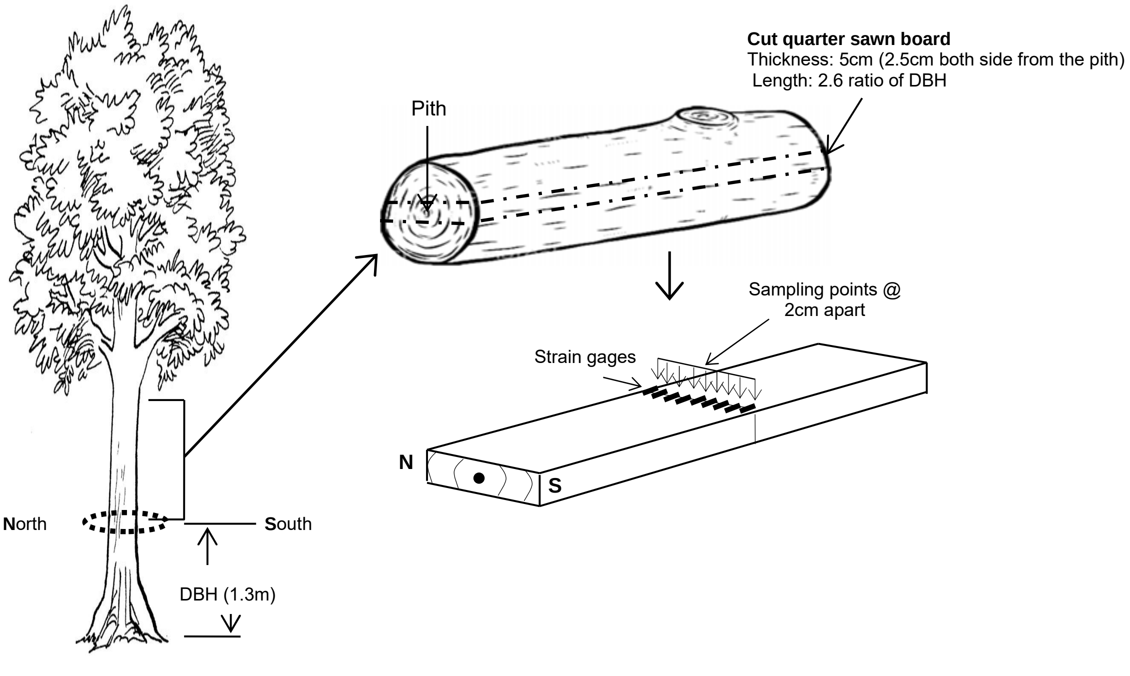


Figure 3-2. Sampling points of radial distribution patterns from the pith to north and south side of quarter sawn board with 2cm interval located at the center (length: 2.6 ratio of DBH).

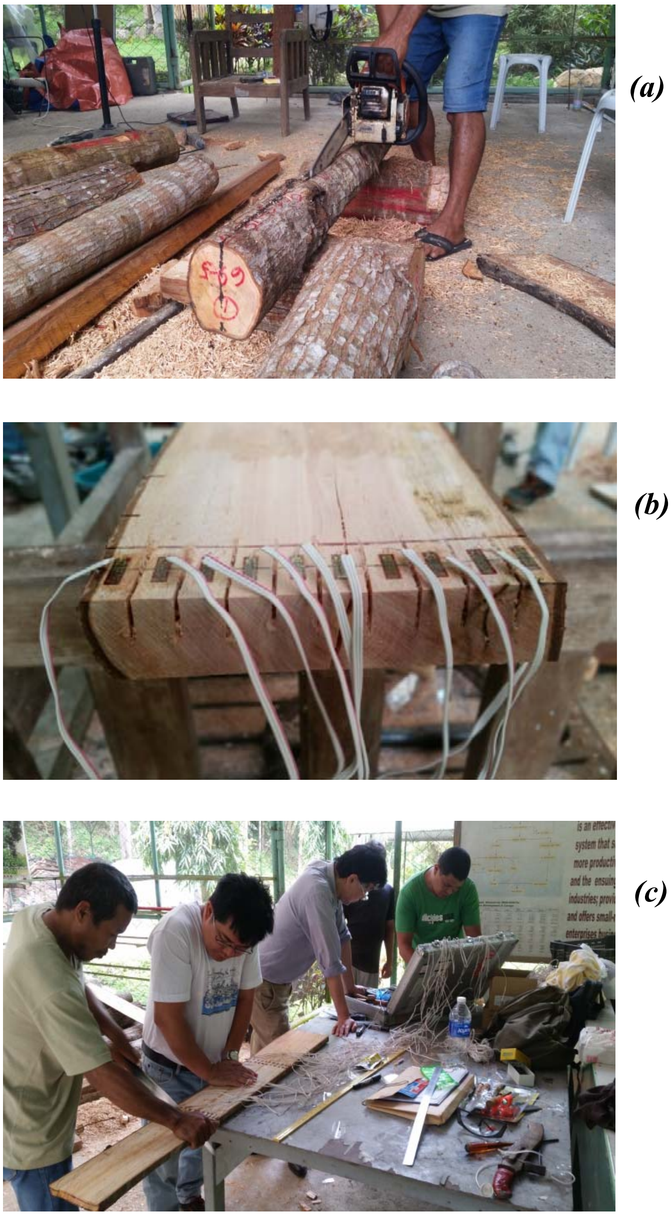


Figure 3-2.a. Collection of wood samples and measurement: Preparation of wood samples *(a)*, Installation of strain gages *(b)* and measurement of radial release strain *(c)*

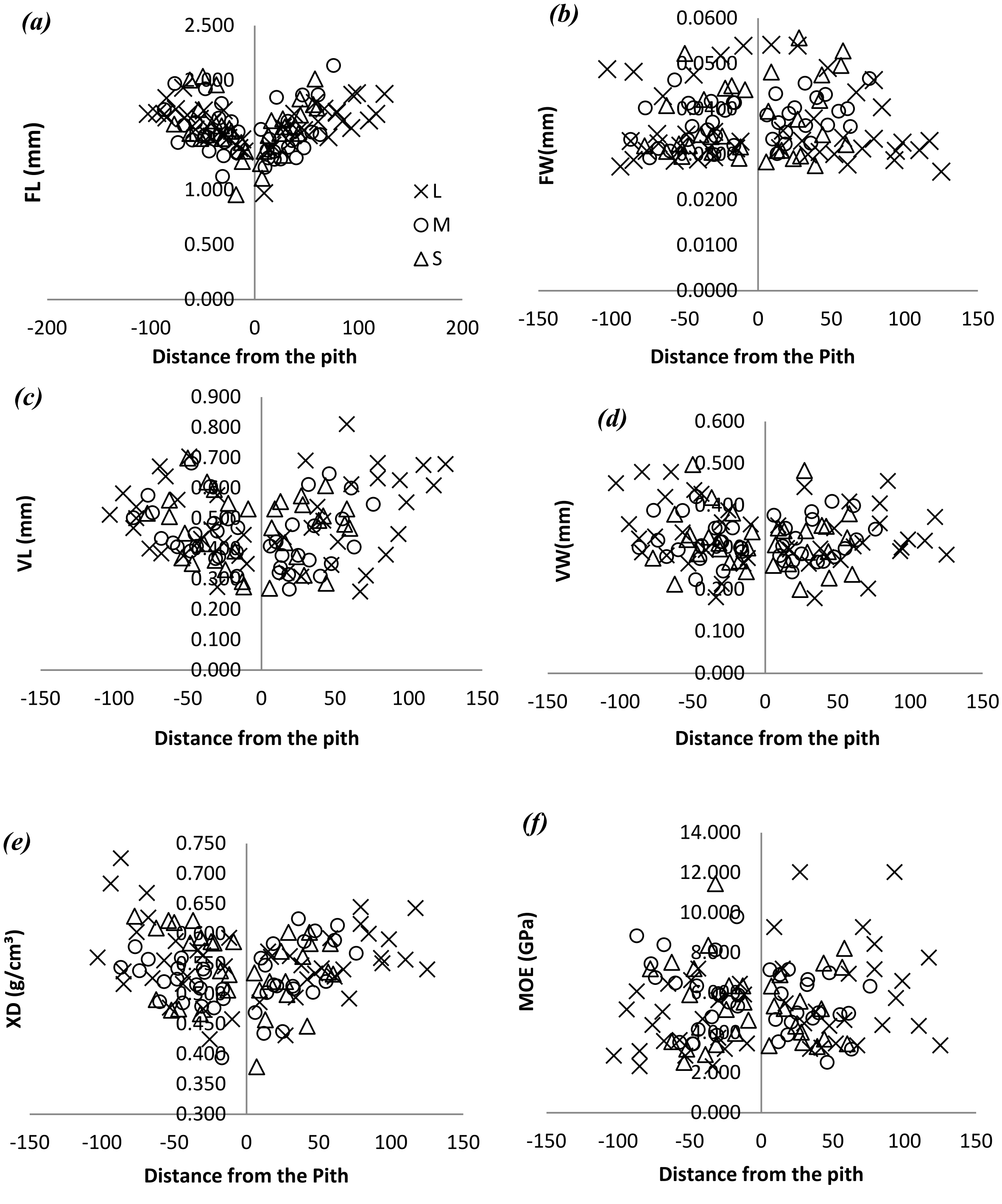


Figure 3-3. Typical radial distribution pattern of different diameter classes; (Δ) Small diameter trees, (○) Medium diameter trees and (x) Large diameter trees in different xylem maturation properties; *(a)* FL, (*b*)FW, (*c*) VL, (*d*) VW, (*e*) XD and (*f*) MOE.

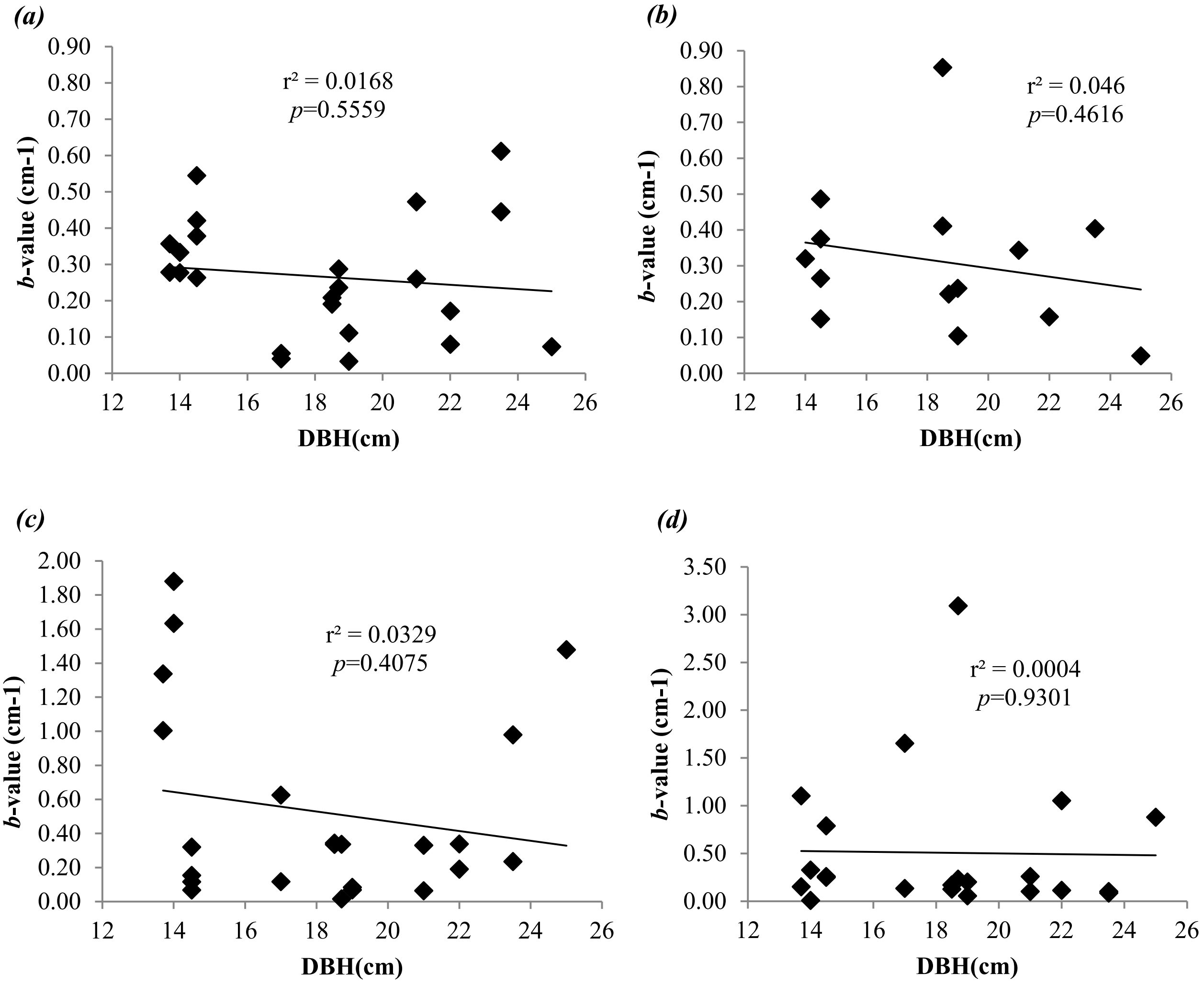


Figure 3-4. The relationship between DBH and *b*-value determined from the radial distribution of different xylem maturation properties; *(a)* FL, (*b*) VL, (*c*) VW, (*d*) XD. r^2 represents the contribution ratio, and p=probability value.

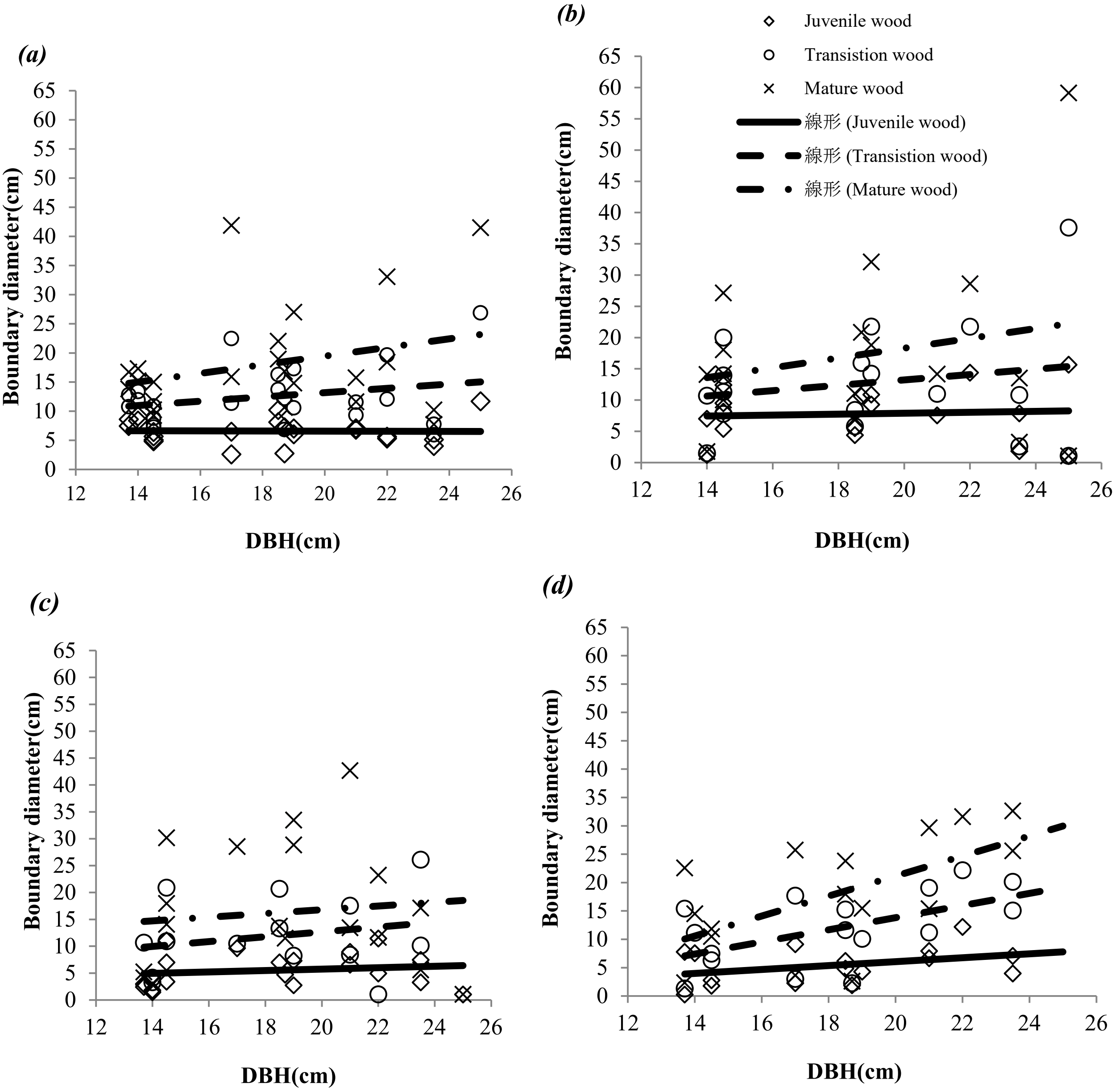


Figure 3-5. The relationship between diameter boundaries of tree wood zones: (◊) juvenile wood, (○) transition wood and (x) mature wood and averaged DBH of selected xylem maturation properties; *(a)* FL, (*b*) VL, (*c*) VW and (*d*)XD.

Chapter 4

The effect of girdling on growth stress reduction of Big-leaf Mahogany *(Swietenia macrophylla* King*)* in the Philippines

4.1 Introduction

Girdling is one of the oldest silvicultural practices used to eradicate vascular plants like trees. Pre-harvest phloem girdling of tree trunks has been used in the logging industry to alter wood properties (MacDougal 1943, Noel 1970, Domec and Pruyn. 2008). Girdling removes the bark and phloem down to the youngest xylem and immediately terminates the flux of photosynthesis from the tree canopy to the roots, while maintaining water transport in the reverse direction for months (Hogberg et al. 2001; Binkley et al. 2006). It is carried out by creating inward incisions around the stem from the peripheral area to the cambium zone. This treatment will stop the transport of sugars and other photosynthetic materials, so the tree will die naturally (Basri, et al. 2015).

A tree exhibits different responses on girdling like the following; the stomatal response observed in girdled trees has been attributed to end-product inhibition of photosynthesis (Kriedemann and Lenz 1972, Urban and Alphonsout 2007) and an accumulation of abscisic acid (ABA) in the leaves (Setter et al. 1980). Stomata can be controlled by growth regulators transported in xylem sap from roots to leaves (Gollan et al. 1985, Zhang and Davies 1989) as shown by experimental manipulations of hydraulic conductance involving loss of root conductivity (Saliendra and Meinzer 1989, Saliendra et al. 1995). Hydraulic properties of girdled wood produced differ from normal wood; including vulnerability to embolism and conductivity (*k*s) (Cernusak and Marshall 2001).Girdling affects annual ring width, duration of cambial growth and the timing and duration of latewood production (Wilson and Gartner 2002). The girdling-induced reductions in growth stress and transpiration were associated with a decrease in leaf hydraulic conductance (Domec and Pruyn. 2008)

In addition, tree girdling has also been used to reduce the moisture content of stems (Noel 1970). Some tree species died during the year they were girdled, but some species can survive several years after girdling (Baldwin 1934; Noel 1970). In tree girdling, wood moisture decreases and the wood becomes lighter. Besides reducing moisture content, girdling is also effective in reducing growth stresses, residual stresses and microfibril angle (Wahyudi et al. 1999). Girdled Weymouth pine (*Pinus strobus*) has lived for more than five years in North America. In general, trees will die within 1–2 years after girdling (Noel 1970). According to Pohjola (1990), in Finland, the aspen will die 1–6 years after girdling. According to Taylor and Cooper (2002) girdling decreased remarkably the moisture content of Red pine (*Pinus resinosa*) and Tamarack (*Larix laricina*), but not that of Red maple (*Acer rubrum*). The moisture content of the Norwayspruce (*P. abies*) (23%) and Downy birch (*B. pubescens*) (33%) was at its lowest point at 14 months after girdling (Laurila et al., 2014).

The reaction forces acting on the mature stem caused by the new cells in the growth layer produce residual stresses within the stem. Thus, the residual stresses within the stem accumulate as a superposition of the initial maturation stress state and the residual stresses generated by subsequent growth layers (Archer, 1986)

CIE(Commission Internationale de l'Eclairage)lab (CIElab) color system is one of the most accurate systems for measuring wood color. According to HUNTER LAB (1995), the CIELab color system estimates the wood color in three coordinates: L* for lightness, represents the position on the black–white axis (L=0 for black, L=100 for white); a* for chrome value, defines the position on the red–green axis (+100 values for red shades,-100 values for green shades); and b* for chroma value, defines the position of the yellow–blue axis (+100 values for yellow shades, -100 values for blue shades).

This study examined the effects of girdling on longitudinal surface released strain, radial distribution of residual released strain, moisture content and color.

4.5 Materials and Methods

4.5.3 Study area and sample trial sites

Experimental samples were randomly selected from two established field trial sites of BL mahogany located in Butuan City and Cagayan de Oro City representing contrasting growing conditions within the target plantation region in northern Mindanao, Philippines (Figure 4-1)(Table 4-1).

The field trials were established in September of 2009 by the Department of Environment and Natural Resources (DENR Philippines) with support from the Commonwealth Scientific and Industrial Research Organization (CSIRO Australia) and the Australian Government (AusAID Public Sector Linkages Program) (Abarquez et al., 2015).

4.5.4 Plant Material

Test trees were randomly selected from 8-year old progeny trial sites of BL mahogany in Mindanao, Philippines. Eighteen test tree samples of different diameter classes were randomly selected in two trial sites. Table 4-2 summarizes the lateral growth data (diameter at breast height) collected prior to the measurement of various material parameters.

Twelve test trees were girdled (3 inches wide strip of bark, periderm, cortex and phloem was removed from each trunk) 2 inches above the buttress while the remaining non-girdled six test trees were considered as controlled. Prior to girdling, data on SRS were collected.

4.2.3 Longitudinal released strain of surface growth stresses (SRS)

Growth data (diameter and height) were collected prior to the measurement of various material parameters measured at four cardinal points at the breast height of every tree. Then, the longitudinal released strain (SRS) of the surface growth stresses was measured. For each standing tree, measurement was conducted at four cardinal points (North, South, East, and West) at diameter breast height (DBH) (1.3 meters from the ground). A strain gauge (electric-wire-strain gauge, 10 mm length, KFG-10-120-C1-11L3M3R, Kyowa Co., Tokyo, Japan) was glued to the exposed secondary xylem surface along the longitudinal direction and was connected to a strain meter (UCAM-1A, Kyowa Co., Tokyo, Japan). After measuring the initial strain on the tree sample, the surface stress was released using a handsaw, and the strain was then recorded. The amount of the longitudinal released strain of the surface growth stress (SRS) was calculated by subtracting the initial measurement from the second reading (Okuyama et. al. 1981, Kollmann et al., 1968)

4.3.4 Radial distribution pattern

There were 18 test trees from different diameter class proportion (large, medium and small) used in the study. From the diameter at breast height (DBH), a quarter sawn board (5cm thickness (center: pith) and ratio of 2.6 of its DBH is the length of the board) were prepared from north to south side of the stem, excluding the bark. Sampling points were set in every 2cm from the pith to the bark portion at the center of the board length (Figure 4-2).

4.3.4.a Residual released strain of growth stresses (RRS)

Sampling area of the board was prepared evenly and cleaned by sanding. A strain gauge (electric-wire-strain gauge, 10 mm length, KFG-10-120-C1-11L3M3R, Kyowa Co., Tokyo, Japan) was glued to the sampling points across the board direction and connected to a strain meter (UCAM-1A, Kyowa Co., Tokyo, Japan). After measuring the initial strain on the tree sample, the residual stress was released using a handsaw, and the strain was then recorded. The difference RRS was derived by subtracting maximum RRS value and minimum RRS value in every tree sample.

4.3.4.b Moisture content (MC)

Oven dry method was used to measure MC. Radial distribution test samples of moisture content were taken from the same location of RRS. Wood samples were prepared from pith to the bark at 2cm interval. Prior to drying, initial of MC as well as oven dry weight were measured, thereafter. *Moisture content* was measured according to ASTM *D 143-94*. The moisture content was calculated using equation 1

$$MC = \frac{initial\ weight - ovendry\ weight}{ovendry\ weight}\ x\ 100 \qquad \text{Equation 1}$$

4.3.4.c Color

Wood sample size: 5mmT; 60mmW; 60mmL was prepared at 2 cm from the pith, with 4 wood samples per test trees. Colour was measured using Spectrophotometer (Shimadzu UV-3100PC). The reflectance spectra were recorded using the standardized CIEL*a*b* chromaticity system as a function of wavelength (BYK-Gardner 2004). For reflection readings, the observer component was set at an angle of 10° with the surface of the specimen. The color space parameter was measured and computed using the standard illuminant D65 (corresponding to daylight at 6500 K).

4.3.5 Statistical Analysis

Simple linear regression models were used to test the correlation between the wood properties: SRS, RRS, MC and Colour. The comparison of means in wood properties between treatments was tested using the simple comparison methods: one-way ANOVA and Scheffe's test for multiple mean comparison using SPSS v20 software.

4.4 Result and Discussion

4.4.1 Survival of girdled trees

The comparisons of percent survival of test trees between the two trial sites and among the diameter classes were shown in Figure 4-3 and Table 4-3. Results show that the percent survival has no significant differences between trial sites, while the difference among the diameter classes was significant. All test trees with small sizes in two trial sites did not survive after 2 years from girdling. However, test trees with large sizes have 100% and 83% survival, and medium sizes have 83% and 50%survival in Butuan and Cagayan de Oro trial sites, respectively. Thus, the two years girdling is insufficient for large and medium size trees of BL mahogany to die. However, some studies reported that trees will die within 1–2 years after girdling (Noel 1970). Girdled weymouth pine (*Pinus strobus*) has lived for more than five years in North America (Laurila et al., 2014). According to Pohjola (1990), in Finland, the aspen will die 1–6 years after girdling. The *Acer rubrum*, *Pinus resinosa* and *Larix laricina* trees were still alive 1 to 2 years after girdling (Taylor 1999).

4.4.2 Longitudinal surface released the strain of growth stresses (SRS)

Figure 4-4 shows the longitudinal surface released the strain of growth stresses (SRS) of test trees classified in three diameter class in different treatments (Non-girdled, 1 year girdled and 2 years girdled). SRS of test trees with large size and medium size have highly significant differences between non-girdled and the 2-year girdled, but no significant variation between non-girdled and 1-year girdled test trees. In addition, the small size test trees were not significantly different among girdling periods (Table 4-3). This assumes that SRS will reduce after 2 years from girdling in large and medium size trees of 8-year old BL mahogany, but not in small size trees. Accordingly, same findings on girdling are also effective in reducing growth stresses, residual stresses and microfibril angle (Wahyudi et al. 1999). Girdling will stop the transport of sugars and other photosynthetic materials, so the tree will die naturally (Bashri, et al, 2015).

4.4.3 Radial distribution pattern

4.4.3.a Residual released strain of growth stresses(RRS)

The residual released strains (RRS) in different diameter class and treatments were shown in Figures 4-5 and 4-6. Using the difference of RRS, the diameter class and treatments gave no significant differences both in longitudinal and tangential releases. The high survival of test tress (shown in table 4-3) after 2 years from girdling reveals insignificant results of residual release strain. Figure 4-6 shows the normal distribution of residual release strain across the tree diameter of 8 year old BL mahogany trees. This pattern of residual strain coincides with the theoretical model of residual stress in the radial direction (Archer & Byrnes 1974; Okuyama & Kikata 1975). Thus, the results indicated a normal distribution of growth stresses on trees. According to Kubler (1959), for a given growth strain at the periphery, small diameter logs show steeper growth stress gradients across the diameter. Therefore, sawn boards from a small diameter log show greater distortion than sawn from a large diameter log with the same peripheral strain.

This progressive easing of growth stress produces a gradient in tensile stresses with a maximum at stem periphery to zero at about one third of radius from periphery and then progressively larger compressive stresses towards the pith, thus counter balancing the tensile stresses toward the periphery (Archer 1986).

4.4.3.b Moisture content (MC)

The radial distribution pattern of percent moisture content between the girdled and non- girdled treatment are shown in Figure 4-7. It was observed that all the test trees with small size were dead, but some of large and medium size test trees were still alive after 2 years from girdling. This observation resulted to significant difference of MC between girdled and non-girdled treatments (shown in Table 4-3). Figure 4-7 shows a different pattern comparing MC of girdled and non girdled treatment with small size test trees. Small size test trees that died after 2 years from girdling have almost same MC that ranges from 11.93% to 14.87% from pith to the bark, as compared to the non-girdled test trees that gradually increases from 37.39% to 64.68% from pith to the bark.

According to Taylor and Cooper (2002) girdling decreased remarkably the moisture content of Red pine (*Pinus resinosa*) and Tamarack (*Larix laricina*), but not that of Red maple (*Acer rubrum*). The moisture content of the Norwayspruce (*P. abies*) (23%) and Downy birch (*B. pubescens*) (33%) was at its lowest point at 14 months after girdling (Laurila et al., 2014).

However, girdled and non-girdled treatments of large and medium size test trees show normal distribution pattern of MC which gradually increases from pith to the bark. Some of the large and medium size girdled test trees that died after 2 years from girdling were observed to have almost the same MC pattern with non-girdled treatments. This observation indicates that the above mentioned test trees are still holding water in the trunk after 2 years from girdling.

4.4.3.c Color

The result of average colorimetry in non-girdled and girdled test trees of BL Mahogany in CIEL*a*b* color scale are shown in Figure 8. The lightness components are the highest proportions in non-girdled and girdled test trees. The wood colors of BL Mahogany are different between non-girdled and girdled test trees. The wood color of non-girdled test trees averages: 70.95 in L* (lightness), 10.64 in a* (redness) and 22.14 in b*(yellowness) while the wood color of girdled test trees averages: 67.80, 13.60 and 24.57, respectively. All color parameters are positive, meaning that wood color is a combination of different tonalities of lightness, redness, and yellowness (Tovar, et al. 2009). One-way ANOVA analysis showed that lightness, redness and yellowish parameters have high significant differences between non-girdled and girdled test trees (Table 4-3).

The relationships among the colour parameters defining the non-girdled and girdled test trees measurements are shown in Figure 8. A significant correlation was found between a* and L*, b* and L*, and a* and b* parameters. Same findings in the study of *Fagus sylvatica*, revealed that the parameters *L** with *a**, *L** with *b**, and *a** with *b**of the CIE*L** *a** *b** color scale were significantly correlated (Liu et al. 2005). The results showed that the variation in wood color of non-girdled and girdled test trees of BL mahogany produced an inverse variation between a* and L*, b* and L*, but not with *a** with *b**.

The color difference (ΔE^*_{ab}) of small, medium and large diameter class between girdled and non girdled test trees were 1.06, 10.47 and 18.72, respectively. The color variation can be detected by the human eye, except the color difference of wood samples from small diameter class. This is according to Gonnet 1993 that when ΔE^*_{ab} is greater than 2, the human eye can detect wood color variation. In the study of Tovar, et al. 2009, the ΔE^* parameter, which measures color difference between two points in a Cartesian plane, was 7.7 and 8.3 in sapwood and heartwood, respectively after kiln drying of *Vochysia guatemalensis* lumber.

In the perspective of wood chemistry, there were several studies that explain the variation of wood color due to changes in water concentration and wood extractives. Keey (2005) mentioned that superficial changes in color of boards after drying are produced by water movement as well as movement of dissolved substances from the interior to the surface. Substances are dissolved in water, then water in the surface is evaporated and wood extractives are concentrated at or near the surface. Sugars of low-molecular weight and nitrogenous compounds such as proteins produce a reddish color. However, wood color change can occur only on surface areas in many species (Sundvist 2002).

4.5 Conclusion

The effects of girdling in different periods (0, 1 year, and 2 years) on the growth stress reduction and basic wood properties of 8-year old planted BL mahogany were almost the same with the non-girdled test trees. The result showed that after 2 years from girdling all test trees with small sizes in two trial sites did not survive. However, test trees with large sizes have 100% and 83% survival; and medium sizes have 83% and 50% survival in Butuan and Cagayan de Oro trial sites, respectively. Longitudinal released strain of surface growth stresses (SRS) of test trees with large and medium sizes have highly significant differences between non-girdled and 2-year girdled, but no significant variation between non-girdled and 1 year girdled test trees. The small size test trees have the same SRS in three treatment periods. Using the difference of residual released strain of growth stresses (RRS), the diameter classes and treatment periods showed no significant differences. Moisture content (MC) of test trees revealed significant differences between girdled and non-girdled treatment. Small size test trees that died after 2 years from girdling have almost the same MC which ranges from 11.93% to 14.87% from pith to the bark, as compared with non-girdled test trees that gradually increases from 37.39% to 64.68% from pith to the bark. Non-girdled and girdled treatments of large and medium size test trees showed normal distribution pattern of MC which gradually increases from pith to the bark. The lightness, redness and yellowish parameters have high significant differences between non-girdled and girdled test trees. The wood color of non-girdled test trees averages; 70.95 in L* (lightness), 10.64 in a* (redness) and 22.14 in b*(yellowness); while the wood color of girdled test trees averages; 67.80, 13.60 and 24.57, respectively. Significant correlations were found between a* and L*, b* and L*, and a* and b* parameters. The results showed that the variation in wood color of non-girdled and girdled test trees of BL mahogany produced an inverse variation between a* and L*, b* and L*, but not with *a** with *b**. The color difference (ΔE^*_{ab}) of small, medium and large diameter class between girdled and non girdled test trees were 1.06, 10.47 and 18.72, respectively (Figure 4-10).

TABLES

Table 4-1. Location and description of sampling sites (Abarquez et al., 2015; PAGASA, 2010)

Trial Site	Location		Elevation (m.a.s.l)	Annual Rainfall (mm)	Soil			
	Latitude	Longitude			pH	Organic Matter (%)	Phosphorus (ppm)	Potassium (ppm)
Butuan	8° 56' N	125° 35' E	13–15	2057	6.8	1.2	4.5	144
Cagayan de Oro	8° 23' N	124° 42' E	413–415	1703	5.8	4.5	1.3	48

Table 4-2. Average lateral growth data (DBH) of tree samples in different diameter classes: averages and standard deviations of diameter.

Diameter Class	No. of test trees	Average DBH (SD) cm
Large	6	**25.00 (4.65)**
Medium	6	**18.70 (2.58)**
Small	6	**14.50 (2.58)**
Total	18	

Table 4-3. Analysis of variance (ANOVA) for the effects of survival, SRS, RRS-longitudinal and tangential release, moisture content and CIELab color scale to diameter class, treatments and colour system

Source of Variance		**df**	**Sum of Squares**	**Mean Square**	**Sig. (*p* - value)**
(a) Survival (%)	Diameter class	2	8,981.13	4,490.56	0.0300
	Site	1	416.67	416.67	0.2254
(b) Surface Released Strain (%)	Large DBH	2	80,304.95	40,152.47	0.0070
	Medium DBH	2	417,863.09	208,931.55	0.0080
	Small DBH	2	49,833.50	24,916.75	0.5570
(c) Difference Residual Releaed Strain (%)	Treatment	2	424,760.78	212,380.39	0.5028
	Diameter class	2	1,382,486.78	691,243.39	0.1834
(d) Moisture content (%)	Treatments	1	864.53	864.53	0.0353
(e) CIELab color scale	***L**** (Lightness)	1	158.63	158.63	0.0153
	a* (Redness)	1	140.48	140.48	0.0000
	b* (Yellowness)	1	94.82	94.82	0.0079

Table 4-4 Correlation matrices of CIE *L** *a** and b* color scale

CIELab color scale		***a**** (Redness)	***b**** (Yellowness)
L* (Lightness)	Pearson Correlation	-.746**	-.402**
a* (Redness)	Pearson Correlation		.790**

**. Correlation is significant at the 0.01 level (2-tailed).

FIGURES

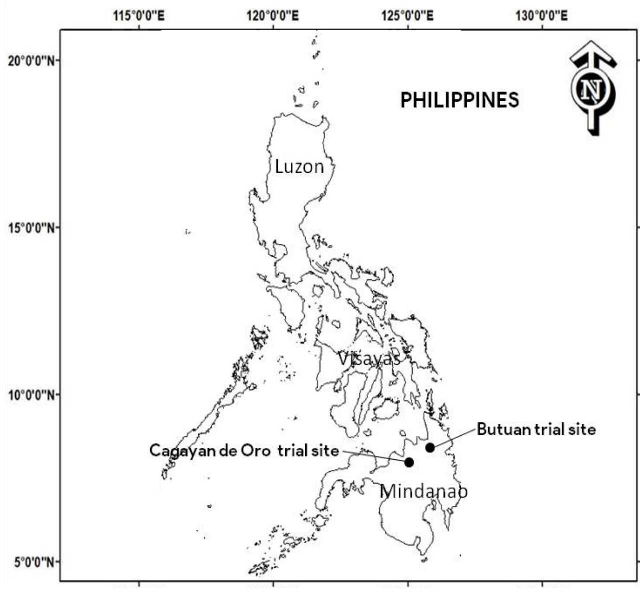


Figure 4-1 Location of the (●) two trial sites of BL Mahogany (*Sweitenia macrophylla* King) in the Philippines.

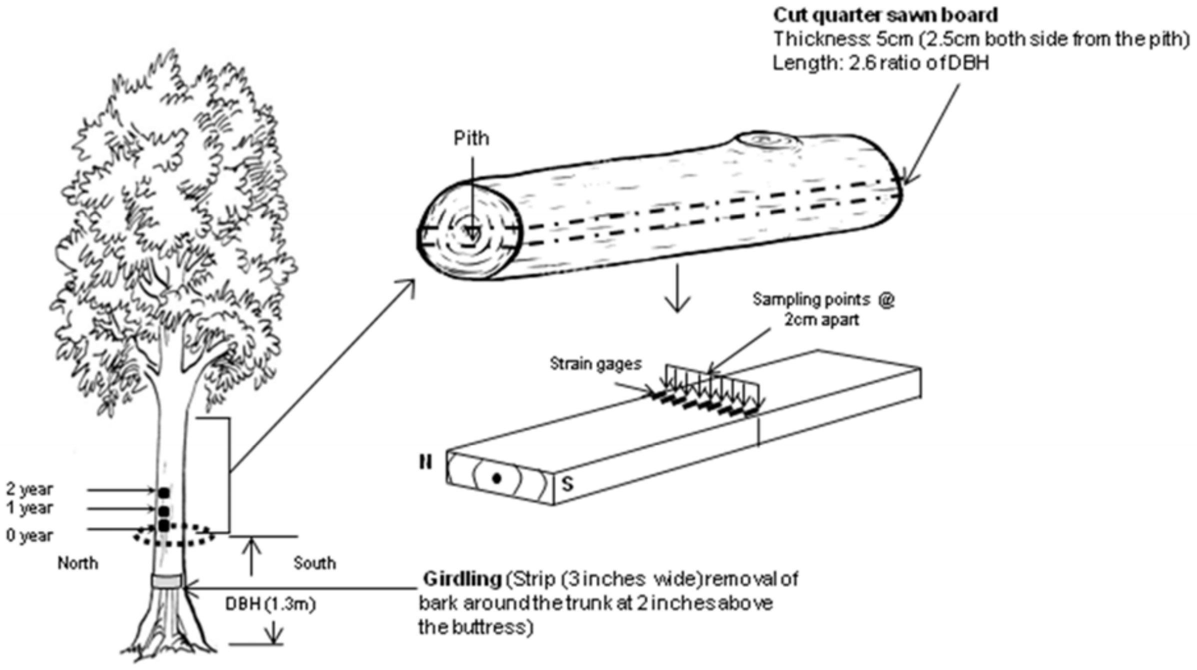
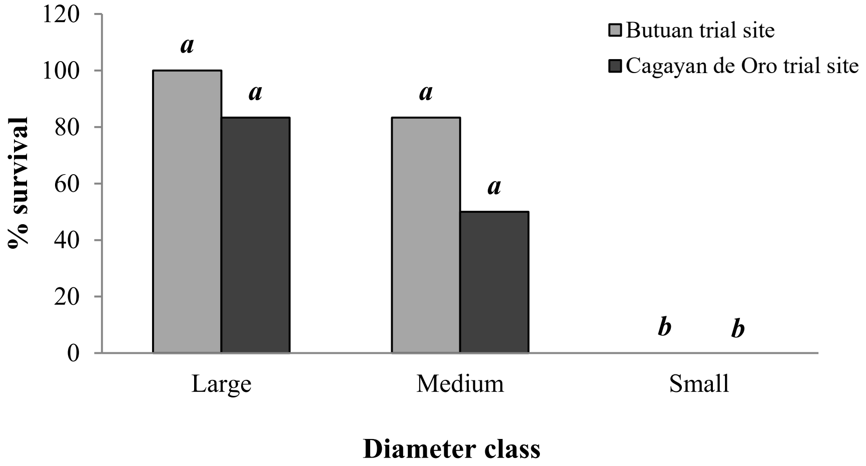


Figure 4-2 Sampling points of radial distribution patterns from the pith to north and south side of quarter sawn board with 2cm interval located at the center (length: 2.6 ratio of DBH).

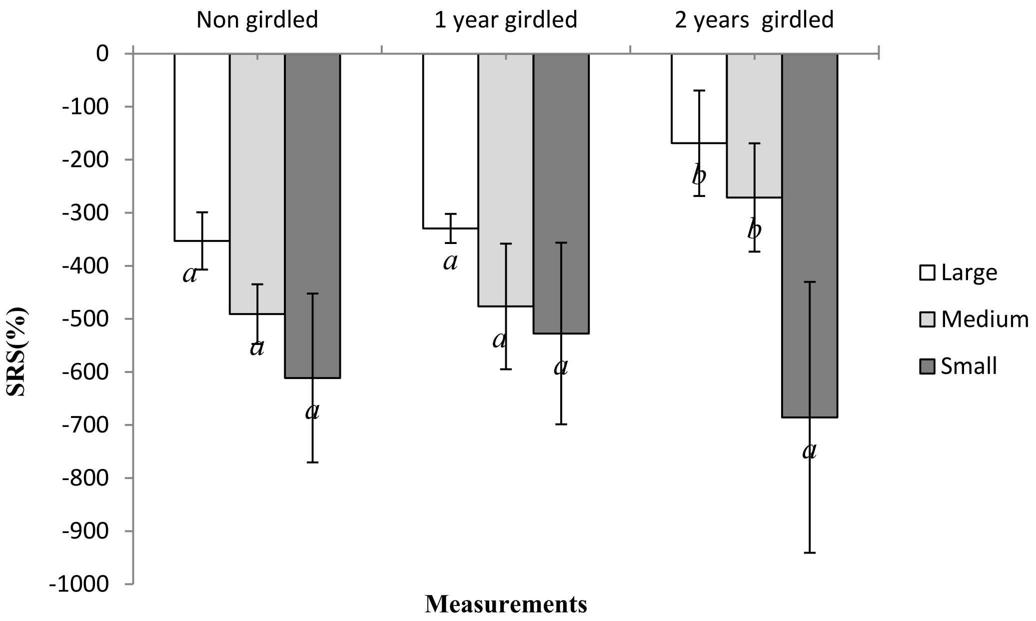
(a) *(b)*

Figure 4-2.a. Girdling treatment : conduct of girdled (*a*) and callus formation after 2 years from girdling (*b*)



Means followed by the same letters (*a*,*b*) in the same row are not significantly different at $p \leq 0.05$ according to Scheffe's method

Figure 4-3. Average percent survival of 8-year old BL mahogany test trees girdled after 2 years



Means followed by the same letters (*a,b*) in the same row are not significantly different at $p \leq 0.05$ according to Scheffe's method

Figure 4-4. Average longitudinal surface released the strain (SRS) of 8-year old BL mahogany test trees in different diameter class and treatments.

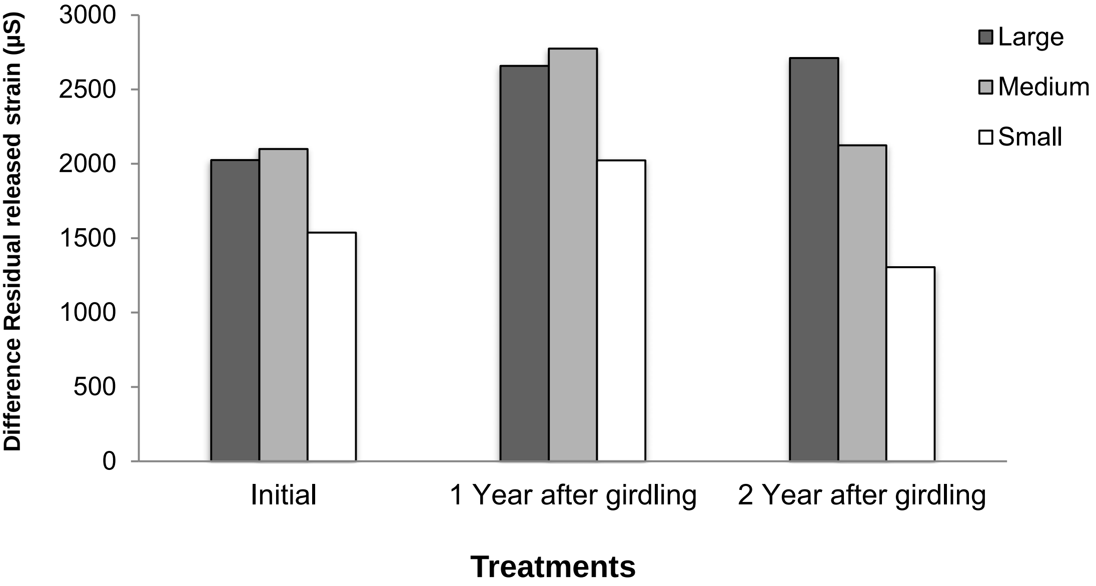


Figure 4-5. Difference of residual released strains (RRS) of 8-year old BL mahogany test trees in different diameter class and treatments

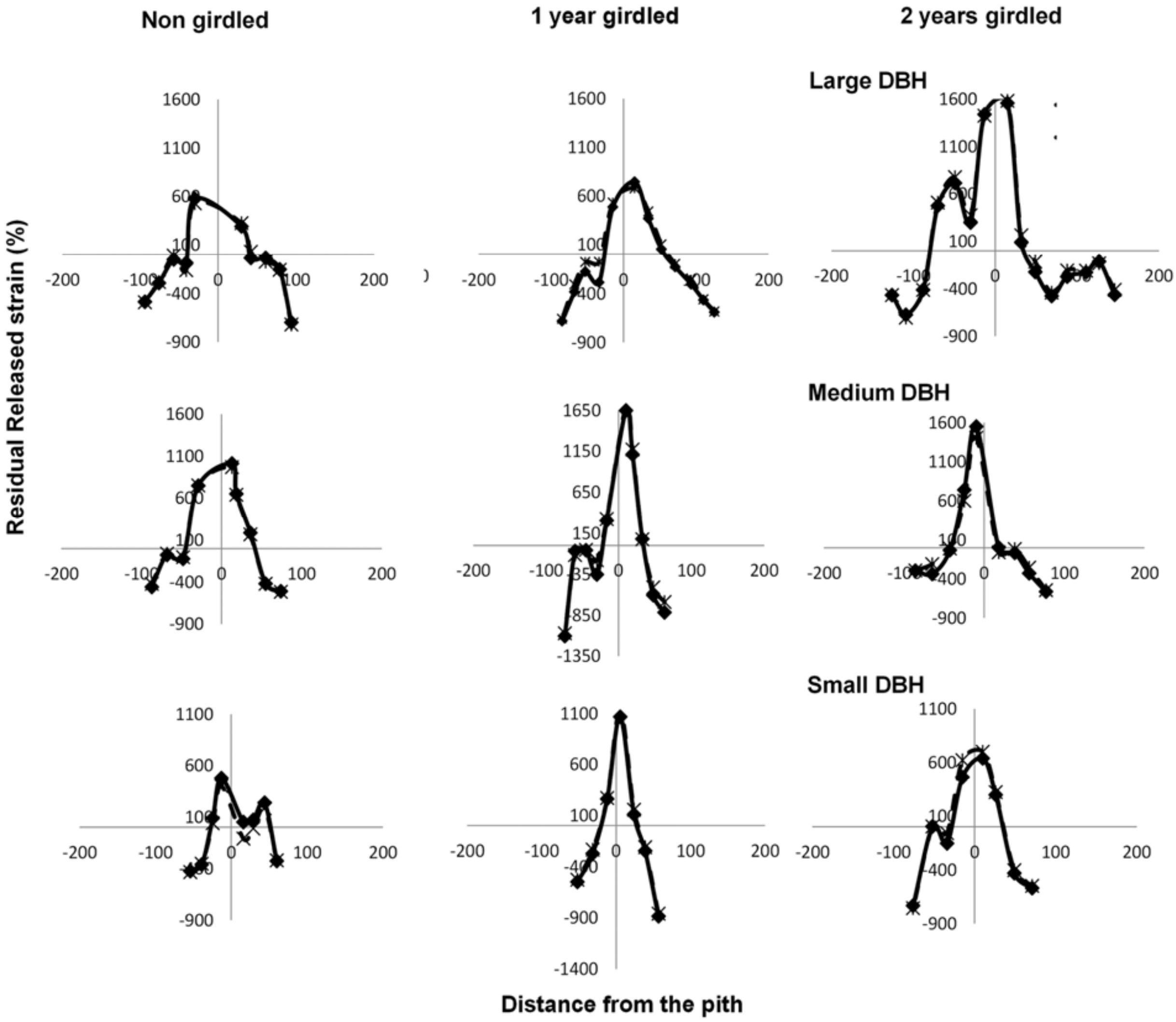


Figure 4-6. Radial distribution patterns of residual released strains – longitudinal and tangential releases of 8-year old BL mahogany test trees in different diameter (DBH) class and treatments.

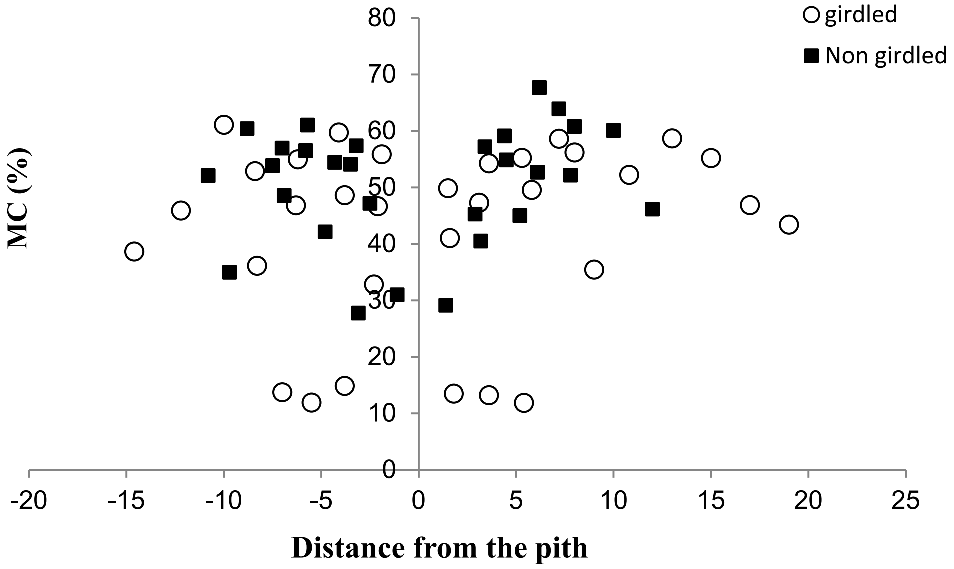


Figure 4-7. Radial distribution pattern of percent moisture content between non girdled and girdled treatment after 2 years

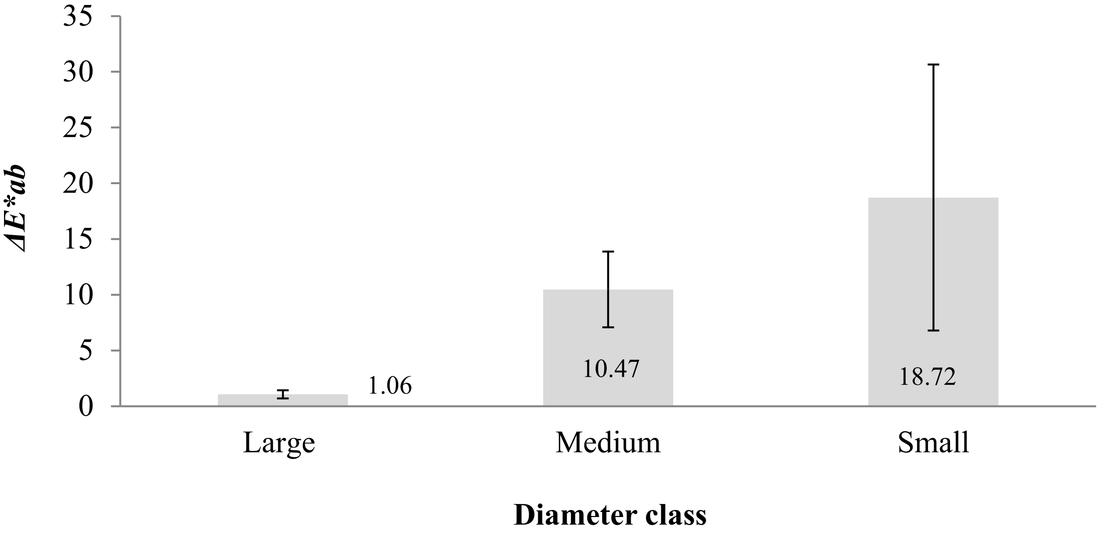


Figure 4-8. Color difference between non-girdled and gridled test tress in different diameter class

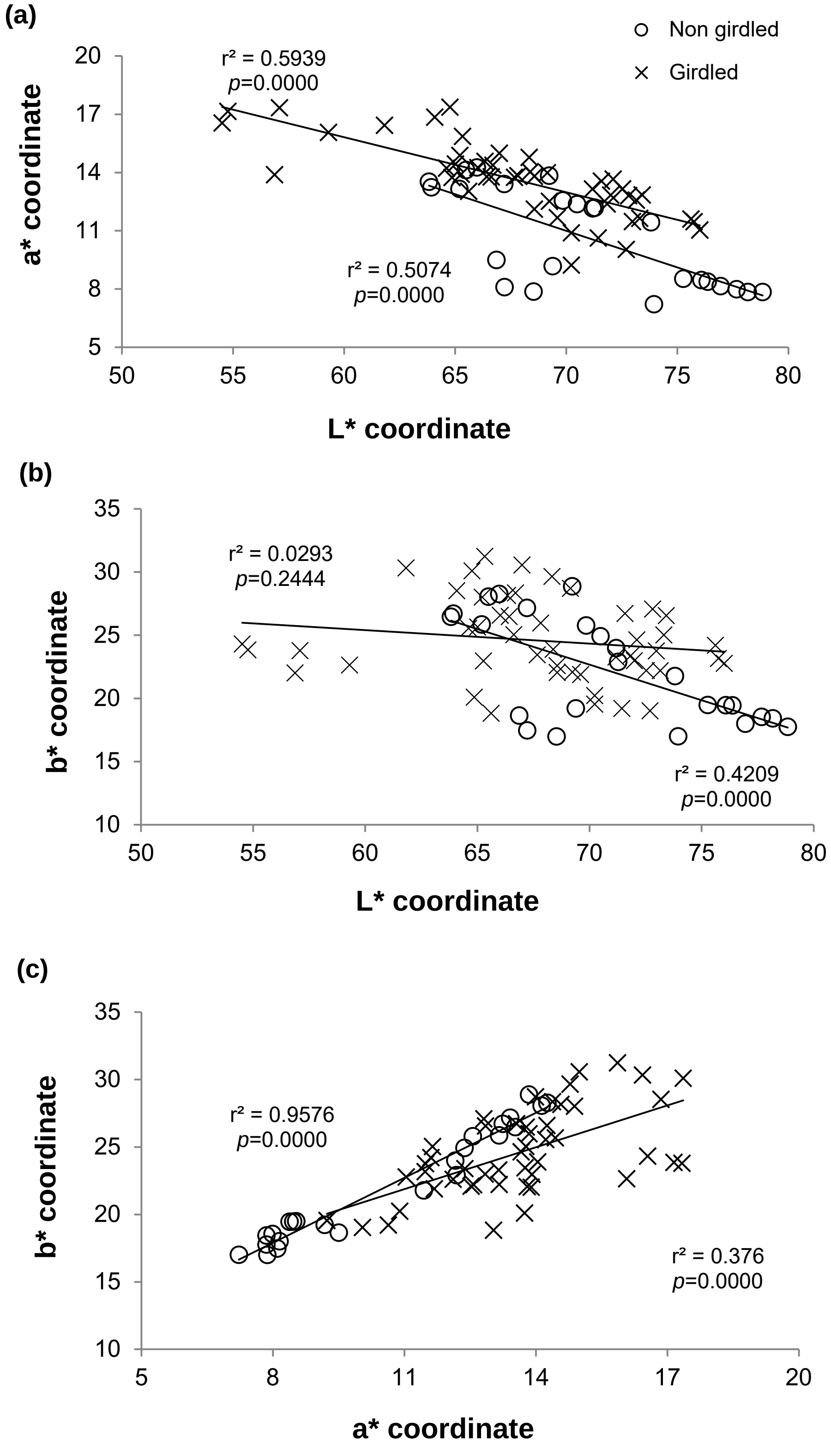


Figure 4-9. Relationship between L^* vs a^* (a), L^* vs b^* (b) and a^* vs b^* (c) for BL mahogany non- girdled and girdled test trees

Figure 4-10. Wood color difference of control (green samples)(left) and girdled treatment (right). Color difference is ΔE^*_{ab} = 18.72(small diameter).

Chapter 5

The effect of water heated treatment on growth stress reduction of Big-leaf Mahogany *(Swietenia macrophylla* King*)* in the Philippines

5.1 Introduction

Accumulation of growth stress during wood development increases the potential of wood defects during its processing into lumber. These attributes degrade the market value of lumber and increases wood waste. Several studies account that the annual addition of wood on the outer side of a tree trunk adds to the longitudinal stress and therefore presents a regular distribution along the longitudinal plane through the pith (Archer and Bynes 1974, Kubler 1987, Fournier et al. 1990, Huang et al. 2005). This stress is superposed in the tree trunk as it increases in diameter, resulting in residual stress distribution inside the log (Okuyama and Kikata, 1975). As a consequence, there is warp when lumber is sawed and end splits that occur at logging, often decreasing the final yield of the wood product (Okuyama and Sasaki, 1979). Growth stress arises from the deposition of lignin within the secondary walls during the maturation of fibrous cells (Boyd 1972. Yamamoto et al. 1991. Guitard et al. 1999). Growth Stress originates in wood maturation causing both rigidification and expansion to the cell-wall material. Locked in strains are partially released by cutting specimens from the tree, and, more completely, by boiling them in a green state, so as to exceed to softening point of lignin (Gril and Thibaut 1994).

There were several methods to reduce the growth stress in the logs. Stress relaxation also occurs at high temperatures induced by boiling (Skolmen, 1967), steaming (Sujan et al, 2015) and smoking (Barber et al, 1964; Noack 1969; Tanaka et al. 2014).

Boiling treatment is one of the efficient methods to reduce the residual release strain inside the logs. Okuyama et al. (1987, 1988. 1990) investigated the effects of direct heating on the reduction of residual stress in green logs of Zelkova, Japanese larch, and Japanese cedar. Abe and Yamamoto (2007) describes the experiment in boiling treatment, tension wood with numerous G-fibers contracted considerably in the longitudinal direction and the longitudinal Young's modulus decreased in spite of the water-saturated condition. The surface growth stress and the internal residual stress of *Zelkova serrata* were reduced by heat treatment (Huang et al 2005). Hygrothermal recovery is the relaxation of the viscoelastic component of growth stress accumulated during the maturation process of sugi (*Cryptomeria japonica*) (Matsuo et al. 2016).

This study examines the effect of heat water treatment in the reduction of residual release strain and changes in wood properties of BL mahogany.

5.3 Materials and Methods

5.2.1 Study area and sample trial sites

Experimental samples were randomly selected from established field trial site of BL mahogany located in Butuan City representing within the target plantation region in northern Mindanao, Philippines (Figure 5-1)(Table 5-1).

The field trials were established in September 2009 by the Department of Environment and Natural Resources (DENR Philippines) with support from the Commonwealth Scientific and Industrial Research Organization (CSIRO Australia) and the Australian Government (AusAID Public Sector Linkages Program) (Abarquez et al., 2015).

5.2.2 Plant Material

Test trees were randomly selected from 8-year old progeny trial sites of BL mahogany in Mindanao, Philippines. Nine test tree samples of different diameter classes were randomly selected. Table 5-2 summarizes the lateral growth data (diameter at breast height) collected prior to the measurement of various material parameters.

Nine test trees were felled down and bucked into desired length of logs (2.6 ratio of DBH). In every test tree, two logs of the same length were sawn into board from north side to south side of the stem, with 5cm thickness or 2.5cm equal distance from the pith. After cutting into desired sizes, lumber clips made of metal strip were immediately punched at both end of the lumber to hold the release of strain during sawing (Figure 5-2.a). The first log was served as green (control) log and the second log was subjected to heat water treatment. An industrial steel drum was fabricated to serve as basin for boiling. The nine quarter sawn boards were arranged in the basin with spacer in between board test samples and filled with tap water. Using firewood the water temperature was constantly monitored using infrared thermometer to maintained 80°C in an accumulated time of 48 hours (Figure 5-2).

5.2.3 Residual released strain of growth stresses (RRS)

There were 9 test trees from different diameter class proportions (large, medium and small) used in the study. From the diameter at breast height (DBH), a quarter sawn board (5cm thickness (center: pith) and ratio of 2.6 of its DBH is the length of the board) were prepared from north to south side of the stem, excluding the bark. Sampling points were set in every 2cm from the pith to the bark portion at the center of the board length (Figure 5-2, 5-2.a, and 5-2.b).

Sampling area of the board was prepared evenly and cleaned by sanding. A strain gauge (electric-wire-strain gauge, 10 mm length, KFG-10-120-C1-11L3M3R, Kyowa Co., Tokyo, Japan) was glued to the sampling points across the board direction and connected to a strain meter (UCAM-1A, Kyowa Co., Tokyo, Japan). After measuring the initial strain on the tree sample, the residual stress was released using a handsaw, and the strain was then recorded. Difference RRS was derived by subtracting maximum RRS value and minimum RRS value in every tree sample.

5.2.4 Color

Wood sample size: 5mmT; 60mmW; 60mmL was prepared at 2 cm from the pith, with 4 wood samples per test tree. Colour was measured using Spectrophotometer (Shimadzu UV-3100PC). The reflectance spectra were recorded using the standardized CIEL*a*b* chromaticity system as a function of wavelength (BYK-Gardner 2004). For reflection readings, the observer component was set at an angle of 10° with the surface of the specimen. The color space parameter was measured and computed using the standard illuminant D65 (corresponding to daylight at 6500 K) and measured wavelength: 380-780 nm.

5.2.5 Statistical Analysis

Simple linear regression models were used to test the correlation between the wood properties: RRS and Colour. The comparison of means in wood properties between treatments was tested using simple comparison methods: one-way ANOVA and Scheffe's test for multiple mean comparison using SPSS v20 software.

5.3 Results and Discussion

5.3.1 Residual released strain of growth stresses (RRS)

The difference residual released strains in different diameter classes are shown in Figure 5-3. The difference RRS of small and medium size trees have significant differences between control and water heated wood samples. The average residual release strains in three diameter classes: small, medium and large of BL mahogany was reduced to 47.98%, 53.57% and 53.19%, respectively (Figure 5-4 and 5-5). Results were similar with the study of Huang et al 2005 where the surface growth stress and the internal residual stress of *Zelkova serrata* were reduced by heat treatment. The residual stress of the 33-h 80°C-heated bolts was relaxed (Nogi et al.2003). However, water heated treatment has no significant effects in the large size trees (Table 5-3).

5.3.2 Color

The result of average colorimetry in control and water heated wood samples of BL Mahogany in CIEL*a*b* color scale are shown in Figure 5-6. The wood color of water heated wood samples averages as: 55.38 in (lightness), 16.79 in a* (redness) and 26.30 in (yellowness) while the wood color of control wood samples averages as: 62.83, 15.80 and 28.78, respectively. All color parameters are positive, meaning that wood color is a combination of different tonalities of lightness, redness, and yellowness (Tovar, et al. 2009). One-way ANOVA analysis showed that L*(lightness) and b*(yellowish) parameters have high significant differences between control and water heated wood samples, but not with the a* (redness). This means that the effect of water heated treatment in BL mahogany enhances the color of redness which this species is known for because of its vibrant wood color and grain that are of great value in the production of furniture and nobility items. Similar are the findings on the effect of boiling in Sugi (*Cryptmeria japonica* D.Don), the lightness was reduced to about 70% for 8 min at 180°C, to about 60% for 8 min at 200°C, and to about 50% for 8 min at 220° C (Inoue, et al. 1992).

In terms of the relationship among the color parameters in control and water heated wood samples, a significant correlation was found only between a* and L*, and not with b* and L*, and a* and b* parameters (Figure 5-7). This result suggests that BL mahogany enhances the color of redness after boiling. According to Burti *et al*. (1998) where during steaming at elevated temperatures, polyphenols compounds found in hybrid walnut heartwood which conferred the dark color to heartwood, may migrate in the sapwood region and change the sapwood colorfrom light to dark changes in wood color. Mitsui *et al*. (2001) and Bourgois *et al*. (1991) also reported that decreased in lightness was resulting from high temperature of heat treatment due to decrement in certain chemical component in wood such as hemicelluloses and lignin. Changes in wood color can be an indication of chemical modification or changes in wood (Burti *et al*., 1998; Bekhta and Niemz, 2003; Sundqvist *et al*., 2004).

The color difference (ΔE^*_{ab}) of small, medium and large diameter class between between control and water heated wood samples were 8.48, 9.18 and 8.33, respectively (Figure 5-8). This color variation is detectable by the human eye. This is according to Gonnet 1993 who stated that when ΔE^*_{ab} is greater than 2, the human eye can detect wood color variation.

5.4 Conclusion

Water heated treatment drastically reduced the average residual release strains in three diameter classes: small, medium and large of BL mahogany to 47.98%, 53.57% and 53.19%, respectively. This significant effect on the reduction of residual released strain was observed in small and medium size trees, but not with the large size trees. It is assumed that that the reduction of residual release strain in large size trees may require high temperature and increase the time duration during water heated treatment. In terms of wood color, the water heated wood samples averages: 55.38 in (lightness), 16.79 in a* (redness) and 26.30 in (yellowness) while the wood color of control wood samples averages: 62.83, 15.80 and 28.78, respectively. The effect of water heated treatment in L*(lightness) and b*(yellowish) parameters have high significant differences between control and water heated wood samples, but not with the a* (redness). A significant correlation was found only between a* and L*, and not with b* and L*, and a* and b* parameters. The color difference (ΔE^*_{ab}) of small, medium and large diameter class between between control and water heated wood samples were 8.48, 9.18 and 8.33, respectively.

TABLES

Table 5-1. Location and description of sampling sites (Abarquez et al., 2015; PAGASA, 2010)

Trial Site	Location		Elevation (m.a.s.l)	Annual Rainfall (mm)	Soil			
	Latitude	Longitude			pH	Organic Matter (%)	Phosphorus (ppm)	Potassium (ppm)
Butuan	8° 56' N	125° 35' E	13–15	2057	6.8	1.2	4.5	144

Table 5-2. Average lateral growth data (DBH) of tree samples in different diameter classes: averages and standard deviations of diameter.

Diameter Class	No. of test trees	Average DBH (SD) cm
Large	3	33.67 (3.06)
Medium	3	25.25 (1.26)
Small	3	18.00 (1.73)
Total	9	

Table 5-3. Analysis of variance (ANOVA) on the effects of residual release strain in different diameter classes and effects of wood color of BL mahogany water heated treatment.

Source of Variance	df	Sum of Squares	Mean of Squares	Sig.
Residual Release strain				
Small DBH	1	515,680.17	515,680.17	0.0441
Medium DBH	1	788,140.13	788,140.13	0.0262
Large DBH	1	2,290,308.17	2,290,308.17	0.1194
Color				
L* (Ligthness)	1	250.00	250.00	0.0000
a* (Redness)	1	4.42	4.42	0.1360
b* (Yellowness)	1	27.63	27.63	0.0180

FIGURES

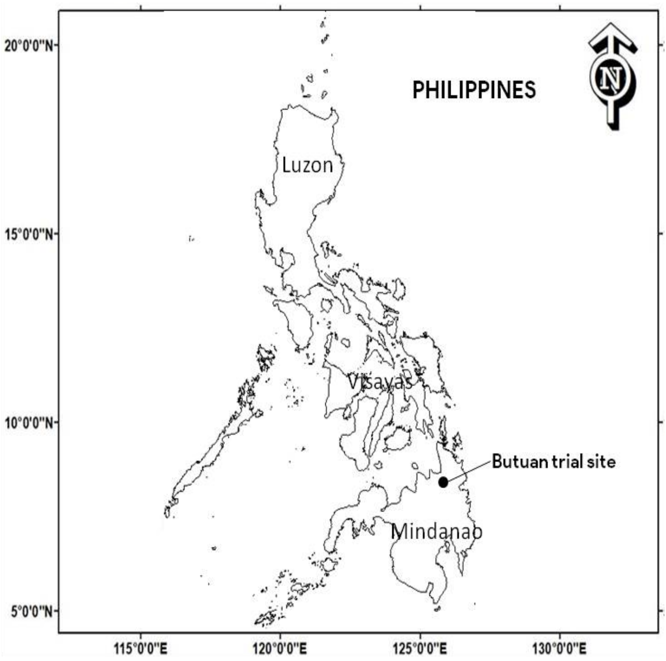


Figure 5-1. Location of the trial sites of BL Mahogany (*Sweitenia macrophylla* King) in the Philippines.

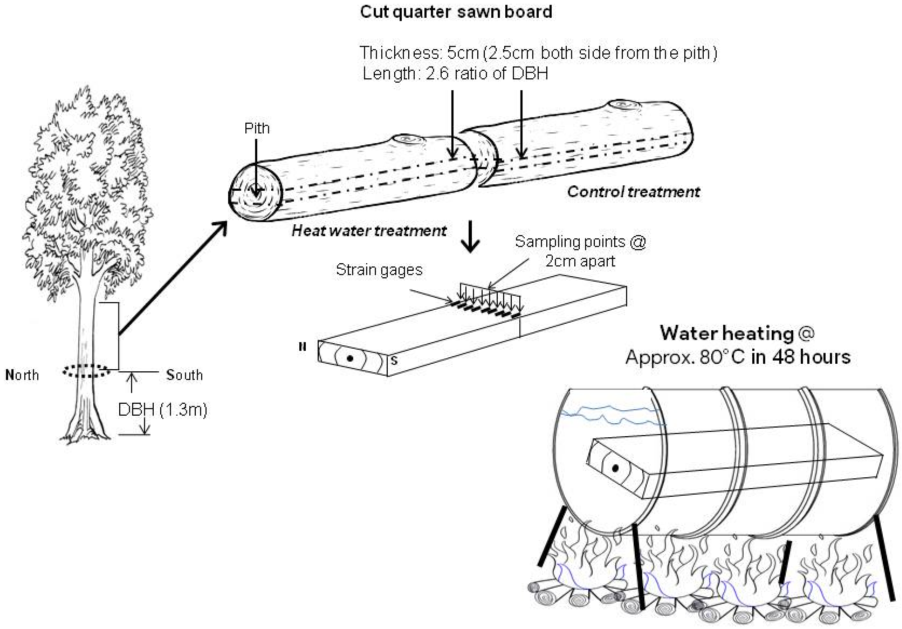


Figure 5-2. Sampling points of radial distribution patterns from the pith to north and south side of quarter sawn board with 2cm interval located at the center (length: 2.6 ratio of DBH).

Figure 5-2.a. Application of lumber clip to arrest cracking (release strain) during sawing.

Figure 5-2.b. Water heated set up using the steel drum and firewood to fuel the water at heating temperature of 80°C accumulated in 48 hours.

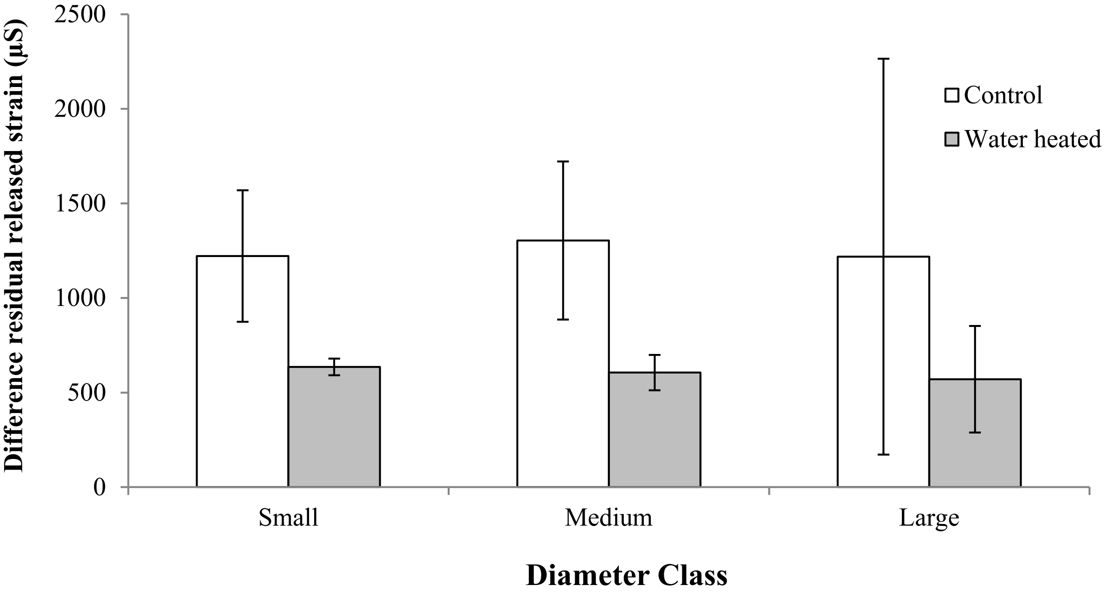


Figure 5-3. Difference residual released strain of BL mahogany in different diameter classes and treatments

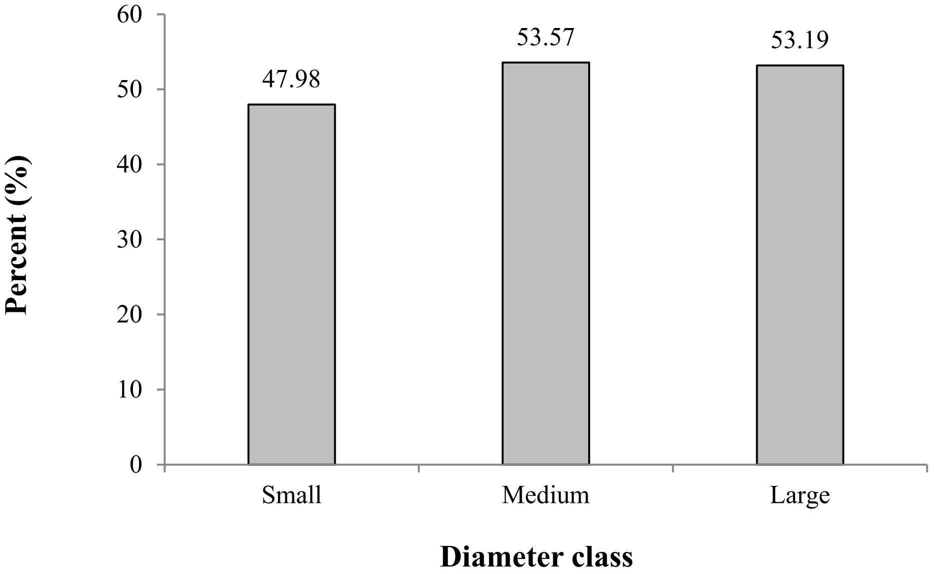


Figure 5-4. Percentage reductions of average residual release strains of BL mahogany in different diameter classes after water heated treatment

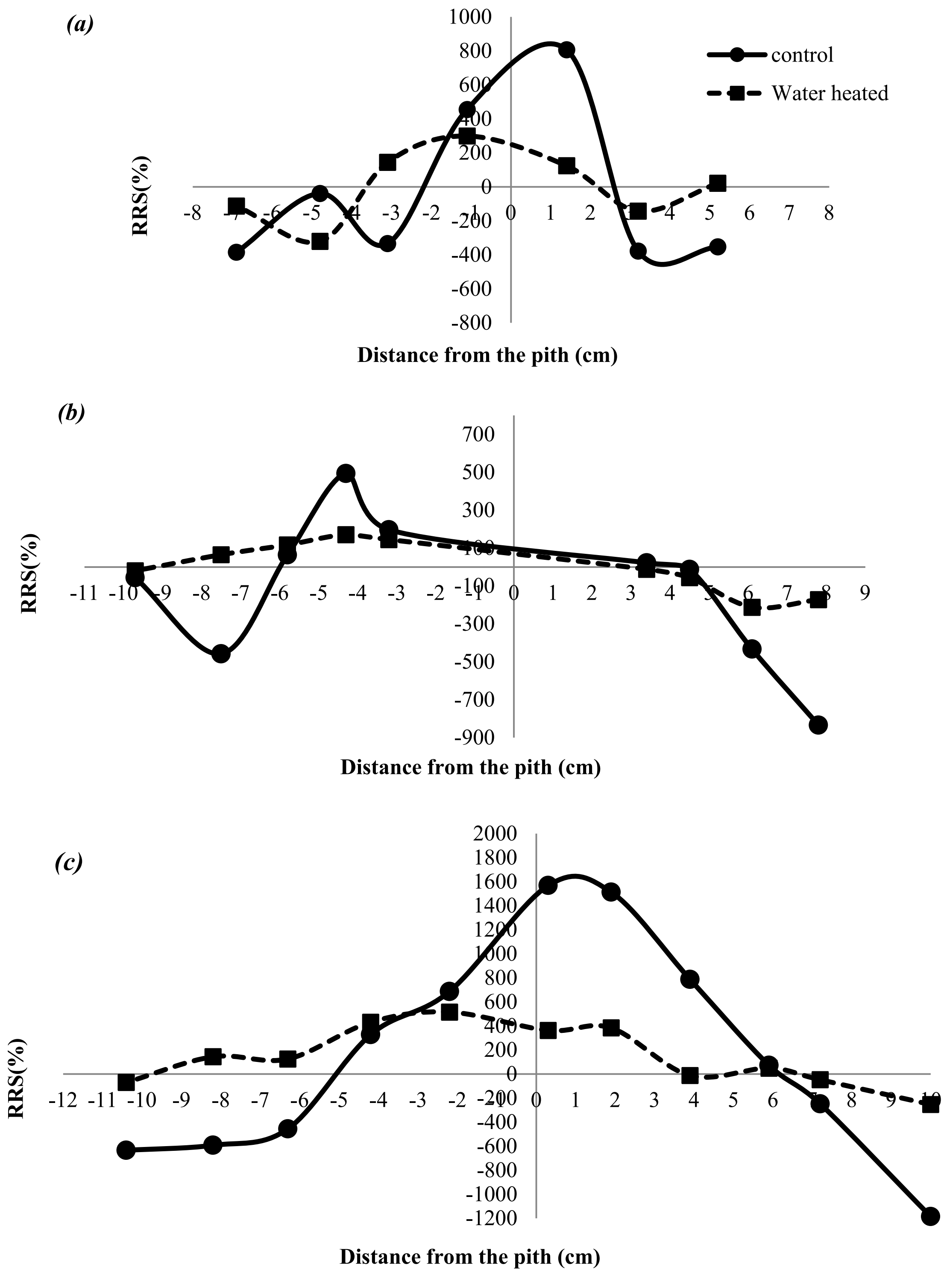


Figure 5-5. Radial distributions of residual release strains of BL mahogany reduced after water heated treatment in different diameter classes: Small *(a)*, Medium *(b)* and Large *(c)*.

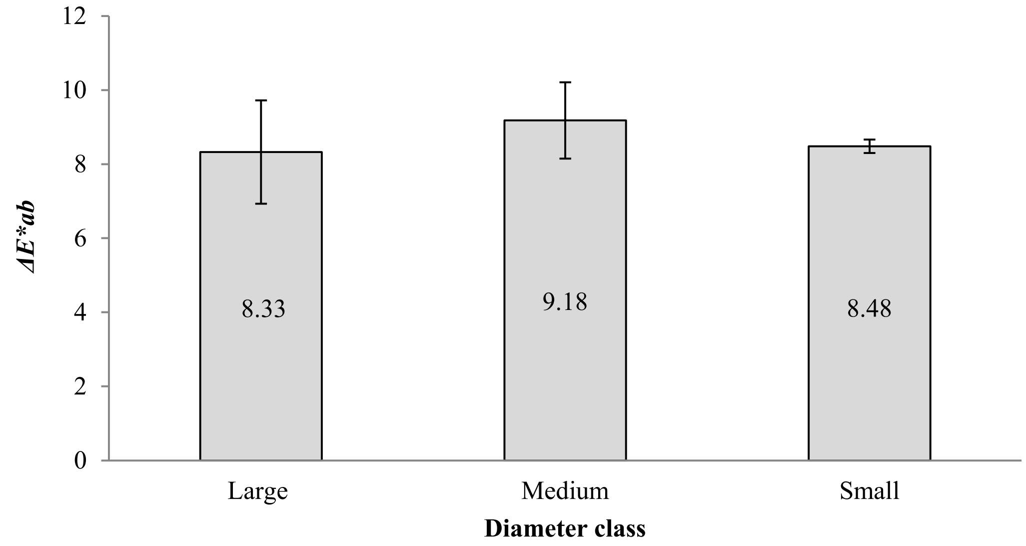


Figure 5-6. Color difference between control and water heated wood samples in different diameter class

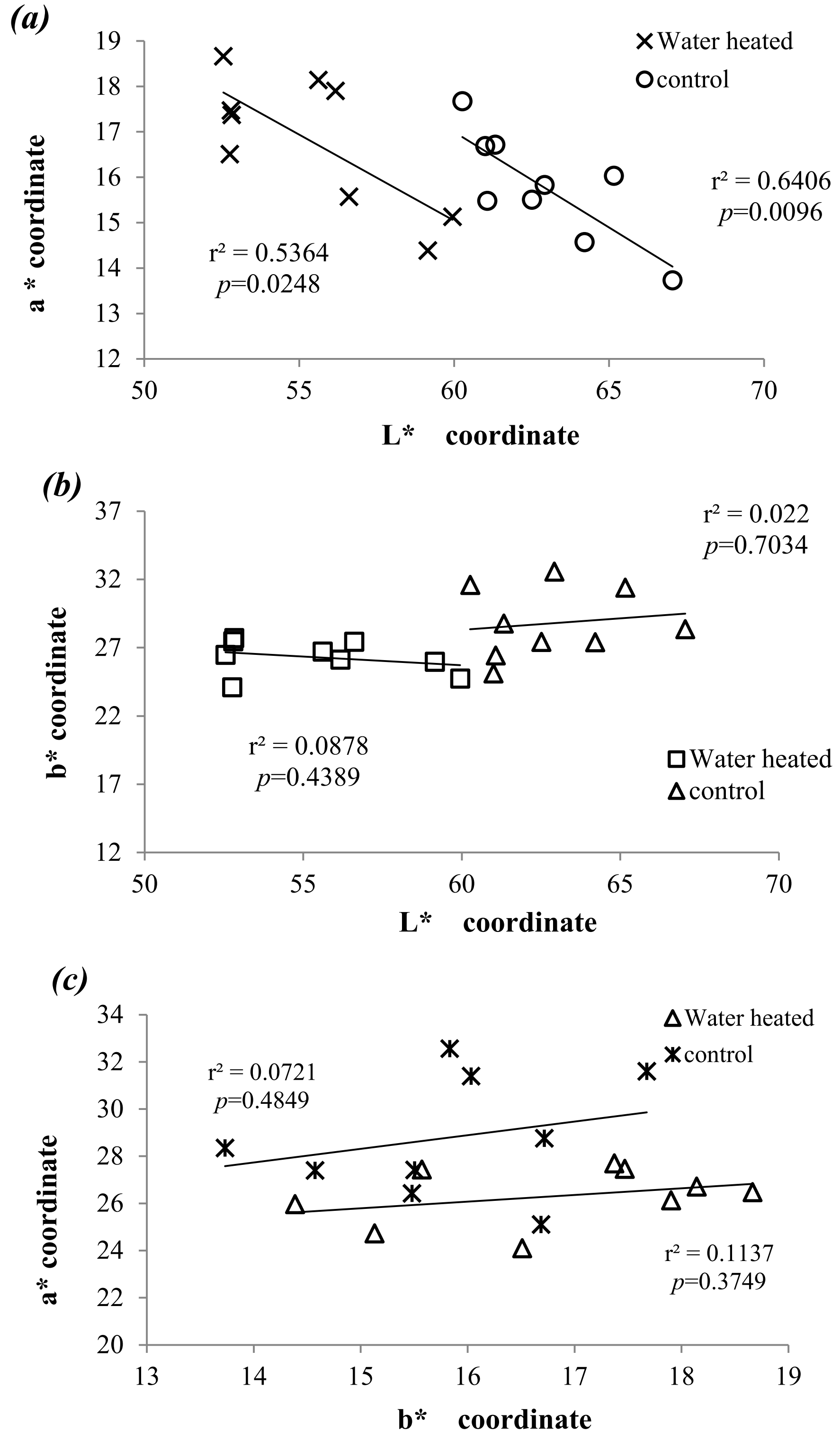


Figure 5-7. Relationship between *L** vs *a** (a), *L** vs *b** (b) and *a** vs *b** (c) for BL mahogany control and water heated wood samples.

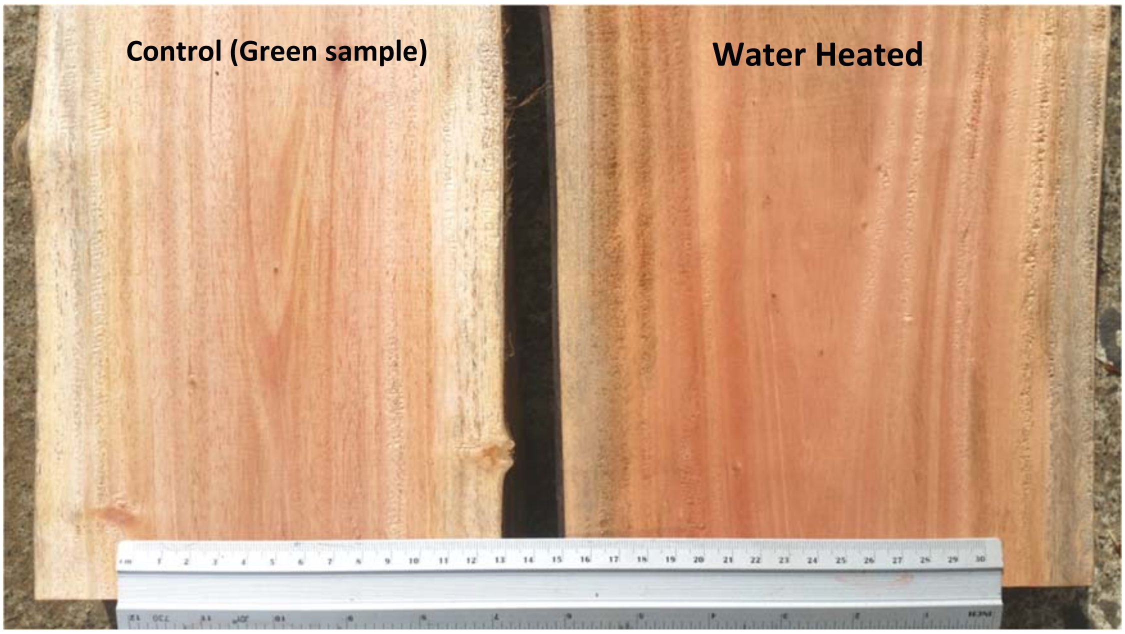


Figure 5-8. Wood color difference of control (green samples)(left) and water heated (right). Color difference is $\Delta E^*_{ab} = 8.66$

Chapter 6 General Conclusion

The goal of this study was to investigate the growth stress and wood properties of Big-leaf mahogany landrace in the Philippines. Growth stress was considered as a serious problem during saw milling, which resulted to deformation of lumber due to release of strain (growth stress) inside the logs. This would give low recovery of finished products after saw milling and decrease the market value of the raw materials. Part of the study also investigated the possible solution to reduce the effect of growth stress in BL mahogany through girdling and heat water treatment.

The first study examined the longitudinal surface release strain(SRS) and some wood properties such as xylem density (XD), fiber length(FL), fiber width(FW), vessel element length(VL), vessel element width(VW) and microfibril angle(MFA) of BL Mahogany landraces in six different provenances and two trial sites.

In chapter 2, the Surface growth stress and wood properties of 8-year old planted Big-leaf Mahogany (*Swietenia macrophylla* King) from different landrace provenances and trial sites in the Philippines were examined.

The results indicated that the SRS was invariable regardless of landrace provenances and trial sites. The wood properties of BL Mahogany like XD, VL, VW and MFA were the same in all provenances, except FL and FW. It was observed that Butuan trial site has a high lateral growth (DBH), high XD, longer FL with a narrow FW and a smaller MFA compared with Cagayan de Oro trial site.

A small diameter tree exhibiting high SRS, small FL, wide FW and large MFA. A high level of SRS was observed in some tested trees with a small diameter growth, which was attributed to tension wood formation. These suggested that the current cambium age was still producing juvenile wood especially in a smaller diameter tree.

The next study addressed the previous study recommendation; to investigate the radial distribution of growth stress and xylem maturation properties of BL mahogany.

Chapter 3 examined the radial distribution of growth stress and Xylem maturation properties of 8-year old Planted Big-leaf Mahogany (Swietenia macrophylla King) in the Philippines

The radial distribution patterns of FL, VL, VW and XD exhibited shorter FL and VL, narrow VW and low density XD from the pith, and suddenly increased outward and became more or less stable near the bark. However, the radial distribution patterns of FW and MOE overlapped each other and scattered regardless of tree diameter sizes. The juvenile wood zone of FL was significantly different to the transition wood zone and to the mature wood zone, vice versa. The juvenile wood zone of VL, VW and XD was significantly different in both transition wood zone and mature wood zone, but no difference between transition wood zone and mature wood zone was observed. Same trends were observed in FL, VL, VW and XD in terms of their relationship between DBH and the *b*-value, and the diameter boundaries of the three wood zones. Using selected xylem maturation properties e.g. FL, VL, VW and XD, BL mahogany starts to mature when it reached the diameter of 18.08cm , 17.36cm,16.23cm and 17.87cm, respectively.

The next two studies investigated the effect of girdling and heat water treatments to reduce the growth stress and some wood properties of BL mahogany. Chapter 4 dealt with the effect of girdling on growth stress reduction of Big-leaf Mahogany (*Swietenia macrophylla* King) in the Philippines

It was found that the effects of girdling in different periods (0, 1 year, and 2 years) on the growth stress reduction and basic wood properties of 8-year old planted BL mahogany were almost the same with the non-girdled test trees. The results showed that after 2 years from girdling all test trees with small sizes in two trial sites did not survive. However, test trees with large sizes have 100% and 83% survival; and medium sizes have 83% and 50% survival in Butuan and Cagayan de Oro trial sites, respectively. Longitudinal released strain of surface growth stresses (SRS) of test trees with large and medium sizes have highly significant differences between non-girdled and 2-year girdled, but no significant variation between non-girdled and 1-year girdled test trees. The small size test trees have the same SRS in three treatment periods. Using the difference of residual released strain of growth stresses (RRS), the diameter classes and treatment periods showed no significant differences. Moisture content (MC) of test trees revealed significant differences between girdled and non-girdled treatment. Small size test trees that died after 2 years from girdling have almost the same MC which ranges from 11.93% to 14.87% from pith to the bark, as compared with non-girdled test trees that gradually increases from 37.39% to 64.68% from pith to the bark. Non-girdled and girdled treatments of large and medium size test trees showed normal distribution pattern of MC which gradually increases from pith to the bark. The lightness, redness and yellowish parameters have high significant differences between non-girdled and girdled test trees. The wood color of non-girdled test trees averages; 70.95 in L* (lightness), 10.64 in a* (redness) and 22.14 in b*(yellowness); while the wood color of girdled test trees averages; 67.80, 13.60 and 24.57, respectively. The color difference (ΔE^*_{ab}) of small, medium and large diameter class between girdled and non girdled test trees were 1.06, 10.47 and 18.72, respectively. This color variation is detectable by the human eye, except the color difference of wood samples from small diameter class.

In chapter 5, the effect of water heated treatment on growth stress reduction of Big-leaf Mahogany (*Swietenia macrophylla* King) in the Philippines was investigated.

Water heated treatment drastically reduced the average residual release strains in three diameter classes: small, medium and large of BL mahogany to 47.98%, 53.57% and 53.19%, respectively. This significant effect on the reduction of residual released strain was observed in small and medium size trees, but not with the large size trees. In terms of wood color, the water heated wood samples averages: 55.38 in (lightness), 16.79 in a* (redness) and 26.30 in (yellowness) while the wood color of control wood samples averages: 62.83, 15.80 and 28.78, respectively. The effect of water heated treatment in L*(lightness) and b*(yellowish) parameters have high significant differences between control and heat water treated wood samples, but not with the a* (redness). The color difference (ΔE^*_{ab}) of small, medium and large diameter class between between control and water heated wood samples were 8.48, 9.18 and 8.33, respectively. This color variation is detectable by the human eye.

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List of publications

Published

1. **Surface growth stress and wood properties of 8-year old planted Big-leaf Mahogany *(Swietenia macrophylla* King*)* from different landrace provenances and trial sites in the Philippines** . – Journal of Wood Science July 24, 2019 (Online published)

In preparation for Submission

2. **Radial distribution of growth stress and Xylem maturation properties of 8-year old Planted Big-leaf Mahogany *(Swietenia macrophylla* King*)* in the Philippines**

3. **The effect of girdling on growth stress reduction of Big-leaf Mahogany *(Swietenia macrophylla* King*)* in the Philippines**

4. **The effect of water heated treatment on growth stress reduction of Big-leaf Mahogany *(Swietenia macrophylla* King*)* in the Philippines**