Influence of Site Conditions on Teak Growth and Traits in the Lao PDR

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LIST OF ACRONYMS AND ABBREVIATIONS

ASCI	Asian Satellite Campus Institute
DBH	Diameter at Breast Height
DoF	Department of Forestry
FAO	Food and Agriculture Organization of United Nation
FRC	Forestry Research Center
LaoGISU	Lao Geographic Information System Unit
Lao PDR	Lao's People Democratic Republic
ITTO	International Timber Trade Organization
JIRCAS	Japan International Research Center for Agricultural Sciences
MAF	Ministry of Agriculture and Forestry
NAFRI	National Agriculture and Forestry Research Institute
VMAI	Mean Annual Increment in Volume

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CHAPTER 1. GENERAL INTRODUCTION

1.1. Natural teak distribution and its application

Teak *(Tectona grandis L.f.)* is a tropical tree species. The species is a member of the family “Verbenaceae” order “Laminales” (Kadambi, 1972; Kaosa-ard, 1989). Teak is a large tree up to 40 m tall and up 2 m in diameter and grows in mixed deciduous forests with *Xylia xylocarpa, Lagerstroemia spp., Afzelia xylocarpa, Pterocarpus macrocarpus, Schleichera oleosa, Haldina cordifolia, Eriolaena candollei, Vitex limonifolia, Garuga pinnata, Tetrameles nudiflora, Spondias pinnata, Bombax insigne* and bamboo sp. Flowering in May-August and fruiting is in December – April (Palanisamy et al., 2009).

Teak is a native tree species in Asia. The natural distribution area range from India, Myanmar, Thailand to Lao’s people democratic republic (Lao PDR) (Kaosa-ard, 1989; Tanaka et al., 1998), has a total area of 29 million hectares, which half-most of the natural teak forest area can be found in Myanmar (Kollert & Cherubini, 2012). In Lao PDR, the natural teak forest is considered the Eastern boundary. Teak occurs in the moist deciduous forests in two northern provinces, Borkeo and Xayabuly, along the Lao-Thai border (Khaing et al., 2017). Over the past decades, illegal logging, and intensification of agricultural commodity production promotion, however, caused degradation of natural teak forest area. Recently, it had a total area of about 15,000 to 16,000 hectares (Kollert & Cherubini, 2012; Maraseni et al., 2018; Midgley et al., 2015), where mainly distributed in provincial protection forest area, namely, Phousack (teak mountain) in Parklay district of Xayabuly province.

Teak is a globally commercial hardwood tree species. Teakwood exhibits a high timber quality, owing to unique properties such as lightness with strength, stability, durability, malleability, resistance to termites and fungi, and high adaptability to environmental variations (Kaosa-ard, 1989; Hansen et al., 1997; Jerez & Coutinho, 2017). Hence, it is widely used to build outdoor and indoor furniture, ships, decorative veneers, paneling, doors, and windows (Thulasidas et al., 2006; Midgley et al., 2012; 2015;). Due to these widespread applications, the production of high-quality timber with a high yield is essential for successful teak plantations.

1.2. Overview of global planted teak forest and trends

Teak had first planted in Java, Indonesia, about 400 – 600 years ago (Kadambi, 1972). Early introductions of teak outside Asia were made in Nigeria in 1902 (Ball et al., 1999). The tree species have been planted in a large range of fundamentally different site conditions inside and outside of its native area across 70 tropical countries for many centuries. In 2017, the teak plantation area grew up to 6.89 million hectares; 83% are found in Asia, primarily in India, Indonesia, and Myanmar. Smallholder farmer plantings are currently a minor component of the global teak estate (Kollert & Cherubini, 2012; Kollert & Kleine, 2017).

Prosperous teak plantations are derived from the good practices of site selection, best genetic material for planting (seed, seedling, clones), good soil preparation and management, effective management system, and adequate hazard prevention plan and control is necessary throughout the rotation. However, a financial factor is essential for the whole process (Jerez & Coutinho, 2017); for example, the community-grown teak plantation in Indonesia had poor-quality timber, was relatively affected by using poor planting material (Unknown genetic origin) and poor maintenance (Hardiyanto & Prayitno, 2007). Therefore, the best quality of seedling with a certain seed origin is essential for the plantation establishment. Many teak grower countries have been attempted to develop the high-yield teak clone and teak genetic improvement, especially Costa Rica, India, Malaysia (Naranjo et al., 2012; Arce & Moya, 2015; Jerez & Coutinho, 2017).

Teak has been commonly recommended across growing countries (Asia, Central America, Brazil, and Africa) to narrow spacing. Having an initial stand density ranges from

1100 trees to 2500 trees per hectare (Guzman et al., 2017; Jerez & Coutinho, 2017). However, in some countries, wider initial spacing (500 trees to 816 trees per hectare) has been recommended if the planter can produce high-quality seedlings (Malmström, 2013). Weeding, fertilizing, thinning, and pruning is crucial activities for teak plantation management; these activities were associated with initial planting spacing, high stand density requires an early intense first thinning to promote stem diameter growth, while weeding and pruning were necessary for low stand density, to avoid poor mode of branching and larger branch size and more taper. In Latin America, the first thinning has been made, starting from 3 and 8 years for dense teak plantation, depends on site quality after canopy closure (Morataya et al. 1999); for example, in Venezuela, two intensive thinning (50%) ages 3 and 12 had greater promoted DBH growth two times when compared with no thinning treatment (Jerez & Coutinho, 2017). In Costa Rica, the pruning system has been conducted four times according to tree height (Víquez & Pérez, 2005).

The growth performance of teak, good sites, and appropriate establishment and management practices at early stages height growth are fast (3 to 6 m per year), slowing after age 15. Diameter increment peaks at 3 – 5 cm when 3 – 6 years old as teak in Java, Indonesia had the best DBH growth compared with other growing countries (Jerez & Coutinho, 2017). The teak yield reported that mean annual increase in volume (VMAI) of 15-20 m^3 per hectare per year is considered excellent; whereas, VMAI below 6 m^3 per hectare per year is the lower limit profitable plantations (Kollert & Cherubini, 2012). However, the clonal plantation in Mexico and Brazil had a greater produced VMAI of 32 m^3 per hectare per year (Ugalde, 2013). Recently, the teak harvested rotation in several growing countries has been implemented in a short rotation of 16-25 years for Latin America (Malmström, 2013), 7 to 20 years for community-teak in Indonesia (Hardiyanto & Prayitno, 2007; Rizanti et al., 2018), 30 to 60 years for Africa (Zahabu et al., 2015), 15 to 20 years for smallholder farmers in Thailand and

Myanmar (Noda & Himmapan, 2014; Htoo et al., 2020) and long rotation of 60 – 80 years for state-owned companies in India and Indonesia.

1.3. Overview of teak plantation in Lao PDR

Teak had first planted with a small-scale demonstration plot in Luang Prabang province in 1915 (Phimmavong et al., 2009). The experimental plot of planted teak was established in other Lao PDR regions, Vientiane prefecture of the central part and two southern provinces, Champasack and Saravanh, in 1942 (Keonakhone, 2005; Midgley, 2006; Phongoudome et al., 2012). Over the decades later, however, planted teak had been limitedly expanded until the 1990s, the Lao PDR's government had strategized forest rehabilitation (Tsechalicha et al., 2000). Teak is the main native tree species has been promoted for reforestation purpose. Consequently, the teak plantation has been established on a larger scale, resulting in plantation area increased from 1,363 hectares in 1991 to 40,000 hectares in 2016 (Hansen et al., 1997; Smith et al., 2017), of which the northern part shared about 64% of total area: Luang Prabang province has the largest area of 15,000 ha (Boer & Seneanachack, 2016), with up 8,000 hectares in Xayabuly province (Maraseni et al., 2018), while the southern part, Champasack province has a bigger area of 5,323 hectares, respectively (Phongoudome et al., 2012). Teak plantations have been established in fundamentally different site conditions across the country; mountainous land in the northern part, flat land in the central and southern region, and southern plateau land of Bolaven. Almost teak plantations belong to farmers and the private sector (people who are not the farmers such as official staffs, traders, etc.), while state-ownership has shared a minor proportion (Midgley, 2006; Phongoudome et al., 2012).

In the boom years of the 1990s and early 2000s, 11 teak tree seed sources were created by the Lao Tree Seed Project (1998 – 2003), having 393 hectares in total with 1532 "mother" trees. The seed production capacity of 27,680 kg per annum, of which four teak seed sources are located in Xayabouly province, and one seed source is in Luang Prabang province (Sirivongs, 2006).

Department of Forestry (DoF) had recommended for an appropriate teak planting system, “taungya system – a practice whereby the trees are planted in association with an agricultural crop which controls weed growth. Once the trees approach crown closure, the agricultural component becomes unviable and is moved to another site” as interplanted teak with annual crops (upland rice, maize, etc.) for the first two or three years; initial spacing is 3 m x 3 m in order to reduce the investment cost of the weeding and pruning during the first stage of rotation because farmers have not enough labor and fund to the maintenance of plantation forest (Kolmert, 2001; Phongoudome et al., 2012). In northern Lao PDR (Hansen et al., 1997; MAF, 2005), reported that smallholders had planted teak in small plots of 0.1 to 1 hectare at the sides of roads, rivers and streams, footpaths and fences, and adjacent to paddy fields and homes using various planting spacing of 2 m x 2 m, and 3 m x 3 m. It seems the distribution of planted teaks was limited by the availability of transportation (Hansen et al., 1997). The teak plantation is, therefore, a promising option for subsistent farmers and local livelihood insurance. The growth and yield of farmer’s teak plantations (Kolmert, 2001; Keonakhone, 2005; Dieters et al., 2014) reported that planted teak forests have the mean annual increment in volume (VMAI), range from 3.4 to 21.3 m^3/hectare per year, average VMAI is approximately 7.4 to 10.8 m^3 per hectare per year where site index (SI) is 19 for reference age 15 years (Dieters et al., 2014).

Planted teak was commonly harvested from a young age of ≥ 10 to 35 years (Wanneng et al., 2014). Tree size is a crucial indicator for harvested consideration; normally, the larger trees with reaching a merchantable size of ≥ 15 cm in diameter were harvest at first (Midgley et al., 2007; Smith et al., 2017). However, farmers were decided to harvest when needs for finance (Midgley et al., 2015). Growers are significantly disadvantaged through a lack of access to market information at very low prices. A standing price of planted teak depends on stem DBH; for example, Midgley (2006) reported that small-size trees of 22 cm to 29 cm in DBH get the price of 7 to 9 USD per tree, while larger-size of 32 cm and 48 cm in DBH had the price of 15 USD and 150 USD per tree, respectively. Log diameter 15 – 19 cm (price 137.50 USD per m^3), 20 -29 cm (177.5USD per m^3), and >30 cm (the price of 237.50 USD per m^3).

Teak log grading (Hopewell & Fitzgerald, 2014; Bouaphavong et al., 2016;) reported that the acceptable dimension of teakwood for Lao wood industry companies was the specification of round log ≥ 10 cm in diameter (under-bark) and 220 cm in length. Log grade is divided into three grades (A, B, C): Grade A is the best quality classified according to the heartwood proportion of ≥ 80% in larger-diameter log end, not permitted for decay, knothole, insect holes, and stain. Grade B is medium quality, having a 60 - 80% heartwood proportion of a larger-diameter log end with not allowed for decay. Grade C is lower quality, heartwood proportion of < 60 % in a larger-diameter log end, and heartwood size on log end of ≥ 4 cm in diameter.

1.4. The factors influence the growth and development of teak

Teak growth and development are controlled by various factors, genotypes: Sreekanth et al. (2014) have studied genetic and morphological in natural teak populations in India revealed that genetic distances and morphological characters had a positive correlation with petiole shape and height of the tree, while Larekeng et al. (2019) has reported that morphophysiological analyses on teak in Indonesia showed provenance did not affect tree height, but significantly affected tree diameter, and leaf area. Environmental factors: teak grows best and reaches large dimensions in a warm-moist tropical climate with annual rainfall ranging from 1,270 – 3,800 mm. Nevertheless, the high timber production requires a periotic marked dry season of 3 – 5 months, while the suitable temperature range from 13 to 40°C. Moreover, teak is a light-demanding species, intolerant of shade and requiring complete overhead light (Kadambi, 1972; Kaosa-ard, 1989). In general, soil-site conditions are significant factors that influence the teak growth and development; for example, it has good growth in fertilized soil with rich calcium contents, well-drainage soil interaction with gentle slope and bottom of valley (Tanaka et al., 1998; Watanabe et al., 2010). The silviculture practices: The establishment of the teak plantation with narrow spacing requires an early intense first thinning to avoid the reduction in diameter increment due to inter-tree competition (Pérez & Kanninen, 2005). Wider spacing is recommended for producing large dimension logs in a shorter time and for reducing costs in plants and site preparation. However, weed control and early pruning are necessary (Víquez & Pérez, 2005). Thus, sufficient silvicultural management of teak, leading to high timber productivity (Jerez & Coutinho, 2017; Pachas et al., 2019b).

1.5. Factors associated with high profitability of planted teak timber

Teak timber quality of teak is mainly obtained from tree quality, tree growth performance, and heartwood quality. The high timber log yield is positively correlated with tree quality. Tree quality characteristics include stem form, axis persistence, branch size, mode of branching, epicormic shoots, protuberant buds, and buttressing (Bhat et al., 1997; Baillères et al., 2000). Among them, stem straightness, buttressing, and protuberant buds/knots are important factors that directly alter the timber yield, grade, and price (Bhat et al., 1997; Baillères et al., 2000; Midgley et al., 2015).

Apart from tree quality, the tree size and heartwood quality, such as heartwood content, wood figure and the defects (e.g., color, grain, and texture), and the amount of clear wood produced are crucial components for higher timber productivity. So, the longer rotation of teak plantations can obtain a higher valuable teakwood than shorter rotation (Midgley et al., 2015; Kollert & Walolek, 2017).

1.6. The challenges and problems of planted teak in Lao PDR

The teak seed sources are available, the production of good seed quality can meet the grower's need across the country (Sirivongs, 2006). Nevertheless, these seed sources have been less utilized, due to the seed supply network has not been constructed (Phongoudome et al., 2012; Pachas et al., 2019b), although many nurseries of seedling have been established. On the contrary, the growers and seedling producers have been gained the seed by self-collection and from local seed collectors, normally seeds picked off from the ground from trees surrounding teak forest area which often unknown "mother" trees. Therefore, mostly the seed and seedlings are from genetically unimproved seeds and unknown seed origin (Hansen et al., 1997; Midgley et al., 2007; Phongoudome et al., 2012), even though there are nurseries of teak seedlings, where the seeds originate from the teak forest with relatively good quality.

Apart from genetic issue, smallholder teak plantation forest management, thinning, and pruning are uncommon practices due to no economic return from the felled small-size tree. Growers believe that all trees have economic value and are reluctant to harvest trees at least the log can be sold (Newby et al., 2012). Considering this might be reasonable for many teak growers encountered low growth performance, especially the least diameter growth and development; for example, Pachas et al. (2019a) reported the effect of initial spacing of planted teak on growth and development showed that low stand density of 423 trees per hectare had a DBH growth of 24.5 cm, while high stand density of 1659 tree per hectare was 14.3 cm when the tree, reaching 10 years of age. Dieters et al. (2014) confirmed that dense teak plantation of 1695 trees per hectare between 8 to 10 years had a DBH growth, ranging from 7.0 to 14.9 cm in Luang Prabang province. Moreover, Bouaphavong et al. (2016) was also confirmed that Lao teak logs were small and had many defects.

Although the government's strategy promoted the increase in teak plantation, the international price of Lao's teak timber has been low (ITTO, 2020), owing to the limited information available on the suitability of environmental conditions for teak plantation compared with Thailand (Tanaka et al., 1998; Sukchan & Noda, 2012;) and Myanmar (Htoo et al., 2020). In northern Lao PDR, Luang Prabang province, a large area had suitable soil conditions for teak plantation, particularly calcium contents (Imaya et al., 2020). Therefore, the present research has assumed that tree age and site conditions were affected on teak timber qualities. Even though genetic is also an essential factor for teak growth and development, but this variable did not conduct in the present research.

Over the past decades, many researchers had been studied various matters of teak in Lao PDR; genetics (Keiding et al., 1986; Kjær et al., 1995), silviculture management techniques related to growth and yield of teak (Keonakhone, 2005; Dieters et al., 2014; Pachas et al., 2019a), and wood quality (Wanneng, 2019). Their studies were not included to site factor variables. Therefore, the research on environmental factors (e.g., climate, soil-site characteristics, etc.) influence teak timber quality in Lao PDR is scares. So, which site and stand characteristic variables most affected teak timber quality were examined in this study.

1.7. The purpose of the study

This study aimed to determine the effect of site conditions on the growth and quality of teak in northern Laos through investigating the suitable site conditions for teak plantations in the north of Lao PDR. The specific objectives are:

- To clarify the relationships among tree quality, stand characteristics, and site characteristics of teak plantation forests in mountainous areas.
- To examine the influence of topographic conditions on teak growth performance in mountainous landscapes.
- To investigate the effect of topographic conditions on teak heartwood quality in mountainous areas.

CHAPTER 2. STUDY AREA AND METHODOLOGIES

2.1. Characteristics of planted teak in Luang Prabang province

Luang Prabang province, a northern mountainous region in the Lao PDR, has 33.65% of its total land area under forest cover (DoF, 2012). This province has a long history of planted teak spanning several decades (Hansen et al., 1997; Midgley et al., 2007), having the largest area of teak plantation shared about 38% of the total area in Lao PDR, covering 11 districts. Both districts, Luang Prabang and Xieng Ngern shared about 43% of the total planted teak area; it distributed in diverse landforms and topography, while other districts had teak plantations are mainly distributed in convenient access area such as along the rivers, roads, nearby villages (Boer & Seneanachack, 2016), which 98% of the teak plantation forests belonging to individual farmers and the private sector - people who are not the farmers such as official staffs, traders, etc. (Midgley et al., 2012; Smith et al., 2017).

Teak plantations were established by replacing fallow land with an integrated planting system as teak grows mixed annual crops such as upland rice, maize, Job's tear, pineapple, banana, etc. for a first few years, the narrow spacing of 2 m × 2 m, 2 m × 3 m, or 3 m × 3 m was commonly used as the stand density range from 1100 to 2500 trees per hectares. Planting material, seedlings were bought from a private's nursery, which the seed had collected from uncertain sources (Hansen et al., 1997). Teak plantation forests were practiced with a flawed management system, for example, careless in weeding, thinning, and pruning due to farmers have more agricultural activities while household labor is limited (Newby et al., 2012; 2014). Thinning regimes were late activated because a small-size log of < 10 cm in diameter (under bark) has not acceptable for local wood factories (Midgley et al., 2007). Therefore, farmer's planted teaks were harvested whenever the tree grows, reaching the marketable size of ≥ 15 cm in diameter (Midgley et al., 2015), normally starting from 10 years old (Wanneng et al. 2014).

2.2. Research site

The research site was located in Luang Prabang and Xieng Ngern districts in the southwestern part of Luang Prabang province. A 31-km transect line was drawn approximately 16 km west of Luang Prabang city (Figure 1). The line started from the flat land of the Mekong riverside (19°48′14.3352″ N; 101°59′53.7936″ E) at the village of Thinxom in Luang Prabang district (elevation, 287 m above sea level). It ran straight across the highland to the southeastern mountainous area of Kiewtaloun village (19°36′7.8228″ N; 102°11′25.584″ E) in Xieng Ngern district (elevation, 867 m.a.s.l.). The research site is in a region with a tropical monsoon climate comprising two distinct seasons, a dry season (October–March) and a wet season (April–September). According to weather data recorded over a 10-year period (2008–2017) at the Luang Prabang meteorology station (Hathian village, 19°54′1″ N 102°10′12″ E; elevation, 297 m.a.s.l.), the mean annual rainfall was 1628 mm (minimum, 1259 mm; maximum, 2233 mm). The mean annual temperature was 26.4 °C (minimum, 20.5 °C; maximum, 32.3 °C), and the average relative humidity was 79% (minimum, 52%; maximum, 95%) (Lao Statistic Bureau, 2018).

The mountainous terrain of this site comprises Paleozoic sedimentary rocks, limestone, and volcano-sedimentary rocks (Department of Geology and Department of Mines, 2008a, 2008b). Acrisols and Alisols are the dominant soil types on the transect line, with Cambisols and Leptosols also present (NAFRI, 2000).

2.3. Temporary sample plots

Data for this research were collected from individual teak plantations with various stand ages and site conditions. Sixty-one target teak plantations were designated along the transect line to establish the temporary sample plots (TSP), with site elevation ranging from 287 to 1057 m.a.s.l (Figure 1). TSP was created for plot sampling according to the specific criteria of the research topics.

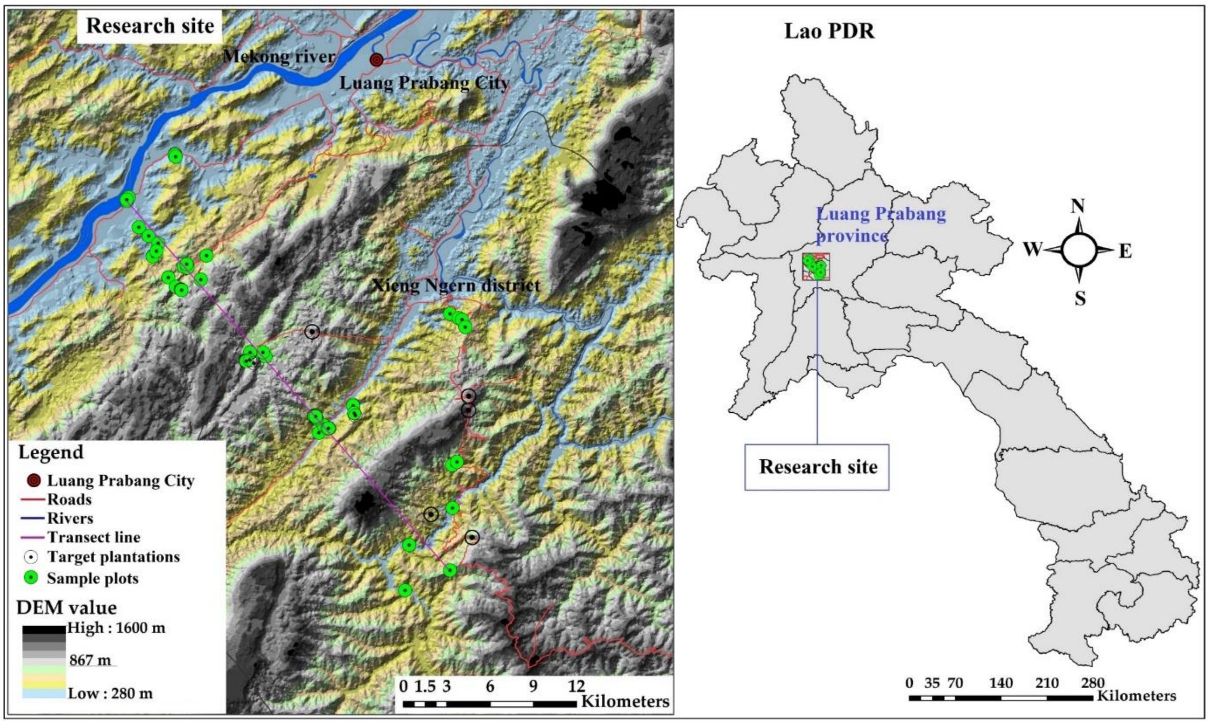


Figure 1. Map of the research site

Source: Drawn by the authors based on Mekong Geographic Information Systems data (LaoGISU, 2020). DEM, digital elevation model.

2.4. Tree measurement and site description of the sample plots

All teak trees in each temporary sample plot were measured; DBH (1.3 m above ground level) was measured using a measuring tape, and bole and total heights were measured using an ultrasound height measurer (Vertex IV, Haglöf, Sweden).

Site characteristics of the sample plots, including coordinates and elevation (EV), were recorded with the aid of a global positioning system receiver (GPSMAP64, Garmin), slope gradient (SG, %) and slope direction (SD) were measured using a clinometer with SD scored as north (1), east (2), south (3), and west (4). The slope position (SP) was scored as the bottom (1), lower (2), middle (3), upper (4), and crest (5). The slope form (SF) classes for this study included straight (S), concave (C), and convex (V), based on the general shape of the slope in both the vertical and horizontal directions (FAO, 2006) and SF were categorized into VV (1), VS (2), VC (3), SV (4), SS (5), SC (6), CV (7), CS (8), and CC (9) to the reflect the soil water condition (Table A1).

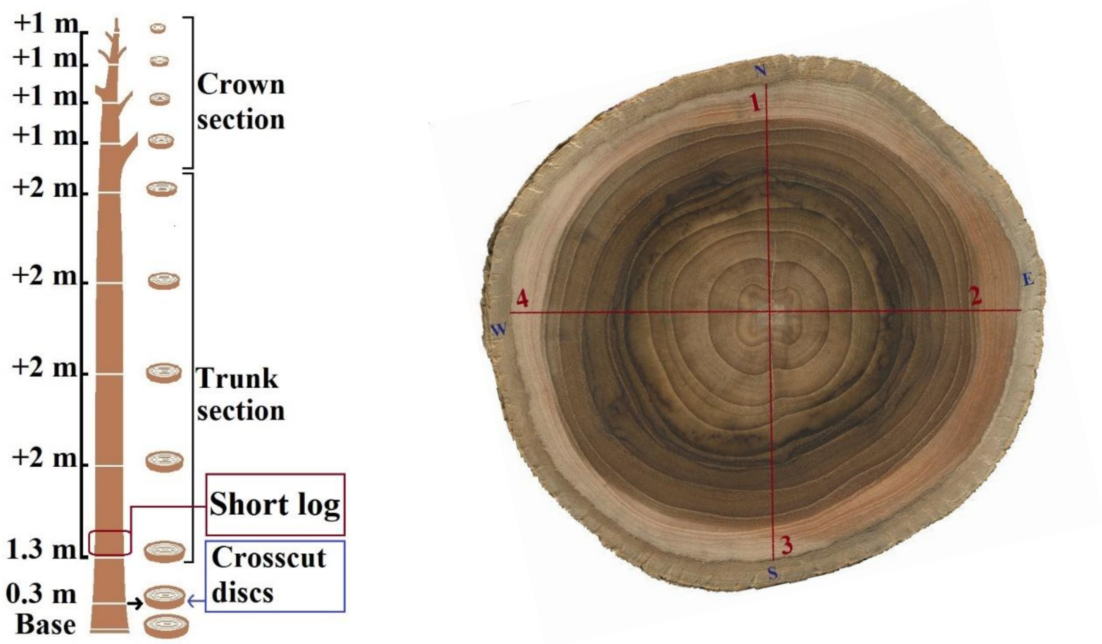
Some site characteristic variables are non-normally distribution data, which was scored according to the natural habitat of teak tree in growing conditions as it grows well in a moist area (Kadambi, 1972; Kaosa-ard, 1989). Therefore, a score of "1" is indicated the site has rich moisture conditions, whereas a bigger score is indicated the site has poor moisture conditions.

2.5. Plot sampling for tree quality assessment

In Luang Prabang province, farmers have been harvested teak trees for commercial purposes at various ages, typically starting from ≥ 10 years old. This research considered selecting the temporary sample plots for tree quality assessment according to the following criteria as stand age of ≥10 years old and optimum site elevation <900 m.a.s.l (Jerez & Coutinho, 2017). Therefore, this research was implemented in 53 sample plots in total. The total number of sample trees (DBH > 5 cm) was 2149, and the average number per plot was 40.6 trees. The stand age of sample plots ranged from 10 to 31 years (Table A1).

2.6. Tree sampling for assessing tree growth and heartwood quality

Dominant trees with no obvious evidence of growth abnormalities or damage were selected for sampling. A total of 183 dominant trees (three trees per plot) of 61 temporary sample plots were felled for stem analysis; the true height of the tree was also measured after harvest. Crosscut discs (disc thickness, 5 cm) from each felled tree were taken at ground level, 0.3 m, 1.3 m (breast height), at every 2.0 m from breast height to the base of the crown in the trunk section, and at every 1.0 m in the crown section (Perez, 2008; Miranda et al., 2011), afterward the short logs (length: 20 cm) from each felled tree were also taken at 1.3 m (breast height) onward (Figure 2a). A total of 2865 crosscut discs and 183 short logs were stored in plastic bags in the field to prevent loss of moisture before analysis. Discs were polished using a sanding machine with sandpaper numbers 40, 80, and 120 to make a flat surface and clarify the pattern of annual growth rings, and afterward, the crosscut discs were scanned with 1200 dpi resolution on a flatbed scanner (EPSON Perfection V370 Photo) to a digital file (Figure 2b).



(a) (b)

Figure 2. Procedure of crosscut disc and short log sampling (a), crosscut disc sample (b)

2.7. Flow of the study

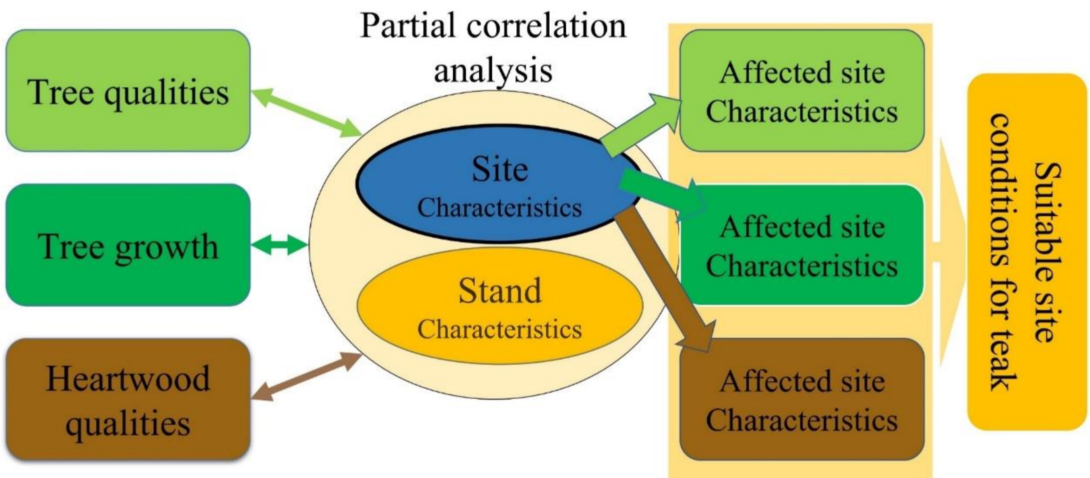


Figure 3. Flow of the study

Assumption of this research, which site and stand characteristic variables most effect on teak timber quality. Therefore, in order to measures the degree of association between two variables, with the effect of a set of controlling variables removed. The partial correlation analysis was applied to find out the site characteristic variables most influence on tree timber quality. Finally, the most suitable site condition variables for teak were found (Figure 3).

2.8. Statistical analysis

The partial correlation analysis helps to reject spurious correlations (i.e., correlations explained by the effect of other variables) as well as to find hidden correlations. This research, statistical analysis was performed by spearman's partial rank correlation analysis using R version 4.0.3 (R Core Team, 2020) with ppcor package (Kim, 2015) in order to investigate the effect of site characteristics after removing the impact of stand characteristics. In addition, the partial rank correlation network diagram (Figure 4) using the qgraph package (Friedman et al., 2011) was used to investigate the effect of site characteristics after removing the effect of stand characteristics.

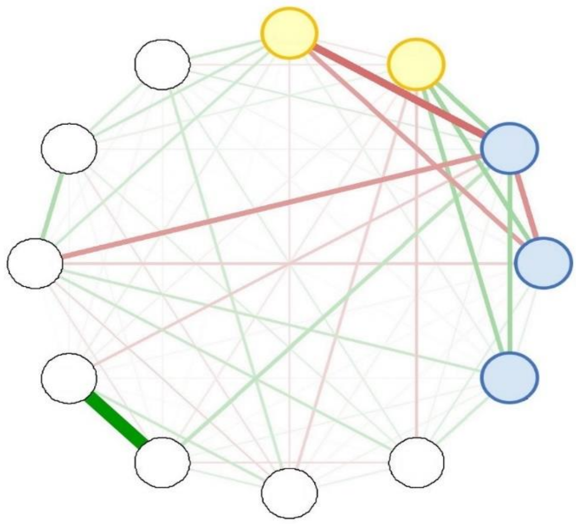


Figure 4. Partial rank correlation network diagram using for presenting the results.

Note: Circle means a variable; color of the circle means types of variables; site characteristics (blue circle), stand characteristics (yellow circle), tree variables (white circle). The color and width of line between two variables mean positive (green) or negative (red) correlation and strength.

CHAPTER 3. CORRELATIONS AMONG TREE QUALITY, STAND CHARACTERISTICS, AND SITE CHARACTERISTICS IN PLANTATION TEAK IN MOUNTAINOUS AREAS

3.1. Introduction

In general, tree quality depends on genetic properties (Larekeng et al., 2019; Sreekanth et al., 2014). In addition, Bouaphavong et al. (2016) indicated that tree age also affects the quality of teak timber logs. In addition to the genetic property and tree age, the teak quality is presumably affected by many environmental factors (Kaosa-ard, 1989; Tanaka et al., 1998; Jerez & Coutinho, 2017). Moreover, silvicultural practices of spacing density, thinning, and pruning are factors that affect teak quality. Stand density significantly affects crown diameter and the proportion of live and dead branches as a result of inter-tree competition (Pachas et al., 2019a). Nevertheless, the interaction among these factors and the mechanism of the effect are not yet fully understood. Considering the lack of control of genetic origin and stand density, this study assumed that the teak tree quality might be affected mainly by tree age in Luang Prabang province. At the same time, the relationship with the other site factors remains unclear. This chapter focused on tree quality and aimed to clarify the relationships among tree quality, stand characteristics, and site characteristics of teak plantation forests.

3.2. Methods

Assessment of tree quality characteristics

The tree quality of all trees in 53 sample plots was assessed according to seven characteristics, based on Kjær et al. (1995) with modifications (Table 1 and Figure 5). The scoring system was used for investigating the tree quality, all assessment items (shown in Table 1), a score of “1” indicates the highest quality whereas higher numbers indicate the lower quality.

Table 1. Description of the appraised scores for tree quality.

Description	Interpretation of appraised Scores
1. Stem Form (SFo) Investigation of stem characters focuses on stem straightness, bends, and crooks. Scored in five classes (Figure 5a).	SFo1: Straight SFo2: Slightly wavering tree, few small bends SFo3: Wavering tree, many small bends SFo4: Crooked tree with one or two severed bends SFo5: Crooked tree with three or more severe bends
2. Axis persistence (AP) Forking defined as two or more leaders, and the stem diameter of smaller leaders is more than 50% of the width of the larger leader just above the fork. Scored in five classes (Figure 5b).	AP1: Axis branches out in the fourth quarter of the tree, or there is complete persistence AP2: Axis branches out in the third quarter of the tree AP3: Axis branches out in the second quarter of the tree AP4: Axis branches out in the first (lowest) quarter of the tree AP5: Double or multiple stems from the ground level
3. Branch size (BS) Branch diameter evaluated in proportion to the stem diameter where the tree forks. Scored in five classes (Figure 5c).	BS1: Very light, less than ¼ of the stem diameter BS2: Light, around ¼ of the stem diameter BS3: Medium, between ¼ and ½ of the stem diameter BS4: Heavy, around ½ of the stem diameter BS5: Very heavy, > ½ to ¾ of the stem diameter
4. Mode of branching (MB) Characteristics of tree branching. Scored in five classes (Figure 5d).	MB1: Regular, spreading branching MB2: Scattered branching-light MB3: Light forking MB4: Scattered branching-pronounced MB5: Double limbs
5. Epicormic shoots (EP) Epicormic shoots occur from a previously dormant bud on the tree stem or a limb. Scored in four classes (Figure 5e).	EP1: Stem has no epicormic shoots EP2: Around 25% of the stem has epicormic shoots EP3: Around 50% of the stem has epicormic shoots EP4: Around 75% of the stem has epicormic shoots
6. Protuberant buds (PB) The presence or absence of protuberant buds on the tree stem. Scored in four classes (Figure 5f).	PB1: Stem has no protuberant buds PB2: Around 25% of the stem has protuberant buds PB3: Around 50% of the stem has protuberant buds PB4: Around 75% of the stem has protuberant buds
7. Buttressing (BU) The distribution of the severity of buttressing at the stem (1 m above the ground level). Scored in four classes (Figure 5g).	BU1: Nearly 100% of the area of the ideal stem BU2: About ¾ of the area is the ideal stem BU3: About ½ of the area is the ideal stem BU4: About ⅓ of the area is the ideal stem

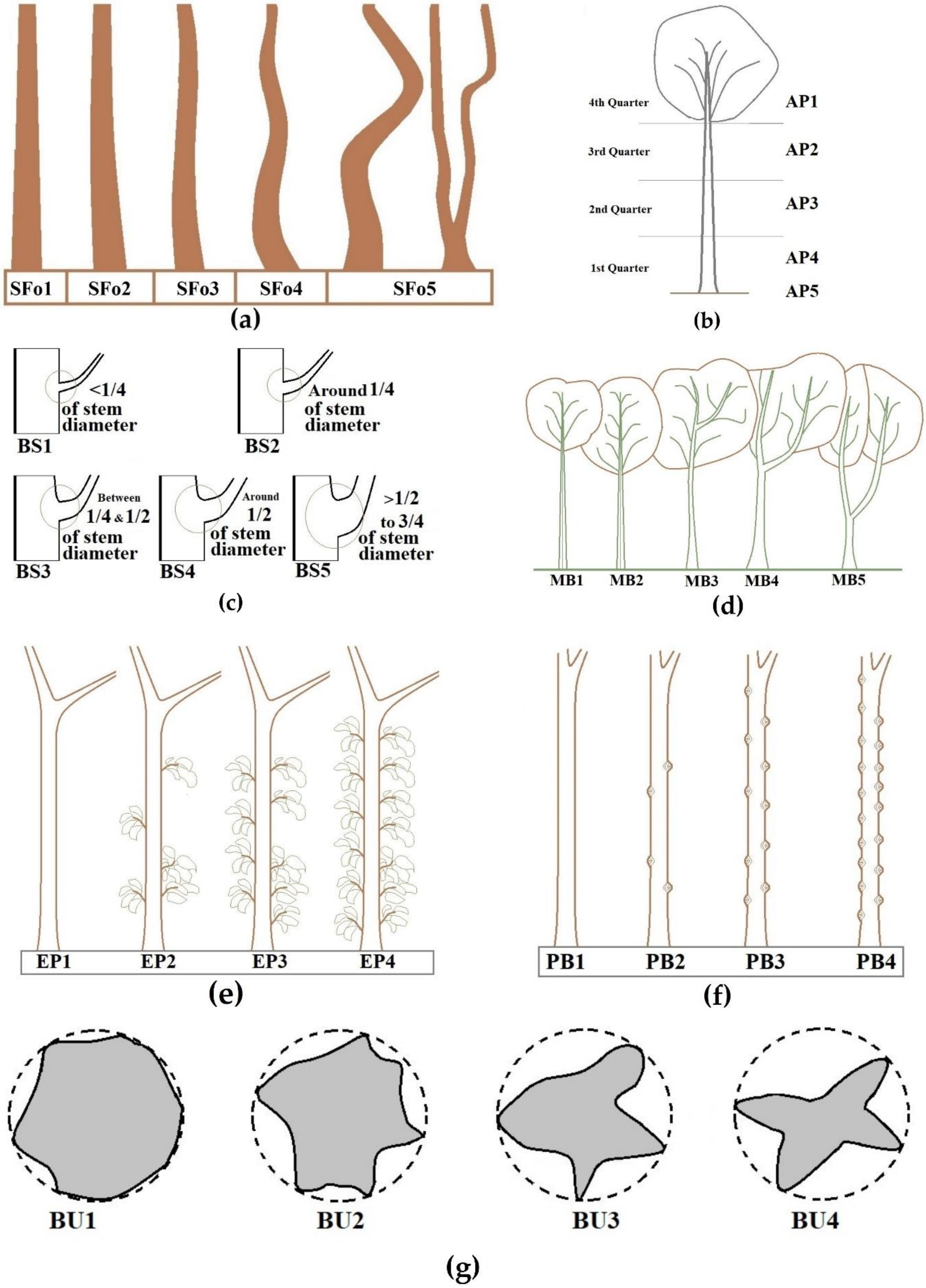


Figure 5. Scoring for tree quality assessment.

Note: (**a**) Stem form (SFo) modified from Keiding et al. (1986). (**b**) Axis persistence (AP) modified from Kjær et al. (1995). (**c**) Branch size (BS). (**d**) Mode of branching (MB) modified from Keiding et al. (1986). (**e**) Epicormic shoots (EP). (**f**) Protuberant buds (PB). (**g**) Buttressing (BU) modified from Kjær et al. (1995).

3.3. Result

The results of Spearman's partial rank correlation analysis are shown as a network diagram in Figure 6. The green and red lines between each parameter indicate positive and negative correlations, respectively, between two given parameters. The strength of the correlations shown in Table A2 is visualized by the thickness of the lines in Figure 6.

Four of the tree quality characteristics, namely, stem form (SFo), axis persistence (AP), protuberant buds (PB), and buttressing severity (BU), were associated mainly with tree age and stand characteristics (Figure 6). The SFo and AP scores had relatively stronger negative partial correlations with stand density ($p < 0.01$), but those of PB and BU scores had relatively stronger positive partial correlations with stand age ($p < 0.01$) (Figure 6 and Table A2). In contrast, three of the tree quality characteristics, namely, branch size (BS), mode of branching (MB), and epicormic shoots (EP), were associated mainly with site characteristics (Figure 6). The BS scores had a relatively stronger positive partial correlation with elevation ($p < 0.01$), but those of MB and EP scores had relatively stronger negative partial correlations with elevation ($p < 0.01$) (Figure 6 and Table A2).

3.4. Discussion

Forest management operations such as thinning are usually conducted as the forests age (ITTO, 2020). However, in the teak plantation of Luang Prabang province, it was obvious that forest management had been insufficient, as seen from the correlation of 0.09 between stand age (SA) and stand density (SDe) (Figure 6 and Table A2). This result is consistent with the information by local forestry officials indicating a lack of forest management for teak plantations in Luang Prabang province. Given that there was no management of genetic origin and no forest management operations such as thinning, this study assumed that the tree quality in the teak plantations might depend on stand age. However, only weak significant partial correlations were found between stand age and five variables of tree quality (Figure 6).

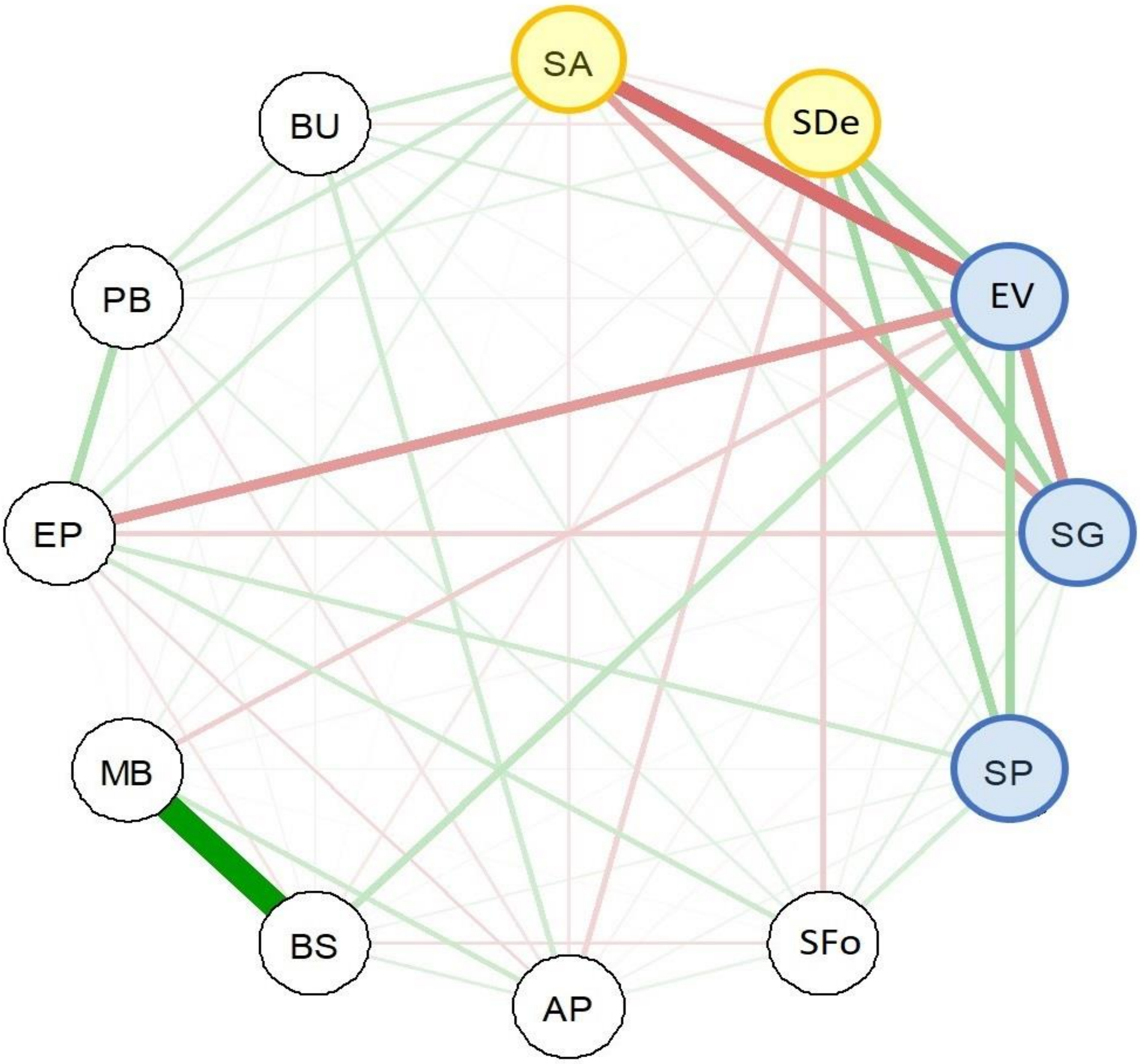


Figure 6. Partial correlation network among the tree quality characteristics, stand characteristics, and site characteristics.

Note: The green and red lines indicate positive and negative correlations, respectively. The line thickness indicates the strength of the partial correlation. Yellow, blue, and white circles indicate the stand characteristics, site characteristics, and tree quality characteristics, respectively. Stand age (SA); stand density (SDe); elevation (EV); slope gradient (SG); slope position (SP); stem form (SFo); axis persistence (AP); branch size (BS); mode of branching (MB); epicormic shoots (EP); protuberant buds (PB); buttressing (BU).

One reason of the weak correlation between SA and tree quality was the relatively strong negative partial correlation between SA and EV ($p < 0.01$), as shown in Figure 6 and Table A2. In Luang Prabang province, teak plantation was started mostly in areas along roads and rivers because individual farmers preferred to plant on the flat land at the bottom of the valley, and then expanded to the upper slopes and crest sites (Hansen et al., 1997). The relatively strong negative partial correlation between SA and EV might reflect the history of teak plantations in Luang Prabang. Moreover, the planted teak trees have grown naturally without any management pruning and weeding, which often resulted in late thinning or harvesting (Dieters et al., 2014; Midgley et al., 2007, 2015; Smith et al., 2017). Since the sample plots were not managed, the observed stand characteristics indicate that the reduction of stand density might be due to natural thinning. However, it is also possible that human activities such as illegal logging might be responsible.

SA showed weak positive partial correlations with MB, EP, PB, and BU ($p < 0.01$). It seems reasonable that all of these variables increase with stand age. The value of teak timber depends on the stem straightness, buttressing, and the number of protuberant buds (Baillères & Durand, 2000; Gogate et al., 2003; Midgley et al., 2015). Therefore, the present study results mean that younger teak plantations have a higher value compared with older ones in terms of buttressing and the number of protuberant buds. On the other hand, AP had a weak negative correlation with SA. This result might be attributable to stand growth with a high stand density.

EV had relatively stronger partial correlations with the scores of MB and EP ($p < 0.01$) (Figure 6 and Table A4). As shown in Figure 7, many epicormic shoots were visible on the stem from the riverside. Thus, less branching and fewer epicormic shoots might be due to the higher elevation. SDe had negative partial correlations with the scores of SFo and AP ($p < 0.01$) (Figure 6 and Table A2). Thus, the lower SDe might promote lower SFo and AP (Dieters et al., 2014; Jerez & Coutinho, 2017; Pachas et al., 2019a). Reflecting on the effect of site characteristics, SFo was positively correlated with SG and SP. This means that the lower position of a gentle slope might produce a good straight shape of teak. SG and SP also showed a partial correlation with EP ($p < 0.01$) (Figure 6 and Table A2). Considering the observed partial correlation with SA and EV, EP is a variable sensitive to both site characteristics and stand characteristics.

The effect of insects on tree quality is also an important consideration. Keonakhone (2005) reported infestation in the planted teak in Luang Prabang by at least two different species of insect larvae, including *Hyblaea puera* Cramer, which eats the leaves, and *Psilogramma spp.*, which eats the cambium. The infestation spread among teak plantations, especially at the bottom of the valley and alongside the river in the lower elevation area. Although an infestation survey was not conducted as part of this study, the present study finding that higher elevation results in higher tree quality might reflect the effect of insects because huge insects are found at lower elevation. Further studies investigating the effect of insects on teak plantation are therefore necessary.

In this study area, the teak seedlings were generally provided by a private nursery and had an uncertain genetic background. The genetics of planted teak is one of the crucial factors in its growth and development (Kjær et al., 1995; Kaosa-ard et al., 1998). Many countries pushing teak plantations have emphasized the importance of using appropriate clones to achieve high productivity (Jerez & Coutinho, 2017). However, in Luang Prabang province, because teak is not a native species (Dieters et al., 2014) and a supply system for seeds and seedlings has not been established (Pachas et al., 2019b), the genetic origin of the planted teak is unknown (Hansen et al., 1997). In addition, not only tree quality but also tree growth is essential for teak forestry. Soil quality is an important factor in tree growth. To establish the best methods for managing teak plantation forests in Luang Prabang province, further analysis, including genetic origin, growth rate, and soil properties, should be conducted.

Figure 7. Photo of a teak tree with many epicormic shoots on its stems
Note: taken from the riverside.

3.5. Chapter summaries

This study assessed the relationships among tree quality, stand characteristics, and site characteristics in planted teak in the mountainous areas of Luang Prabang province, Lao PDR. The results of Spearman's partial rank correlation analysis revealed that the higher-density plantation at higher elevation might be suitable for teak tree quality, whereas the lower position of the gentle slope might produce a straight shape of the teak log. In addition, the elevation was related to stand age and showed a correlation with some tree quality characteristics such as epicormic shoots, mode of branching, and branch size. Therefore, a longer rotation (> 25 years) in forest management might degrade tree quality, and therefore might not be suitable for teak plantations in Luang Prabang. Further studies on the effect of insect infestation, genetic origin, tree growth, and soil properties are necessary for establishing a suitable forest management strategy to produce high-quality teak timber in this province.

CHAPTER 4: INFLUENCE OF TOPOGRAPHIC CONDITIONS ON TEAK GROWTH PERFORMANCE IN MOUNTAINOUS LANDSCAPES

4.1. Introduction

The high yield of teak plantations is derived from optimum site conditions. The planted teak's growth performance is an important element for timber productivity. Teak is a calcicolous tree species; it requires a large calcium content for its growth and development (Kaosa-ard, 1989; Watanabe et al., 2010; Jerez & Coutinho, 2017). However, although there is the same amount of nutrient content in soil (calcium (Ca), phosphate (P), potassium (K), magnesium (Mg), and nitrogen (N), etc.), the best performance is significantly correlated with the valley's gentle slope and bottom (Kolmert, 2001). Thus, topographic conditions (e.g., slope gradient, slope positions, etc.) might affect the growth performance. By the way, Imaya et al. (2020) was studied soil physicochemical properties in Luang Prabang and Xieng Ngern districts reported that the soil having suitable soil characteristics for teak growth distributed on a large scale, particularly, calcium contents can meet a requirement of the optimum condition (>4.0 $cmol_c$/kg soil) about 64% of this area. Nevertheless, more teak plantations have poor growth performance as lower site index (SI) is found; Dieters et al. (2014) reported that the growth performance as SI ranged from 15 – 23 for reference age 15 years, and Imaya et al. (2020) also reported that SI ranged from 13 – 27 for reference age 20 years, when compared with other tropical regions such as Venezuela had SI ranged from 15 – 27 for reference age 16 years (Jerez & Coutinho, 2017) and Mexico had SI ranged from 12 – 24 for reference age 10 years (Minoche et al., 2017), although it's similar to neighboring countries such as Thailand had SI ranged from 14 – 30 for reference age 30 years (Vacharangkura, 2012). Thus, even where soils suitable for teak growth are found on a large scale, the lacking control of genetic management and silviculture practices prevents the attainment of good growth performance. Therefore, this study was assumed that topographic conditions might influence the growth performance of planted teak in this area. However, there is little research on this perspective in Lao PDR. This chapter aimed to investigate the relationship between teak growth performance and topographic conditions in mountainous landscapes.

4.2. Methods

4.2.1. Plot sampling and stem analysis

Tree growth is increased with tree age (Perez, 2008); Teak had a fast height growth at early stages of stem development, slowing after 15 years at the good sites and appropriate establishment and management practices (Jerez & Coutinho, 2017). In the present research, using the Mitscherlich growth function to be investigating the relationship between canopy tree height and tree age of 183 trees among 61 target teak plantations implied that younger teak of < 20 years is not saturated in tree height growth (Figure 8). By this result, the sample trees of ≥ 20 years old were selected; having 1374 crosscut discs of 81 dominant trees among 27 temporary sample plots (three trees per plot) were used for this research.

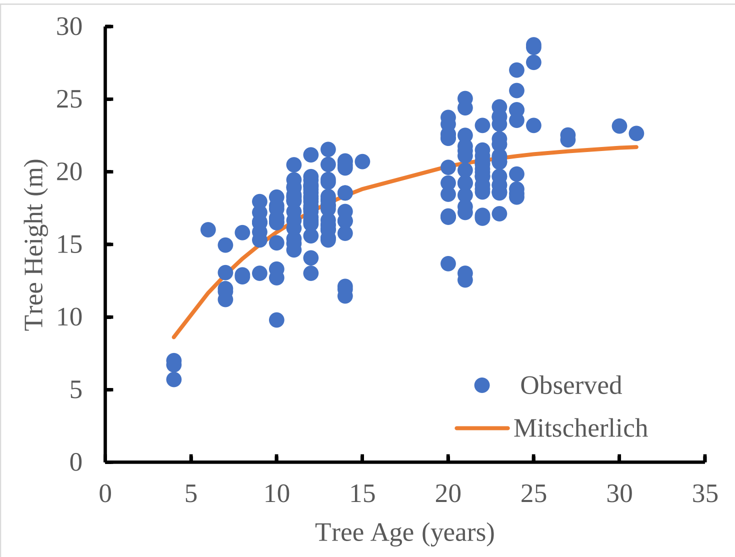


Figure 8. Relationship between tree height and tree age of 183 trees

Note: This investigation was conducted among 61 teak plantations (three trees per plot) located around the transect. A solid line indicated that the tree height based-age curve according to Mitscherlich function.

Each crosscut disc photo was analyzed using Imageviewer software (Yamamoto, unpublished) to investigate the annual tree growth rings from inner bark to pith in four directions: north, east, south, and west (preceding marked in the field). The tree age was derived from the number of rings at a base disc of the stem. The annual tree growth rings data obtained from the crosscut discs were applied to estimate the annual height growth base on a tree's annual radial growth method (Kariuki, 2002).

4.2.2. Assessing the tree growth curves

Several growth functions, such as Richards, Korf, and Mitscherlich, have been used to investigate the relationship between tree height and DBH growth of tree species; all of these functions are optimal fitting models (Liao et al., 2003; Luo et al., 2018). The Mitscherlich growth function was considered to be an appropriate tool; Nagashima et al. (1980; 1987) reported that height growth and diameter growth follow the Mitscherlich growth process. Thus, this growth function (Eq1) was selected for this study.

$$\mathrm{Y} = A\left(1 - \exp\left(-k(t_i - t_0)\right)\right) \qquad (1)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i-0}^{n}(y_i - \widehat{y_i})^2}{n}} \qquad (2)$$

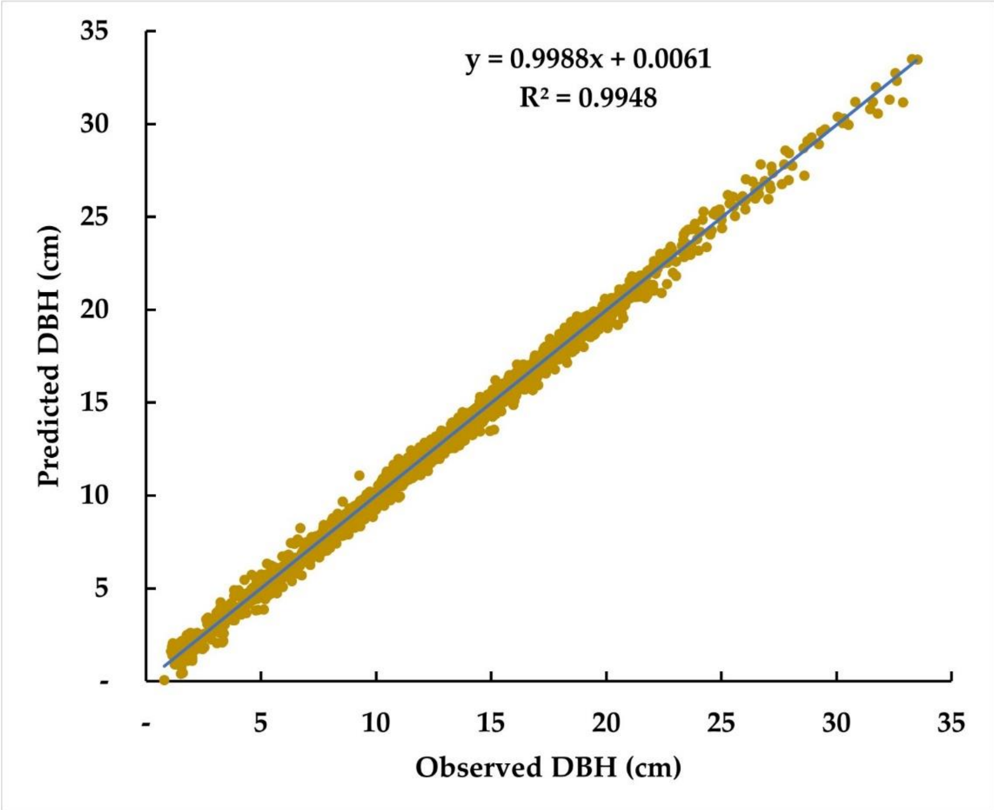
where *Y* is the predicted DBH (cm) or tree height (m) at age t_i (years); *A* (upper limit of tree growth), *k* (curvature of tree growth curve or intrinsic growth speed), t_0 (initial tree growth) are fitted tree growth curve parameters; RMSE is root mean square error of fitted tree growth curve; y_i is observed DBH or height, $\widehat{y_i}$ is predicted DBH or height; *n* is the number of observations.

The Mitscherlich growth function was fitted to the DBH-age and tree height-age relationships obtained from the stem analysis data using the nonlinear regression function with the lowest values of RMSE (Eq. 2) in the Excel solver. The obtained parameters of tree growth curves and their performance were shown in Table 2 and Figure 9 and 10, respectively.

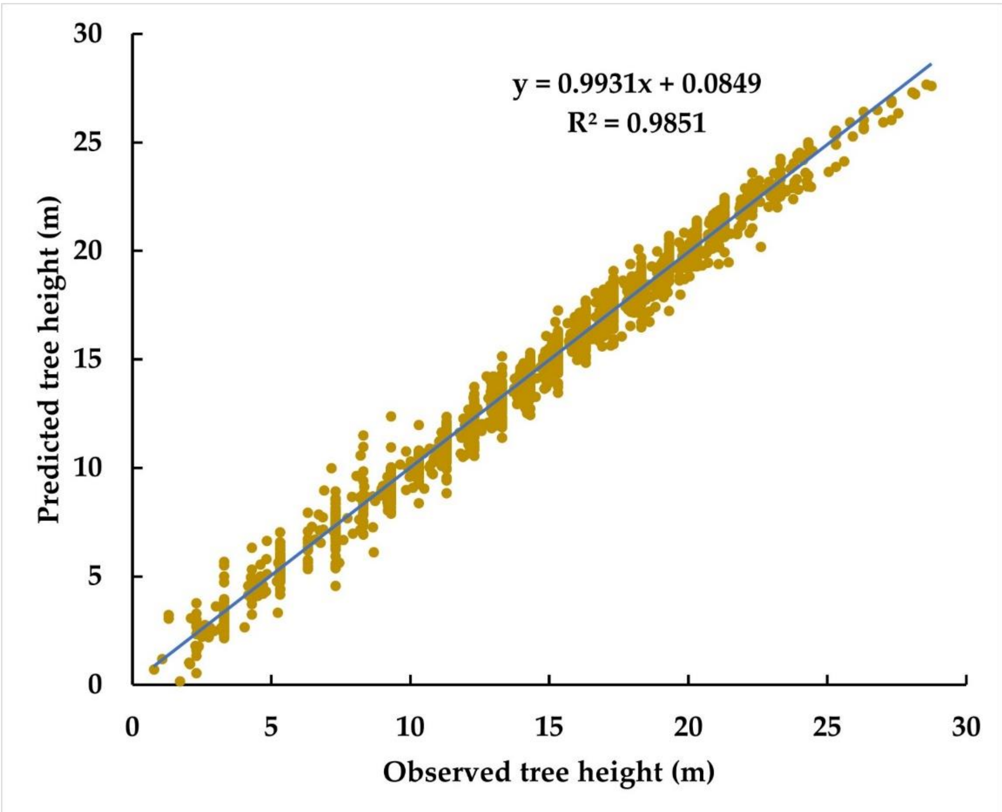
Table 2. Individual tree growth curve parameters of Mitscherlich growth function

Sites	DBH-age				Height-age				SI_{20}
	A	k	t_0	RMSE	A	k	t_0	RMSE	
1	27.42±6.05	0.07±0.02	2.25±0.98	0.36±0.07	26.16±2.50	0.11±0.02	2.11±0.56	0.83±0.08	22.53±0.61
2	41.04±18.66	0.05±0.04	0.00±0.00	0.47±0.13	24.35±2.97	0.11±0.04	0.00±0.00	0.78±0.21	21.14±0.66
3	100.58±69.05	0.02±0.01	1.51±1.28	0.56±0.16	32.98±11.05	0.06±0.03	1.29±1.38	1.18±0.25	18.93±0.73
4	15.34±1.20	0.14±0.03	0.09±0.16	0.35±0.11	17.91±0.95	0.21±0.02	0.64±0.69	0.58±0.07	17.59±1.06
5	22.02±0.53	0.13±0.02	1.59±0.61	0.33±0.13	25.37±0.81	0.09±0.00	1.06±0.46	0.61±0.21	21.17±0.66
6	24.78±8.28	0.06±0.04	0.28±0.48	0.30±0.02	20.83±2.73	0.08±0.02	0.01±0.01	0.51±0.06	16.43±0.36
7	34.74±6.74	0.07±0.02	0.04±0.06	0.54±0.26	27.15±1.71	0.10±0.01	0.00±0.00	0.74±0.28	23.16±1.27
8	21.56±1.29	0.13±0.04	1.22±0.87	0.43±0.12	20.17±1.19	0.15±0.03	0.89±0.77	0.53±0.15	18.85±0.74
9	25.25±6.70	0.09±0.04	0.37±0.64	0.53±0.08	22.28±1.42	0.13±0.00	0.27±0.39	0.63±0.32	20.66±1.44
10	19.33±0.70	0.14±0.02	0.99±0.64	0.39±0.06	20.65±1.13	0.17±0.02	0.84±0.48	0.46±0.03	19.84±0.82
11	19.59±3.14	0.11±0.03	0.63±0.41	0.54±0.16	21.64±2.38	0.11±0.01	0.21±0.28	0.65±0.15	19.11±1.87
12	20.92±1.39	0.09±0.01	1.87±1.15	0.39±0.14	18.25±1.63	0.15±0.03	2.02±0.68	0.56±0.11	16.74±0.71
13	22.18±5.98	0.07±0.03	0.74±0.36	0.37±0.05	21.12±1.18	0.11±0.02	0.78±0.36	0.65±0.03	18.40±0.49
14	19.45±2.62	0.12±0.03	0.14±0.24	0.27±0.04	24.70±0.88	0.12±0.01	0.06±0.05	0.53±0.09	22.60±0.69
15	23.80±3.96	0.14±0.01	0.37±0.41	0.50±0.08	24.08±0.53	0.16±0.01	0.03±0.05	0.68±0.11	23.08±0.35
16	13.35±0.68	0.21±0.04	0.00±0.00	0.48±0.21	16.16±0.35	0.23±0.02	0.00±0.00	0.69±0.12	15.98±0.37
17	27.45±5.44	0.05±0.03	0.22±0.38	0.19±0.07	22.89±0.83	0.10±0.02	0.44±0.40	0.46±0.08	19.62±0.95
18	16.46±1.18	0.13±0.04	0.32±0.55	0.42±0.10	19.37±1.60	0.13±0.04	0.05±0.08	0.53±0.07	17.72±0.64
19	16.80±0.51	0.15±0.04	1.72±0.27	0.34±0.10	19.75±1.21	0.17±0.01	1.32±0.54	0.66±0.10	18.87±0.97
20	16.50±1.25	0.20±0.01	1.40±0.28	0.37±0.07	19.71±0.75	0.19±0.01	0.96±0.40	0.58±0.13	19.21±0.75
21	19.68±3.35	0.14±0.03	0.82±0.17	0.38±0.15	21.39±1.02	0.15±0.02	0.54±0.48	0.66±0.09	20.07±0.49
22	30.12±6.77	0.11±0.03	1.54±0.29	0.44±0.16	31.17±1.36	0.08±0.00	0.27±0.33	0.78±0.12	25.17±0.56
23	20.22±8.90	0.08±0.02	0.84±0.24	0.32±0.24	16.15±2.76	0.08±0.02	0.00±0.00	0.37±0.14	12.60±0.90
24	18.34±2.31	0.12±0.03	0.65±0.57	0.30±0.08	21.04±1.29	0.10±0.00	0.08±0.13	0.53±0.21	18.27±1.22
25	18.35±1.81	0.13±0.03	0.23±0.26	0.38±0.08	17.92±1.14	0.15±0.00	0.00±0.00	0.64±0.11	16.94±1.00
26	60.24±73.38	0.06±0.05	0.65±0.63	0.34±0.11	21.24±3.58	0.10±0.01	0.00±0.00	0.78±0.14	18.12±2.62
27	20.36±1.29	0.14±0.05	0.32±0.56	0.40±0.04	21.80±2.10	0.15±0.03	0.10±0.18	0.89±0.37	20.52±1.46
Total	26.51±23.97	0.11±0.05	0.77±0.79	0.40±0.14	22.08±4.56	0.13±0.04	0.52±0.72	0.65±0.21	19.38±2.74

Note: RMSE: root mean square error. SI_{20}: site index based on age 20 years. *A* (upper limit of tree growth), *k* (curvature of tree growth curve or intrinsic growth speed), t_0 (initial tree growth) are fitted tree growth curve parameters. Mean ± standard deviation. Larger t_0 values indicate slower initial tree growth. The values of the site index based on age 20 years ranged from 12 to 26 and were highly correlated with parameter *A* in the height-age curve.

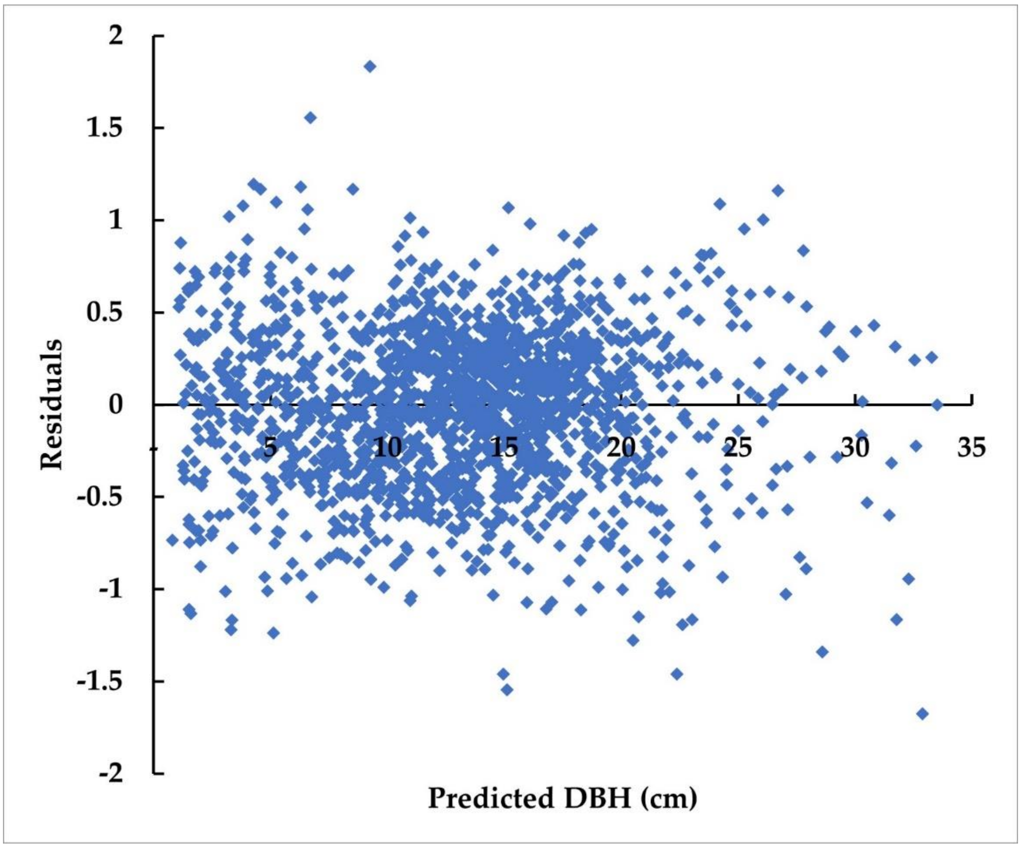


(a)

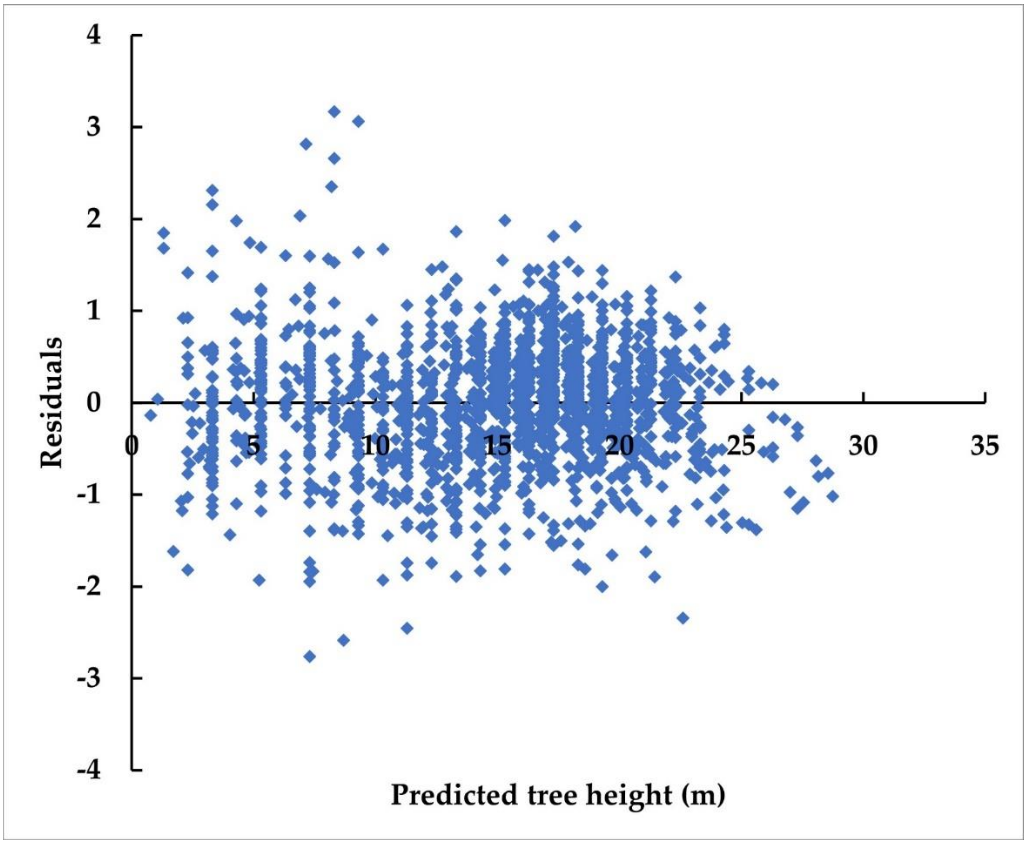


(b)

Figure 9. Relationship between predicted DBH and observed DBH (a); between predicted tree height and observed tree height (b). R^2 is the correlation coefficient.



(a)



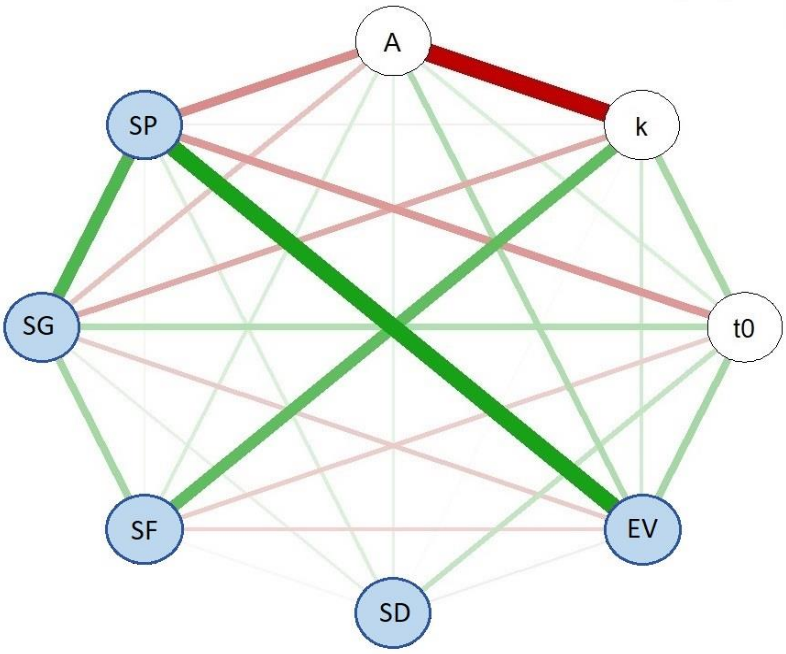
(b)

Figure 10. Residual versus predicted DBH (a) and versus predicted tree height (b)

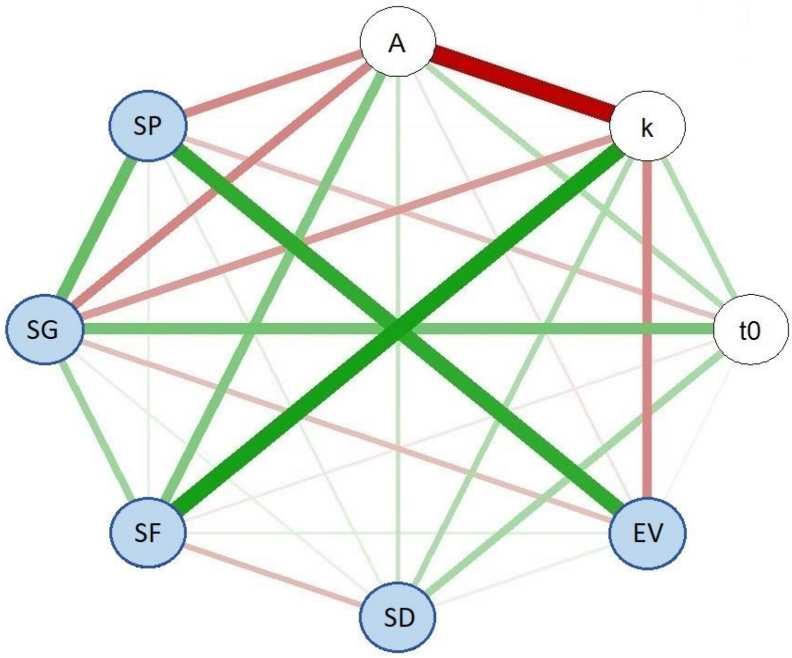
4.3. Results

The results of Spearman's partial rank correlation analysis indicate that the DBH-age curve parameters (Figure 11a and Table A3) and t_0 had a significant negative correlation with SP. Simultaneously, EV showed a positive correlation ($p < 0.05$). Meanwhile, k showed a significant positive correlation with SF ($p < 0.01$). A had a significant negative correlation with SP ($p < 0.01$). Moreover, the results revealed that tree height-age curve parameters (Figure 11b and Table A4) for initial growth showed a significant positive correlation with SG ($p < 0.01$), k had a significant positive correlation with SF ($p < 0.01$), while EV ($p < 0.05$) and SG ($p < 0.01$) had a negative correlation. Separately, A showed a significant negative correlation with SP and SG, while SF showed a significant positive correlation ($p < 0.01$).

The analysis results show that DBH had faster initial growth at higher slope positions with lower elevations. However, the intrinsic growth speed was faster on concave slopes, and the upper limit of growth was greater at lower slope positions. Tree height showed faster initial growth with decreasing slope gradient. The intrinsic growth speed was faster on gentle concave slopes, similar to the relationship with DBH, and was slower at higher elevation unlike that of DBH. The upper limit of tree height growth was greater at lower slope positions, similar to that of DBH and also on gentle slopes with concave shape unlike for DBH.



(a)



(b)

Figure 11. Partial correlation network between growth curve parameter and topographic conditions

Note: Correlation network diagram between DBH-age growth curve parameters and topographic conditions (a) and height-age growth curve parameters and topographic conditions (b). The green and red lines indicate positive and negative correlations, respectively. The line thickness indicates the strength of the spearman's partial rank correlation. The letter shown in the white circles indicate variables of the tree growth parameters as A, k, t_0 and the topographic conditions as elevation (EV); slope gradient (SG); slope direction (SD); slope form (SF); slope positions (SP).

4.4. Discussion

This study found that the upper asymptote of the teak growth was greatest for stands in lower slope positions with a gentle slope ($p < 0.01$) while a concave slope increased the intrinsic growth speed ($p < 0.01$) and the upper limit of the tree height growth ($p < 0.01$). These findings extend the reports of Kolmert (2001) and Imaya et al. (2020), confirming that bottom (flat), foot slope with gentle slope promoted higher growth of planted teak than on other sites because of these sites have re-sedimented deeper soil, accumulate soil organic matter and nutrient (Kaosa-ard, 1989; Tanaka et al., 1998), and wellness drainage (Vaides-Lopez et al., 2019). Further, Watanabe et al. (2010) confirmed that teak growth was significantly correlated with volumetric water content and maximum water holding capacity of soil, as soil moisture is an essential factor that controls the growth of teak. The present study results corroborated the findings of Vaides-Lopez et al. (2019), who reported that terrain with a flat topography and a lower slope show the best growth and productivity, and site elevation and slope are negatively correlated with teak growth variables. Notwithstanding, the present study results disagreed with the findings of Watanabe et al. (2010), who reported that the growth performance of planted teak had no significant correlation with site factors, particularly slope position and slope gradient for site elevations ranging from 134 to 460 m.a.s.l along with different parent material, groundwater, and soil classifications.

Teak requires high light conditions (Kadambi, 1972; Kaosa-ard, 1998). The present study showed that the higher slope position, especially in the middle and upper slope promoted greater initial DBH growth ($p < 0.05$), while gentle slope encouraged greater initial height growth ($p < 0.01$). This study area has complex landforms; the deep valley had shorter hours of sunlight in a day than upper slope positions. As confirmed by Dieters et al. (2014), Pachas et al. (2019a), and Zahabu et al. (2015), stand density has a significant effect on diameter growth, crown diameter, and proportion of live and dead branches as the results of the inter-tree competition. Thus, the results for initial growth in this study might be the interaction of light requirement with initial high stocking density in upper slope positions (Table A1) (Roder et al., 2001; Vongkhamho et al., 2020).

Therefore, the present study indicates that teak exhibits better growth on gentle slopes, especially when the bottom and concave slope area might be influenced by soil moisture, although soil factors were not investigated in this study. Most remarkably, this is the first study to my knowledge to examine the effect of topographic conditions on growth performance.

4.5. Chapter summaries

The growth performance of planted teak is highly dependent on relevant environmental factors. This study examined the relationship between growth performance and topographic conditions to clarify which topographic factors have the most influence. The result of Spearman's partial rank correlation indicated that the upper limit of DBH and height growth showed a significant negative correlation with slope position, while the intrinsic speed of DBH and height growth had a significant positive correlation with slope form. Moreover, the slope gradient showed a significant negative correlation with the upper limit and intrinsic speed of height growth. However, initial DBH growth had a significant negative correlation with slope position, while the slope gradient was positively correlated with initial height growth. These analyses suggest that planted teak in this area has faster growth in lower slope positions with a gentle concave slope. The present study results are the scientific evidence, critically contribute to developing a long-term teak plantation management strategy to improve the economic potential of timber production for small-scale farmers. High timber productivity of teak plantations is based on tree quality, tree size, and heartwood quality. Therefore, further study of the effects of topographic conditions on heartwood quality is warranted.

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CHAPTER 5. EFFECT OF TOPOGRAPHIC CONDITIONS ON TEAK HEARTWOOD QUALITY IN MOUNTAINOUS AREAS

5.1. Introduction

High-quality teakwood has been obtained from tree dimension, wood quality (e.g., heartwood content, wood properties, wood characteristics, and defects) (Midgley et al., 2015; Thulasidas & Baillères, 2017). Heartwood factor is a crucial component that alters to log yield, grading, and price, directly affecting wooden productivity and profitability (Wanneng, 2019). Heartwood content increased with the growth rate of trees with increasing stem DBH (Thulasidas & Bhat, 2009), while growth rate increased with tree age (Moya et al., 2003). Furthermore, wood density was also increased with tree age, but it had no relationship with stand density (Pérez & Kanninen, 2005).

Apart from tree age, heartwood had a larger content in dry sites than wet sites (Pérez Cordero & Kanninen, 2003). Besides, heartwood content was influenced by silt content in the soil, while wood density was affected by soil depth, soil water retention, and *Zinc* content (Moya & Perez, 2008). At the same time, heartwood color was controlled by a suitable genetic selection (Thulasidas & Baillères, 2017), while there are no environmental variables that were affected to heartwood color parameters, particularly lightness (L*) and redness (a*) (Moya & Calvo-Alvarado, 2012). In addition, wood properties; wood shrinkages were not influenced by soil properties due to the large range of suitable soil for teak in Costa Rica (Moya & Perez, 2008).

In Lao PDR, there is little research on teakwood quality (Wanneng et al., 2014; Bouaphavong et al., 2016). Despite this, wood quality is vital for the Lao wood industry sector. Considering the previous results of several researchers related to teak plantations in Luang Prabang province (Kolmert, 2001; Midgley et al., 2007; Pachas et al., 2019a; Imaya et al., 2020), the assumption of the present study was that heartwood quality was control by tree age. But the research on the environmental factor (e.g., climate and soil-site condition) influenced teak heartwood quality in Lao PDR is very rarely. This chapter aimed to clarify which topographic condition variables most affect teak heartwood quality.

5.2. Methods

5.2.1. Plot sampling

This study has the specific criteria, according to commenced harvest year of ≥ 10 years (Wanneng, 2019) along with optimum site elevation of <900 m.a.s.l (Jerez & Coutinho, 2017) and without evidence of damage in heartwood. Forty-nine sample plots in total were selected from target plantations, having 147 short log samples obtained from the felled tree (three trees per plot) using for heartwood quality assessment.

5.2.2. Assessing heartwood content

In Lao PDR, the marketable size of the teak log is approximately ≥ 12 cm in diameter (Hopewell & Fitzgerald, 2014). This study focused on examining both heartwood content of the basal area and commercial volume.

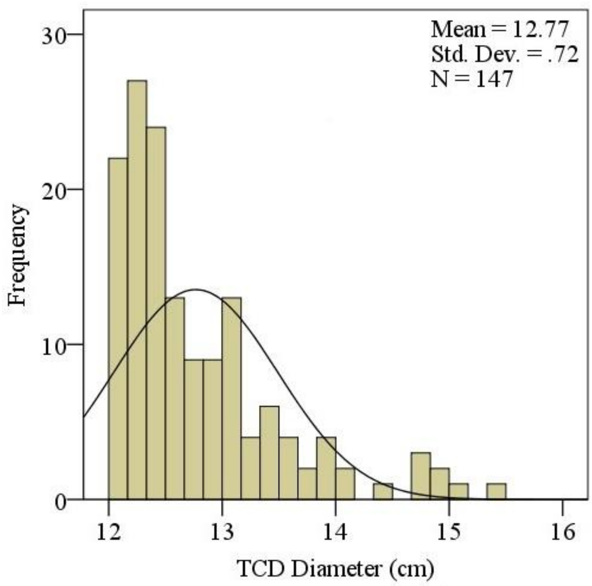


Figure 12. Histogram of tip crosscut discs (TCD) diameter

A total of 1177 crosscut-disc photos of ≥ 12 cm in diameter with the mean value of tip crosscut discs is approximately 12.77 cm in diameter (Figure 12) were taken from 147 sample trees of 49 sample plots were selected for assessing heartwood content. The selected crosscut-disc photos were analysed using Imgviewer software (Yamamoto, unpublished) to measure the radius of heartwood and stem from outer bark to pith in four directions: north, east, south, and west. Mean stem (under and over bark) and heartwood radius was obtained from four directions. Heartwood content was calculated using geometric formula (Tewari & Mariswamy, 2013). The data of the heartwood content of basal area (HCB) and commercial volume (HCV) ranged from 10.10 to 62.18 % and 6.05 to 68.30%, respectively (Figure 13).

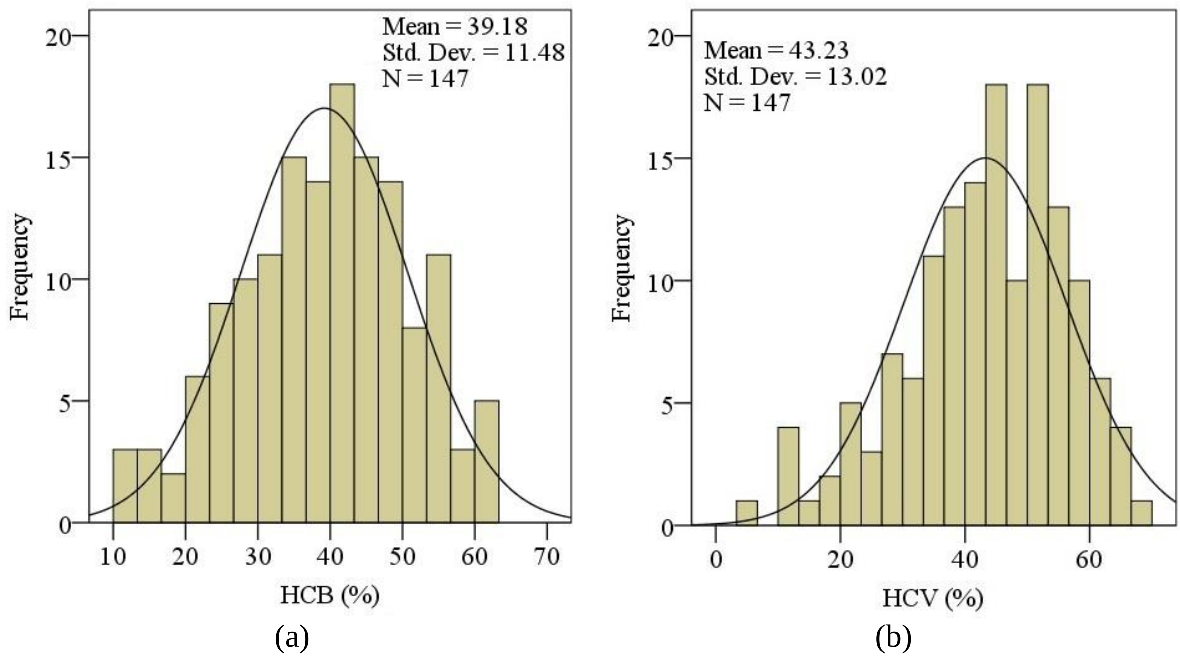


Figure 13. Histogram of heartwood content.

Note: Heartwood content of basal area "HCB" (a); heartwood content of commercial volume "HCV" (b).

5.2.3. Assessing heartwood properties and color

a. Wood specimen preparation

The 147 sawed wood samples (size of 15 cm lengths, 4 cm thickness, width depends on log's diameter) were taken from the short logs (Figure 14) using a circular sawing machine in Lao PDR. All sawed wood samples were restored in plastic bags and kept in refrigerators before import to Nagoya University, Japan.

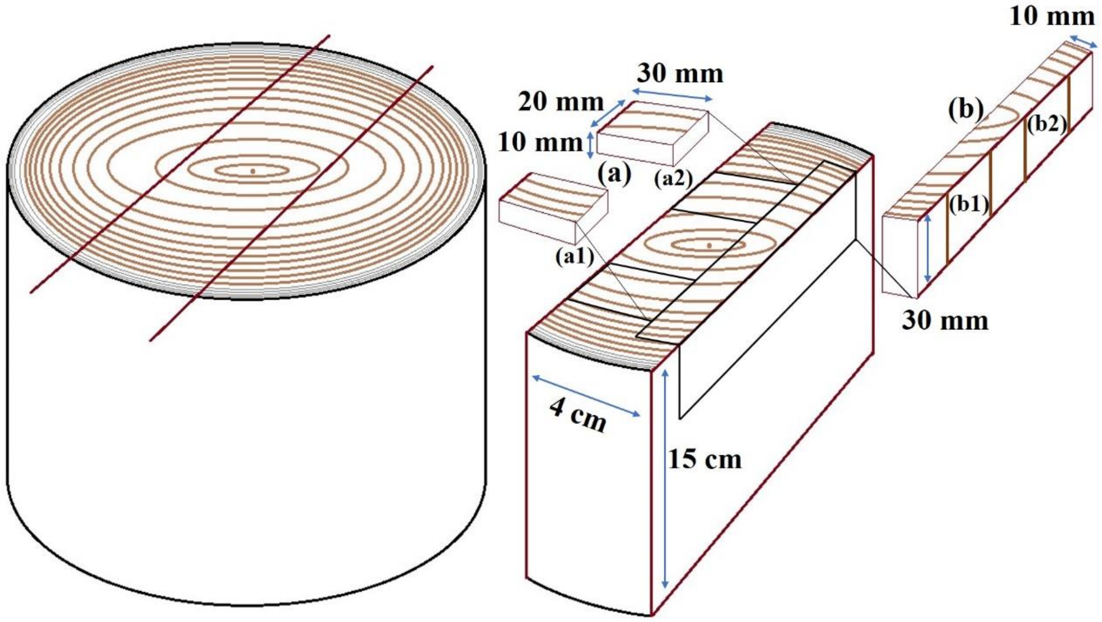


Figure 14. Wood specimen preparation

Note: Heartwood specimens for assessing basic density and shrinkage (a): taking 2 specimens (a1 & a2) from each sawed wood sample, having 294 specimens in total. Heartwood specimen for color measurement (b): taking a specimen from each sawed wood sample, having 147 specimens in total.

Afterward, the wood specimens for wood properties and color measurement (Figure 14a and 14b) purposes were processed using a circular sawing machine at the wood workshop, wood sciences laboratory, Nagoya University.

b. Basic density and shrinkage measurement

A total of 294 wood specimens (dimension of 10 mm in axial, 20 mm in radial, and 30 mm in tangential direction) (Figure 14a) were immediately brushed after sawing and marked crosscut line on disc surface for measuring work, then the green dimension and weight was assessed using digital caliper and scales. The wood specimens had air-dried at the laboratory's room temperature for a week. Finally, they were conducted for oven-dry with 100°C within 24 hours. The dimension and weight (oven-dried wood specimens) were measured in the same procedure. Basic density (BD), tangential shrinkage (TS), and radial shrinkage (RS) were calculated using the following equations (Miranda et al., 2011):

$$\text{Basic Density} = \frac{Oven\text{-}dried\ Weight\ (kg)}{Green\ volume\ (m^3)}$$

$$\text{Shrinkage} = \left(\frac{(Ls - Lo)}{Ls}\right) \text{x}100\%$$

where *Ls* is green dimension; *Lo* is oven-dry dimension.

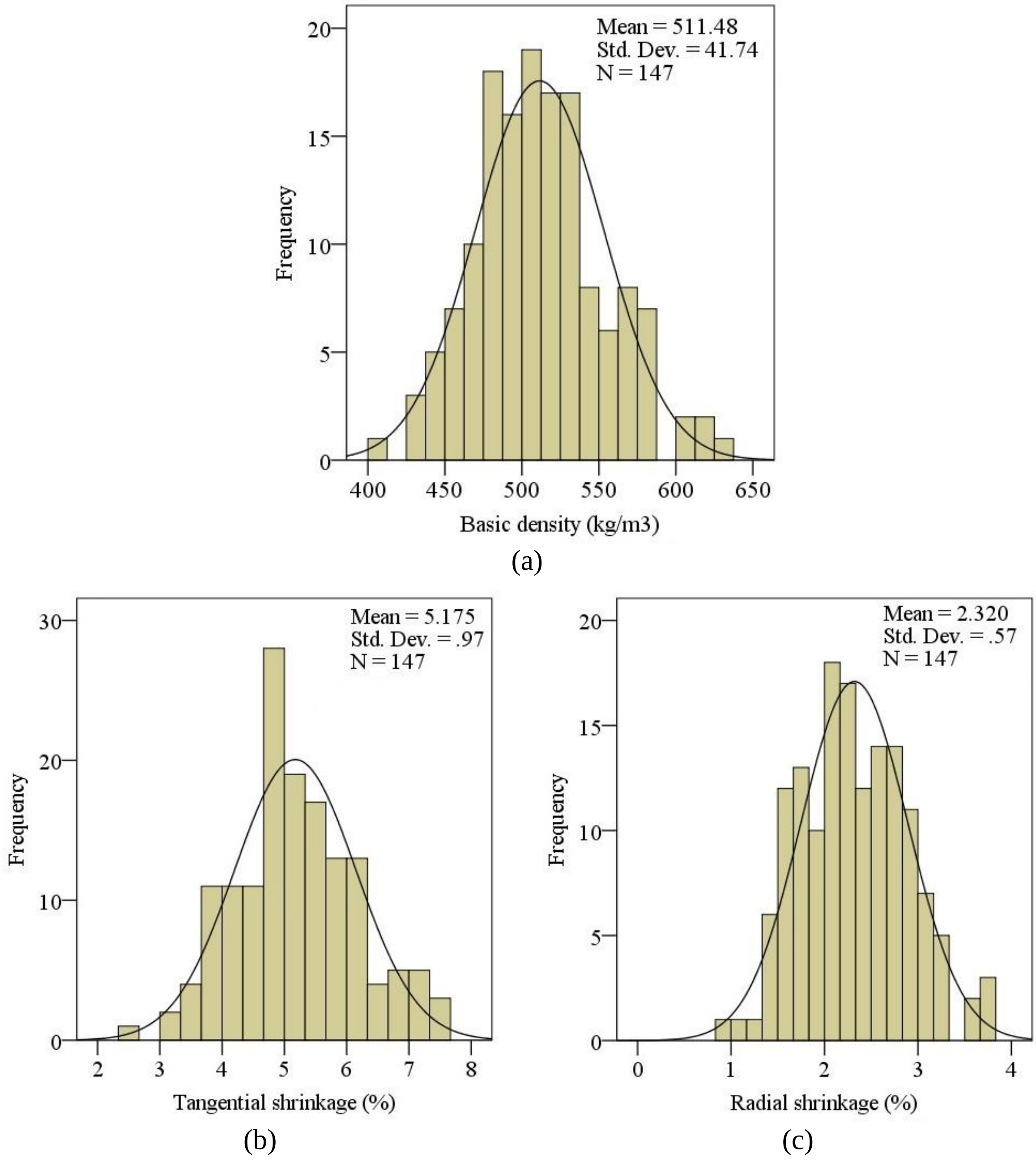


Figure 15. Histogram of heartwood properties

Note: Basic density (a); Tangential shrinkage (b); Radial shrinkage (c).

BD ranged from 404 to 628 kg/m^3 (Figure 15a), while TS and RS ranged from 2.61 to 7.48 %, and 0.89 to 3.82 %, respectively (Figure 15b & 15c).

c. Heartwood color measurement

A total of 147 cross-sectional wood specimens (dimension of 10 mm in tangential, 30 mm in axial, width depends on sawed wood sample's diameter) for color measurement (Figure 14b) were placed on the plastic tray at the laboratory's room temperature for air-drying in several weeks without touching its axial surface of heartwood section. The air-dried cross-sectional wood specimen was prepared by a chop in two pieces (Figure 14b-b1 and 14b-b2: the axial surface dimension of 30 mm x 30 mm for each) of the heartwood section, which taken from the different part where is in between the pith and sapwood using sharp shears one by one. A total of 294 pieces of heartwood were conducted to evaluate the color values.

Heartwood color measurement were performed by a portable spectrophotometer (NF-555, Nippon Denshoku; UV-3100pc, Shimadzu) with an opening diameter of 8 mm (NF-555) or 10 mm (UV-3100pc) using the CIELab color system. The value L* describes psychometric lightness (0=black to 100=white). The value a* represents a color parameter on the red/green axis; a positive a* value represents red color, whereas a negative a* value represents green color. The value b* represents a color parameter on the yellow/blue axis; a positive b* value represents yellow color, whereas a negative b* value represents blue color (Lukmandaru, et al., 2009; Moya & Calvo-Alvarado, 2012). This study showed the frequency of color parameters; Lightness (L*) ranged from 50.93 to 74.85 (Figure 16a), redness (a*) ranged from 7.22 to 12.96 (Figure 16b), and yellowness (b*) range from 20.89 to 32.09 (Figure 16c).

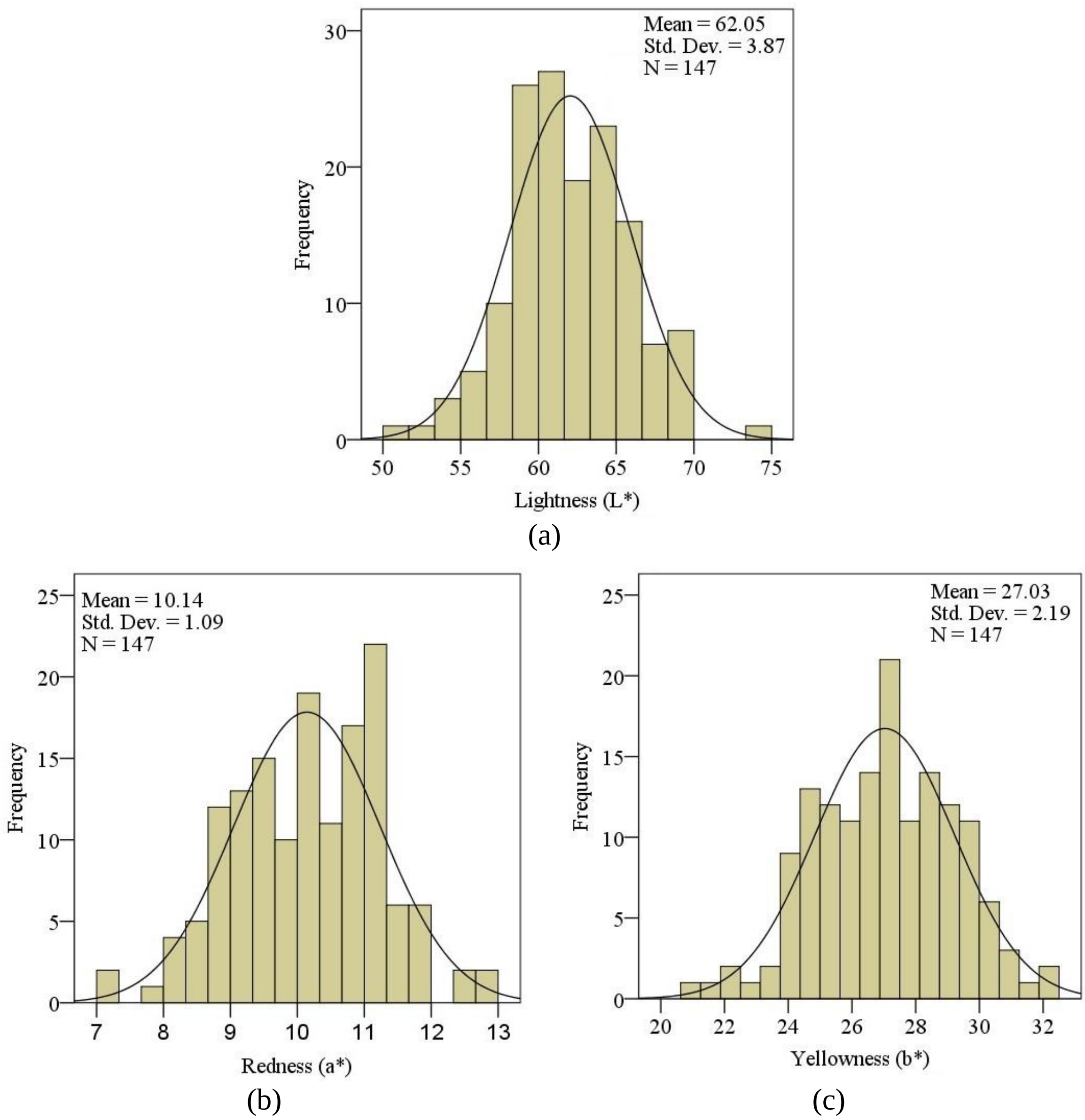


Figure 16. Histogram of teak heartwood color parameter.
Note: Lightness (a); redness (b); yellowness (c).

5.3. Result

5.3.1. Heartwood content

The results of Spearman's partial rank correlation analysis (Figure 16a and Table A5) indicate that HCV and total height (HT) had a significant positive correlation with tree age (TA). In contrast, HCB and diameter at breast height (DBH) had no relationship with TA. DBH showed a significant positive correlation with HT and HCB, while stand density (SDe) and

HCV was a negative correlation ($p < 0.01$). HT had a significant positive correlation with HCB. The analysis results (Figure 16a and Table A5) revealed that SDe had a significant positive correlation with EV and SF. HT had a significant negative correlation with SG and SP, while SF was a positive relationship ($p < 0.01$). HCV had a significant negative and positive correlation with EV and SP, respectively. Notwithstanding, HCB and DBH had no relationship with any topographic conditions, excluding a significantly positive relationship between EV and DBH.

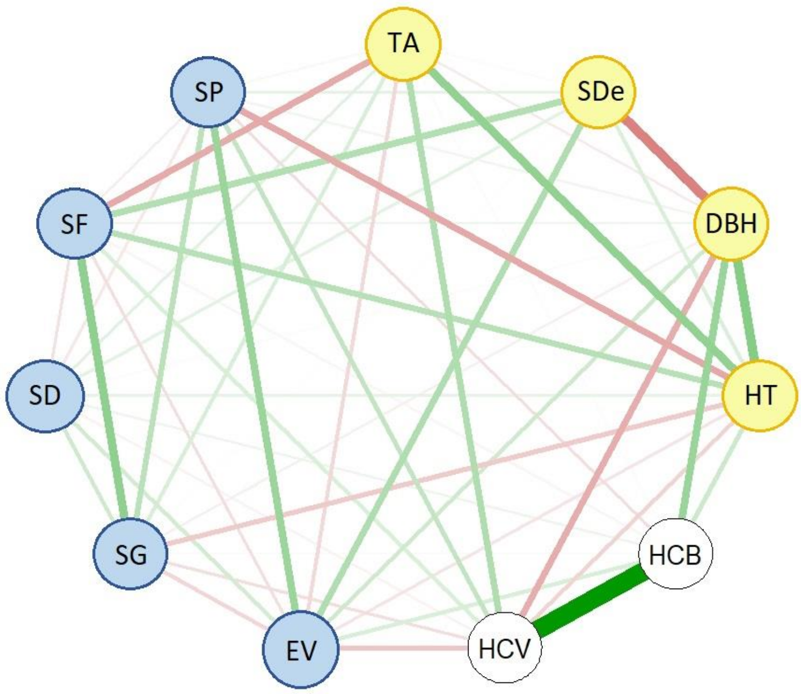
The analysis results stated that HT and HCV increased with TA, while HCB and DBH were also increased with HT. But HCB and DBH in neither young nor old age of teak in this study (10 to 31 years old) had not significantly different. Higher stand density of planted teaks is found in concave slope where an area of higher elevation, which teak had least DBH growth at higher stocking plantations. Further, teak had a greater HT at the lower gentle concave slope, while HCV had a larger proportion at the higher slope position, where the lower elevation and HCB showed no relationship with any topographic conditions.

5.3.2. Heartwood properties

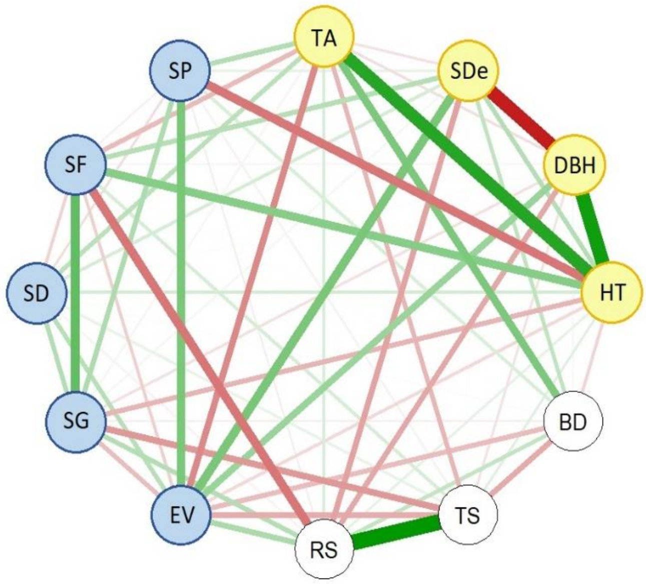
The spearman partial rank correlation analysis (Figure 16b and Table A6) indicate that HT showed a positive correlation with SDe ($p < 0.05$). BD had a significant positive and negative correlation with TA and TS, respectively. TS showed a significant negative correlation with TA, SG, and EV. Besides, RS had a significant negative correlation with SDE, DBH, and SF, while EV and SG were positive ($p < 0.05$). Moreover, TS had the highest positive correlation with RS ($p < 0.01$). Lower TS and RS with higher BD mean better wood properties. Therefore, the analysis results suggest that teak’s heartwood properties; BD and TS have an increasing quality with tree age, slope gradient, and elevation, while RS showed a good value with larger stem diameter at gentle concave slope along where an area of lower elevation.

5.3.3. Heartwood color

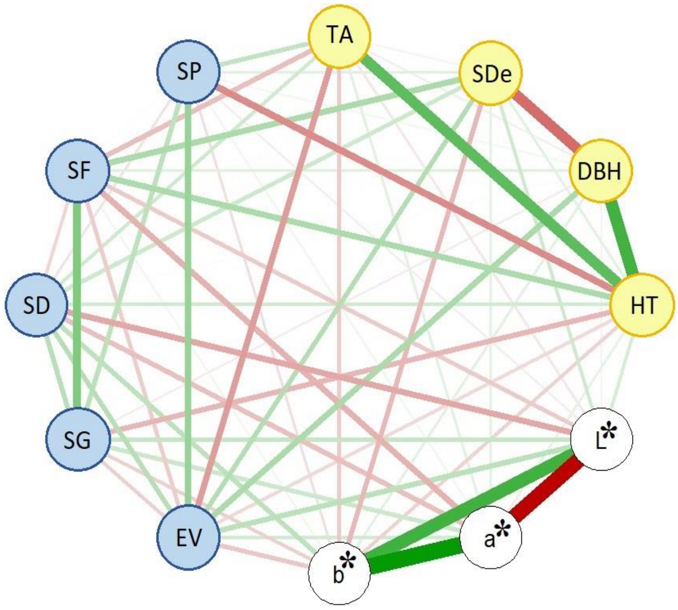
The results of Spearman's partial rank correlation analysis (Figure 16c and Table A7) indicate that the heartwood colors had a mutual correlation as lightness ($L*$) and redness ($a*$) showed a strong positive correlation with yellowness ($b*$) ($p < 0.01$). However, redness $a*$ had a significant negative correlation with $L*$. The analysis result showed that $L*$ and $a*$ had a significant negative correlation with SD, while b* was positive. However, EV showed a significant correlation with $L*$ and $b*$, while SF was negatively correlated with $a*$ ($p < 0.05$). Moreover, $L*$ showed a positive relationship with SG ($p < 0.05$). And $b*$ had a significant negative correlation with SDe. The analysis results suggest that teak heartwood color; $L*$ has a darker color associated with the south-west facing gentle slope at lower elevation. The redder color showed a relationship with south-east facing convex and straight slope, while yellow has a higher value at lower stand density whereas south-west facing slope in lower elevation.



(a)



(b)



(c)

Figure 17. Partial correlation network between heartwood quality and topographic conditions.

Note: heartwood contents and topographic conditions (a); heartwood color and topographic conditions (b); heartwood properties and topographic conditions (c). The green and red lines indicate positive and negative correlations, respectively. The line thickness indicates the strength of the spearman's partial rank correlation. The letter shown in the white circles indicate tree age (TA); stand density (SDe) tree size variables: dimeter at breast height (DBH), total height (HT); heartwood quality variables: heartwood content (%) of basal area (HCB), heartwood content (%) of commercial volume (HCV), basic density (BD), tangential shrinkage (TS), radial shrinkage (RS), lightness color (L*), redness color (a*), yellowness color (b*); topographic conditions: elevation (EV), slope gradient (SG), slope direction (SD), slope form (SF), slope positions (SP)

5.4. Discussion

5.4.1. Heartwood content

The heartwood content of teakwood has been studied across tropical growing countries for over the decades; for example, (Pérez Cordero & Kanninen, 2003) had studied on heartwood content of teak with ages between 7 to 47 years in Costa Rica of Central America, showed that heartwood content was ranged from 0.4 to 61% of total stem volume. In Togolese of West Africa, Kokutse et al., (2004) reported that the heartwood content of teak between 11 to 70 years and with different ecological zones ranged from 26.1 to 72.3 % of basal area. In Karnataka of India, (Tewari & Mariswamy, 2013) reported that heartwood content of teak in different ages of 30 and 32 years old was ranged from 37.1 to 56.3% of total stem volume. The heartwood content of both basal area and commercial volume shown in Figures 13a & 13b of the present study was comparable with those previous results.

The present study was found that DBH and HCB have not only insignificantly correlated with TA, but it also has no relationship with any topographic conditions, although DBH and HCB increased with HT. This finding has the consistent with the current challenges and problems of planted teak that have the least DBH growth and development (Dieters et al., 2014; Pachas et al., 2019a) due to initial spacing of high stand density interaction thinning and pruning were uncommon in this area (Hansen et al., 1997; Midgley et al., 2007), which there is enough evidence to corroborate that establishment of teak plantation with initial narrow spacing and managing without intensive thinning regimes cause affected to less diameter growth and development (Jerez & Coutinho, 2017). In addition, the result of present study showed that HCV had a larger proportion at smaller-size DBH, even though HCB increased with DBH might be affected by insufficient management (e.g., weeding, thinning and pruning) in this area.

This study showed HCV and HT were increased with TA, and HCV had a greater proportion at lower elevation, these result consistent with Luang Prabang's teak plantation were commenced to establishing in the lower site elevation, then expand to higher elevation (Roder et al., 2001; Midgley et al., 2007); teak tree ages showed significant negative correlation with elevation, while slope position was positive (Vongkhamho et al., 2020).

Teak has a faster growth with larger size at bottom site and lower gentle slope (Kolmert, 2001; Vaides-Lopez et al., 2019); due to higher soil moisture content (Watanabe et al., 2010). Heartwood content increase with tree age (Kokutse et al., 2004), larger-size tree produced higher heartwood content (Víquez & Pérez, 2005). However, heartwood content had a larger proportion in dry sites than wet sites (Pérez Cordero & Kanninen, 2003). Those author's previous findings were consistent with the present study results as HT had a greater growth at lower gentle concave slope, and HCV had larger proportion at middle, upper slope (Figure 17a and Table A5).

5.4.2. Heartwood properties

Lower shrinkage with higher BD means better wood properties. Therefore, the analysis results suggest that teak's heartwood properties; BD and TS have an increasing quality with TA. The present study's findings were similar results had been reported that wood basic density had higher at high stocking plantation, and its increasing with tree age (Pérez Cordero & Kanninen, 2003). In addition, the present study results were agreed with finding of Pérez & Kanninen (2005) who reported that wood density increased with tree age, but no relationship with stand density. Nevertheless, The present finding disagreed with Wanneng et al. (2014) who reported that wood density, and shrinkages of different ages (10 to 25 years old) had no significance, this may cause by limited wood samples of 9 trees in their study. Further, the present study revealed that RS had a greater quality with larger stem diameter (Moya et al., 2003) at gentle concave slope, whereas lower elevation, while TS had a better value at steep land where an area of higher elevation might be affected by soil condition factors as Moya & Perez (2008) had reported TS and RS had most correlated with soil characteristic variables such as phosphorus, silt content, iron content.

5.4.3. Heartwood color

The present study's result showed that teak heartwood color; L^* has a darker color associated with the south-west facing gentle slope in lower elevation. The redder color showed a relationship with south-east facing convex and straight slope, while yellow has a higher value at lower stand density whereas south-west facing slope in lower elevation. Thulasidas & Baillères (2017) summarized that the color of teak heartwood can be controlled by a suitable genetic selection, while Derkyi et al. (2009) reported that environmental factors had a stronger effect on the teak heartwood color than the stand age, especially soil pH decreased moderately with increasing darkness in Ghana. Moreover, teak heartwood being darker in wetter areas that drier ones. In addition, yellowish brown color of heartwood was produced more at drier and fertile sites in Costa Rica (Moya & Calvo-Alvarado, 2012). In Luang Prabang province, planting material using for teak plantation establishment as the seed and seedings are from genetically unimproved seeds and uncertain seed origin (Roder et al., 2001; Midgley et al., 2007; Phongoudome et al., 2012). Besides, soil pH distributed in flat, gentle and slope area has no significant differences (Kolmert, 2001). Therefore, present study showed that teak heartwood had a darker at lower elevations might be affect by wet-soil conditions and soil properties, and even genetic factor.

5.5. Chapter summaries

This study concludes that the heartwood content of the basal area (HCB) mainly increases with tree size. However, it had slightly affected by topographic conditions. Heartwood content of commercial volume (HCV) increases with tree age, having a greater proportion in the middle to upper slope. Lower TS and RS with higher BD mean better wood properties. Therefore, the analysis results suggest that teak's heartwood properties; BD and TS have an increasing quality with tree age, slope gradient, and elevation, while RS showed a good value with larger stem diameter at gentle concave slope along where an area of lower elevation, while TS had a better value at steep land where an area of higher elevation might be affected by soil condition factors. Teak heartwood color; $L*$ has a darker color associated with the south-west facing gentle slope in lower elevation. The redder color showed a relationship with south-east facing straight slope, while yellow has a higher value at lower stand density whereas south-west facing slope in lower elevation.

CHAPTER 6. GENERAL DISCUSSION

6.1. Effect of site characteristics on tree quality in teak plantation forests

The results presented in chapter 3 (figure 6 and Table A2) have reflected the effect of farmer teak plantation development history in Luang Prabang province and confirmed the current challenges and problems. Particularly, use of uncertain genetic origin for plantation establishment and insufficient management practices (no thinning and pruning regimes) (Hansen et al., 1997; Midgley et al., 2007) may cause the effect on tree quality in planted teak forests, while teak tree bending increases as the tree age (Guzman et al., 2017). On the other hand, Pérez & Kanninen (2005) reported that intensive thinning have a positive effect on stem form. In addition, under an intensive pruning regime, a teak tree at rotation (20 years) may yield over 40% of knot-free volume (over 60% of the merchantable tree volume) (Víquez & Pérez, 2005). Moreover, in the present study, the extreme occurrence of protuberant buds/knots and epicormic on the tree stem are found at lower elevations where the flat land, the bottom of the valley, along the riversides. However, Kolmert (2001) suggested that teak had faster growth in those areas. The infestation of insect disease may cause these results to become a problem, damaging the teak plantation at flat land, whereas lower elevation (Keonakhone, 2005; Midgley et al., 2007). Still, poor tree quality leads to the reduction of valuable teak timber.

The growth rate and yield of farmer teak plantations vary from site to site, the site index (mean tree height of teak) for reference age of 15 years was ranged from 11 to 19 (Dieters et al., 2014), mean annual increment in volume of young tree plantation between 5 – 16 years old, ranging from 3.4 to 21.3 m^3/ hectare per year (Kolmert, 2001; Keonakhone, 2005; Dieters et al., 2014). The current farmer planted production was comparable to the growth and yield of farmer teak in other countries, especially Indonesia, due to similar backgrounds of plantation management and development (Hardiyanto & Prayitno, 2007). However, Lao teak timber price in the international market has been low because of the small-size log with many defects (Bouaphavong et al., 2016; ITTO, 2020). There are some researchers were confirmed that the presence of high number of knots had the highest detrimental impact on price, followed by the higher bend fraction, presence of hollows at top end and middle of the log, presence of heart rot and presence of buttresses, respectively (Midgley et al., 2015; Jayawardhane et al., 2016)

6.2. Influence of site conditions on teak growth performance

The tree size and stem quality is the most important thing for growers because standing price increased with tree size (Midgley et al., 2007). Luang Prabang province is a mountainous region with characterizing complex landforms, having suitable soil conditions for teak growth distributed on a large scale, particularly, calcium contents can meet a requirement of the optimum condition (>4.0 $cmol_c$/kg soil) about 64% (Imaya et al., 2020). In addition, adequate evidence is available from different regions of tropical growing countries in the world to indicated that teak is a calcicolous and light-demanding tree species, it has good growth in moisturizing soil area, fertile soil with well-drainage (Kadambi, 1972; Kaosa-ard, 1989, 1998; Tanaka et al., 1998). The results presented in Chapter 3 and 4 suggested that the optimum site condition for promoting good tree growth with high-tree quality is lower, middle gentle concave slope where higher elevation in this area. Thus, this result was extended, agreed upon, and consistent with several previous reports such as Kolmert (2001); Watanabe et al. (2010); Zahabu et al. (2015); Pachas et al. (2019a); Vaides-Lopez et al. (2019).

6.3. Effect of site and stand characteristics on teak heartwood quality

Generally, tree size and tree quality are important for wood manufacturers, but heartwood quality is essential for Lao wood industry sector. Its crucial factor influenced timber quality, grade and price and directly affected wooden productivity and profitability (Midgley et al., 2015; Wanneng, 2019). High-quality teak heartwood was derived from the large proportion of heartwood content, high-quality wood properties such as low shrinkage with high basic density and golden brown or dark golden yellow color of heartwood (Khanduri et al., 2008; Palanisamy et al., 2009; Midgley et al., 2015; Thulasidas & Baillères, 2017). The results presented in chapter 5 (figure 17a) indicated that teak heartwood content had increased with tree age. It had larger proportion at the middle, upper slope at the lower elevation, which was consistent with the findings presented in chapter 3 and previous report of Pérez Cordero & Kanninen (2003); Kokutse et al. (2004); Pérez & Kanninen (2005). The present results in chapter 5 (figure 17b) revealed that teak's heartwood properties; basic density and tangential shrinkage has an increasing quality with tree age at the steeper slope, especially tangential shrinkage had high-quality value with increasing slope gradient. In this case, high gradient or steep slope of > 30% cause heavy soil erosion in teak plantation (Song et al., 2020). Besides, heartwood color information showed in chapter 5 indicated that lightness (L*) ranged from 50.93 to 74.85 (Figure 16a), redness (a*) ranged from 7.22 to 12.96 (Figure 16b), and yellowness (b*) range from 20.89 to 32.09 (Figure 16c), which was defined as light brown and yellowish brown color when compared with teak heartwood color information of other tropical growing countries such as Costa Rica (Moya & Calvo-Alvarado, 2012; Moya et al., 2013), Indonesia (Lukmandaru & Takahashi, 2008) and India (Thulasidas et al., 2006) had slight different. The present study showed the heartwood color (figure 17c) had darker (low $L*$) and yellowish (high $b*$) at the south-west facing gentle slope of lower elevation was consistent with the previous finding of Derkyi et al. (2009); Moya & Calvo-Alvarado (2012). Therefore, suitable site conditions for high-quality teak heartwood might be middle, upper gentle concave slope interaction with south facing straight slope at higher elevation in this area.

6.4. Options for improving the smallholder planted teak forests in northern Lao PDR

High-quality teak timber varies from tree size, tree quality, and heartwood quality, long rotation obtained higher valuable teakwood than a shorter one (Thulasidas et al., 2006;

Thulasidas & Bhat, 2012; Thulasidas & Baillères, 2017), and successful teak plantation was derived from the establishment with good genetic quality, appropriate site selection and preparation, sufficient management practices and prevent the insect disease infestation (Jerez & Coutinho, 2017). Smallholders can make to overcome successful teak plantations if they have the know-how, enough labour, and budget.

Northern Lao PDR is dominated by mountainous areas, shifting cultivation remains a dominant livelihood strategy in these regions (Epprecht et al., 2018). Due to shifting cultivation practices became a major cause of deforestation, the Lao government had formulated the land and forest allocation policy in 1989 in order to stabilization shifting cultivation and forest rehabilitation; the policy had first demonstrated in northern mountainous regions (Tsechalicha & Gilmour, 2000; MAF, 2005). A system of tree intercropping with annual crops (e.g., upland rice, maize, Job's tear, sesame, fruit trees, etc.) was introduced to be practice in the existing shifting cultivation system of the mountainous farmers; teak is the main tree species that it had been extensively promoted to planting across the northern provinces, particularly Luang Prabang and Xayabouly provinces (Hansen et al., 1997; Roder et al., 2001; Phongoudome et al., 2012). Stabilization of shifting cultivation policy cause to limit the rotational practice of fewer than eight years (Hansen, 1998; Epprecht et al., 2018) that why the teak plantations were normally established to permanent replacement of the fallow land with the small plots of 0.1 to 1 hectare where convenient access area (e.g., roads, rivers, the nearby village, paddy field, etc.) (MAF, 2005).

The mountainous shifting cultivators have the diversification of agricultural production system such as livestock, rice, and other cash crops cultivation, NTFPs collections (e.g., broom grass, bamboo shoots, mushroom, paper mulberry, Malabar tree "*Boehmeria glomerulifera")* , etc., while they have limited labor and asset (Roder et al., 2001). Teak was established intercropped with upland rice and other cash crops at the first three years or until canopy closure of tree; weeding was commonly activated only in the interplanted period. The initial spacing and planting materials used vary from grower to grower and site to site; typically, high stand density was ranged from 1100 to 2500 trees per hectare with using uncertainly seedling (e.g., unselected seedling with unknown seed origin) (Hansen et al., 1997; Midgley et al., 2007). The teak plantation is a source of farmer's livelihood insurance; all planted teak trees have economic value as farmers decided to harvest the merchant-sizable tree of > 15 cm in diameter when the need for finance, resulting in thinning regimes was uncommon (Newby et al., 2012; Midgley et al., 2015). In addition, pruning was also uncommon due to farmers experienced that it caused a flush of unwelcome epicormic growth (Midgley et al., 2007).

Although Pachas et al. (2019a) were recommended that initial stand density of < 1000 trees per hectare can significant increase growth rate and yield of teak. In addition, they were also suggested to using wider initial stand density of 600 trees per hectare for the rotation without thinning regimes or agroforestry system purpose. Wider initial spacing of teak planting require early weeding and pruning, and occurrence of stem taper or poor mode of branching (Jerez & Coutinho, 2017). According to household profile of farmers in northern Lao PDR, they have limit labor, budget and more agricultural activities. By this reason, given present study results, the options for further improving the smallholder plantation productions would be recommended:

- Provide the information of optimum site conditions for high-quality teak timber to concerning authorities, policy maker to developing the long-term sustainable teak plantation management strategy in Lao PDR.
- Mapping the optimum site conditions for high-quality teak timber in Lao PDR.
- Demonstrate the commercial teak plantation matching with optimum site conditions for high-quality teak timber with using good genetic seeding and appropriate plantation spacing and effective management system.

CHAPTER 7: GENERAL CONCLUSION

High timber quality of teak is derived from tree quality, tree growth and heartwood quality. In this study aimed to find out the suitable site conditions for teak plantation forests through clarify which site condition variables most influence high timber quality of teak in northern mountainous regions of Lao PDR.

The results of Spearman’s partial rank correlation analysis suggest teak timber has a best quality with high productivity at lower, middle gentle slope interaction with straight concave slope at higher elevations in this area. The results presented in this study provide a scientific evidence, critically contribute for developing the long-term teak plantation management strategy to improve timber productions' economic potential for small-scale farmers with teak plantations in this area.

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SUMMARY

Teak (*Tectona grandis* Linn. f) is a globally valuable hardwood tree species whose growth performance and tree quality characteristics are controlled by various factors. High timber quality of teak is mainly obtained from tree quality, tree growth performance, and heartwood quality. This study is aimed to investigate the suitable site conditions of teak plantations in Luang Prabang province, Lao PDR.

In Luang Prabang, the 61 target teak plantations ranged from 287 to 1057 m.a.s.l. and from 10 to 31 years in stand age were selected in various modes of topography. Then, in each target plantation, a temporary sample plot with 20 m x 20 m was established. Among 61 temporary sample plots, 53 plots, 27 plots and 49 plots were selected for assessing tree quality, tree growth performance and heartwood quality, respectively. The tree qualities of all trees within a plot were assessed using a scoring system. The growth performance was assessed by parameters of growth curve of the Mitscherlich function obtained by applying it to stem analysis data of three trees felled within a plot. In addition, several methods were applied to assess the teak heartwood quality, such as heartwood content and color, using geometric formula and CIELab color system, respectively. The spearman's partial rank correlation analysis was used for investigating the influences of stand and site characteristics using R version 4.0.3 with ppcor and qgraph packages.

For tree quality, the elevation was negatively correlated with poor tree quality characteristics such as epicormic shoots, mode of branching, and branch size. The stand density was also negatively correlated with poor tree quality such as stem form and axis persistence. However, the stand age was positively correlated with poor tree quality such as protuberant buds and buttressing. Therefore, it was suggested that higher-density plantations at the higher

elevation sites might be suitable for teak plantations, but a longer rotation in forest management might degrade tree quality in this area.

For teak growth performance, the upper limit of DBH and height growth curve had a significant negative correlation with slope positions, while the intrinsic speed of DBH and height growth had a significant positive correlation with slope forms. Moreover, the slope gradient showed a significant negative correlation with the upper limit and subsequent speed of height growth. However, the initial DBH growth had a significant negative correlation with slope position, while the slope gradient was positive to initial height growth. Therefore, it was suggested that the planted teak grows faster in the lower slope position interaction with a gentle concave slope in this area.

For teak heartwood quality, the heartwood content of basal area (HCB) mainly increases with tree size. However, it had slightly affected by topographic conditions. Heartwood content of commercial volume increased with tree age, having a greater proportion in the middle to upper slope. Lower shrinkage with higher basic density means better wood properties. Therefore, it was suggested that teak's heartwood properties, basic density, and tangential shrinkage had an increasing quality with tree age, medium to high gradient, and middle to upper slope. In contrast, radial shrinkage had a greater quality at gentle concave slope might be affected by soil condition factors. On the other hand, teak heartwood color; L^* has a darker color associated with the south-west facing gentle slope in lower elevation. The redder color showed a relationship with south-east convex and straight slope, while yellow has a higher value at lower stand density whereas south-west facing slopes in lower elevation.

In conclusion, it was found that teak timber has the best quality with high productivity at lower, middle gentle slope interaction with straight concave slope at higher elevations in this area.

APPENDIX I. SITE AND STAND CHARACTERISTICS OF THE SAMPLE PLOTS

Table A1. Site and stand characteristics of the sample plots.

Sites	SD	SP	SF	SG (%)	EV (m.a.s.l)	SA (Years)	SDe (trees/ha)	Basal Area (m^2/ha)	DBH (cm)	Bole Height (m)	Total Height (m)	Dominant Height (m)
1[(a), (b), (c)]	S	BO	SV	17	287	23	811	17.8	18.0 ± 6.8	10.1 ± 5.1	16.6 ± 5.6	21.0 ± 1.6
2[(a), (b), (c)]	W	BO	SS	6	308	23	1005	22.8	18.8 ± 4.4	11.9 ± 3.0	18.6 ± 3.3	21.3 ± 1.5
3[(a), (b), (c)]	E	BO	SS	11	309	31	526	20.8	22.8 ± 6.8	7.6 ± 3.3	16.7 ± 4.6	18.9 ± 2.9
4[(a), (c)]	N	LS	VS	17	350	13	837	13.0	15.2 ± 2.6	7.4 ± 2.0	14.2 ± 1.1	15.0 ± 0.5
5[(a), (b), (c)]	W	MS	SV	20	376	23	1096	18.3	15.8 ± 2.8	10.0 ± 2.6	15.6 ± 2.7	18.3 ± 1.0
6[(a), (c)]	N	US	SS	30	407	11	731	12.1	16.3 ± 3.6	7.9 ± 1.7	13.9 ± 2.2	15.3 ± 0.7
7[(a), (c)]	E	CR	VV	15	445	12	607	11.5	18.2 ± 4.6	6.0 ± 2.8	14.8 ± 2.8	17.1 ± 0.9
8[(a), (c)]	N	MS	CS	19	501	12	967	19.5	17.4 ± 5.9	5.9 ± 2.3	13.1 ± 4.1	16.5 ± 1.0
9[(a), (c)]	N	MS	CS	50	511	14	894	17.6	17.5 ± 5.4	7.0 ± 3.3	14.7 ± 4.0	16.4 ± 1.8
10[(a), (b), (c)]	E	LS	VV	17	667	23	1065	31.5	20.6 ± 5.8	11.1 ± 3.5	19.9 ± 3.9	23.2 ± 1.3
11[(a), (b), (c)]	S	LS	VV	17	659	20	980	16.5	15.7 ± 3.4	7.4 ± 2.0	14.3 ± 2.4	16.2 ± 0.8
12[(a), (b), (c)]	S	MS	VV	17	671	24	710	32.5	25.1 ± 7.0	10.5 ± 4.4	21.4 ± 4.7	25.1 ± 1.2
13[(a), (c)]	E	BO	CS	12	674	11	1108	19.0	16.4 ± 3.6	8.6 ± 3.1	16.3 ± 2.8	18.6 ± 0.5
14[(a)]	N	LS	SC	27	675	10	1398	16.1	14.2 ± 3.2	8.3 ± 2.5	14.7 ± 2.6	17.3 ± 0.6
15[(a), (c)]	N	CR	VV	17	867	13	2128	21.0	13.1 ± 3.3	7.2 ± 2.1	12.5 ± 2.1	14.9 ± 0.7
16[(a)]	S	LS	SC	20	826	12	1096	15.9	15.9 ± 5.8	8.0 ± 2.6	14.2 ± 3.5	17.3 ± 1.0
17[(a)]	W	LS	SS	47	779	10	1657	19.8	14.2 ± 3.7	9.1 ± 2.4	15.1 ± 2.5	17.9 ± 1.3
18[(a), (c)]	W	BO	SS	3	797	13	1151	25.5	18.8 ± 2.9	10.1 ± 3.8	18.8 ± 1.7	20.5 ± 0.6
19[(a), (b), (c)]	E	LS	CC	43	515	21	898	16.2	16.6 ± 5.9	8.7 ± 3.3	13.9 ± 4.1	17.7 ± 1.2
20[(a), (b), (c)]	E	LS	CC	60	485	20	525	13.6	20.2 ± 4.8	10.9 ± 4.4	17.6 ± 4.5	18.2 ± 3.8
21[(a), (b), (c)]	S	LS	CC	15	459	23	1264	24.5	16.9 ± 3.4	12.5 ± 2.5	17.2 ± 2.4	19.9 ± 1.1
22[(a), (c)]	E	MS	VV	24	435	12	1080	11.6	13.9 ± 3.4	8.9 ± 3.1	13.9 ± 3.2	17.0 ± 1.2
23[(a), (c)]	E	MS	SS	40	429	13	1562	20.7	14.8 ± 2.8	9.5 ± 2.0	15.8 ± 1.5	17.3 ± 0.4
24[(a), (b), (c)]	E	LS	SV	33	402	24	737	24.2	21.6 ± 6.0	10.9 ± 3.3	17.9 ± 4.2	20.9 ± 2.8
25[(a), (b), (c)]	W	MS	VV	50	412	24	978	19.6	18.0 ± 4.3	9.6 ± 2.6	15.7 ± 2.1	17.5 ± 1.0
26[(a), (b), (c)]	W	LS	CV	62	405	24	1059	20.8	17.4 ± 3.1	11.3 ± 2.7	16.5 ± 2.6	19.0 ± 0.7
27[(a), (c)]	N	MS	SV	20	622	14	943	14.0	15.8 ± 2.8	10.0 ± 2.1	15.1 ± 1.7	16.3 ± 0.4

Sites	SD	SP	SF	SG (%)	EV (m.a.s.l)	SA (Years)	SDe (trees/ha)	Basal Area (m^2/ha)	DBH (cm)	Bole Height (m)	Total Height (m)	Dominant Height (m)
28[(a), (c)]	W	MS	VV	16	648	13	1063	17.7	16.2 ± 3.2	10.4 ± 2.1	15.5 ± 1.7	16.9 ± 0.5
29[(a), (b), (c)]	N	BO	CC	7	389	20	875	20.0	17.7 ± 3.8	12.4 ± 2.6	19.4 ± 3.7	22.0 ± 1.3
30[(a), (c)]	E	CR	SV	10	819	12	980	14.0	14.6 ± 6.1	5.9 ± 2.6	11.3 ± 3.7	14.7 ± 0.8
31[(a), (b), (c)]	W	BO	CV	6	292	23	875	26.3	20.4 ± 5.7	14.3 ± 2.9	22.1 ± 4.0	25.4 ± 1.6
32[(a), (b), (c)]	N	LS	CV	45	323	24	1650	17.6	12.1 ± 2.6	9.2 ± 1.6	12.9 ± 2.2	15.4 ± 0.7
33[(a), (b), (c)]	N	MS	CV	40	350	22	1075	19.5	16.0 ± 3.5	11.4 ± 2.8	16.4 ± 3.5	19.6 ± 1.1
34[(a), (b), (c)]	N	US	CV	34	390	22	1350	18.3	14.1 ± 3.8	10.0 ± 2.3	14.2 ± 2.7	17.0 ± 0.7
35[(a), (b), (c)]	S	LS	CC	27	432	22	1150	26.3	17.2 ± 3.1	10.8 ± 2.3	17.6 ± 2.1	19.7 ± 0.9
36[(a), (b), (c)]	S	MS	CC	21	452	22	1300	26.9	16.4 ± 2.9	11.1 ± 2.9	17.2 ± 2.3	19.3 ± 0.7
37[(a), (b), (c)]	S	US	CC	23	473	23	1350	31.2	17.3 ± 2.8	10.9 ± 2.2	17.3 ± 1.7	19.0 ± 0.6
38[(a), (c)]	N	BO	CC	9	385	14	625	18.7	19.5 ± 5.7	7.6 ± 3.0	17.1 ± 3.1	19.2 ± 1.2
39[(a), (c)]	E	LS	CC	75	401	12	950	17.6	15.4 ± 5.4	8.2 ± 3.4	14.5 ± 4.2	17.9 ± 1.3
40[(a), (c)]	N	MS	CC	40	498	11	1725	24.4	13.4 ± 3.0	8.5 ± 2.6	14.8 ± 2.3	17.1 ± 0.5
41[(a), (c)]	N	LS	SC	40	715	11	1535	22.1	13.6 ± 3.1	7.0 ± 2.0	13.6 ± 2.1	15.3 ± 0.8
42[(a), (c)]	N	MS	SC	56	731	11	1519	14.8	11.1 ± 2.4	4.7 ± 1.2	9.8 ± 1.5	11.4 ± 0.7
43[(a), (c)]	W	US	SC	56	751	11	1748	23.4	13.1 ± 2.5	5.8 ± 1.5	12.6 ± 2.0	14.4 ± 0.5
44[(a), (b), (c)]	E	BO	VV	3	629	25	575	28.4	26.6 ± 8.0	11.3 ± 4.2	24.8 ± 6.1	27.7 ± 2.2
45[(a), (c)]	S	LS	VV	35	652	10	1075	22.0	16.2 ± 3.7	6.4 ± 2.2	14.6 ± 1.7	16.2 ± 0.5
46[(a), (b), (c)]	E	US	VV	23	707	21	925	13.5	13.6 ± 3.7	4.2 ± 1.4	11.1 ± 1.9	12.6 ± 0.9
47[(a), (c)]	W	LS	CC	65	420	12	1275	16.0	12.8 ± 3.3	7.1 ± 2.5	13.2 ± 2.8	15.7 ± 0.6
48[(a), (c)]	W	MS	CC	53	546	13	1275	20.3	14.2 ± 4.1	7.5 ± 2.5	14.2 ± 1.9	16.1 ± 0.5
49[(a), (b), (c)]	W	US	CC	45	610	23	1175	28.6	17.6 ± 3.7	10.0 ± 2.9	16.7 ± 2.1	19.1 ± 1.1
50[(a), (b), (c)]	E	CR	CC	11	758	21	1375	28.2	16.2 ± 4.5	8.5 ± 2.9	16.6 ± 3.0	19.5 ± 0.8
51[(a)]	W	LS	VC	36	802	12	1150	23.9	16.3 ± 3.5	6.7 ± 2.1	16.9 ± 1.8	18.4 ± 0.6
52[(a), (b), (c)]	N	BO	VS	4	386	22	1325	21.9	14.3 ± 5.0	8.8 ± 3.2	14.5 ± 2.9	17.7 ± 1.6
53[(a), (b), (c)]	N	LS	SC	9	369	21	750	14.6	15.7 ± 4.9	9.5 ± 3.3	15.0 ± 4.6	18.8 ± 1.4

Note: Sites[(a)] are the sample plots for chapter 3, Sites[(b)] are the sample plots for chapter 4, Sites[(c)] are the sample plots for chapter 5. Mean ± standard deviation. Slope direction (SD); north (N); east (E); south (S); west (W). Slope position (SP); bottom (BO); lower slope (LS); middle slope (MS); upper slope (US); crest (CR). Slope gradient (SG). Slope form (SF); Straight (S), Concave (C), Convex (V). Stand age (SA). Stand density (SDe). Diameter at breast height (DBH). Basal Area (BA).

APPENDIX II. SPEARMAN'S PARTIAL RANK CORRELATION MATRIX AMONG TREE QUALITY, STAND CHARACTERISTICS, AND SITE CHARACTERISTICS

Table A2. Spearman'**s** partial rank correlation matrix among tree quality, stand characteristics, and site characteristics.

VR	SA	SDe	EV	SG	SP	SFo	AP	BS	MB	EP	PB	BU
SA	1.00											
SDe	-0.09**	1.00										
EV	-0.43**	0.25**	1.00									
SG	-0.24**	0.29**	-0.29**	1.00								
SP	0.12**	0.16**	0.31**	0.19**	1.00							
SFo	-0.01	-0.15**	0.06**	0.08**	0.10**	1.00						
AP	-0.09**	-0.13**	-0.02	-0.04	0.02	0.07**	1.00					
BS	0.03	-0.11**	0.19**	0.04	0.07**	-0.12**	0.11**	1.00				
MB	0.06	0.01	-0.14**	-0.03	0.00	0.01	0.19**	0.70**	1.00			
EP	0.17**	-0.01	-0.25**	-0.11**	0.14**	0.15**	-0.12**	-0.07**	0.00	1.00		
PB	0.12**	0.07**	0.03	-0.01	0.02	0.08**	-0.05**	0.03	0.04*	0.22**	1.00	
BU	0.15**	-0.06**	0.11**	0.04	-0.05*	0.07**	0.09**	0.06**	-0.04	0.03	0.11**	1.00

Note: Variables (VR). Stand age (SA). Stand density (SDe). Elevation (EV). Slope gradient (SG). Slope position (SP). Stem form (SFo). Axis persistence (AP). Branch sizes (BS). Mode of branching (MB). Epicormic shoots (EP). Protuberant buds (PB). Buttressing (BU). *Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level (2-tailed).

APPENDIX III. SPEARMAN'S PARTIAL RANK CORRELATION MATRIX BETWEEN TREE GROWTH CURVE PARAMETERS AND TOPOGRAPHIC CONDITIONS

Table A3. Spearman's partial rank correlation matrix between DBH-age curve parameters and topographic conditions.

VR	A	k	t_0	EV	SD	SF	SG	SP
A	1.00							
k	-0.64**	1.00						
t_0	0.09	0.22*	1.00					
EV	0.21	0.12	0.23*	1.00				
SD	0.06	-0.02	0.16	-0.05	1.00			
SF	0.1	0.40**	-0.13	-0.11	-0.02	1.00		
SG	-0.16	-0.22	0.2	-0.14	0.07	0.23*	1.00	
SP	-0.30**	-0.05	-0.26*	0.58**	0.09	0.03	0.45**	1.00

Note: Variable (VR). DBH-age curve parameters as upper limit of growth (A); curvature of the tree growth curve (k); initial tree growth (t_0). Elevation (EV). Slope Gradients (SG). Slope Directions (SD). Slope Form (SF). Slope Positions (SP). * Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed).

Table A4. Spearman's partial rank correlation matrix between Height-age curve parameters and topographic conditions.

VR	A	k	t_0	EV	SD	SF	SG	SP
A	1.00							
k	-0.62**	1.00						
t_0	0.20	0.20	1.00					
EV	-0.07	-0.30**	0.04	1.00				
SD	0.15	0.21	0.22	0.06	1.00			
SF	0.32**	0.57**	-0.06	0.08	-0.18	1.00		
SG	-0.31**	-0.25*	0.34**	-0.16	0.06	0.25*	1.00	
SP	-0.30**	0.02	-0.16	0.51**	0.08	0.07	0.38**	1.00

Note: Variable (VR). Height-age curve parameters as upper limit of growth (A); curvature of the tree growth curve (k); initial tree growth (t_0). Elevation (EV). Slope Gradients (SG). Slope Directions (SD). Slope Form (SF). Slope Positions (SP). * Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed).

APPENDIX IV. SPEARMAN'S PARTIAL CORRELATION METRIX BETWEEN HEARTWOOD QUALITY AND TOPOGRAPHIC CONDITIONS

Table A5. Spearman's partial rank correlation matrix between heartwood contents and topographic conditions.

VR	TA	SDe	DBH	HT	HCB	HCV	EV	SG	SD	SF	SP
TA	1.00										
SDe	-0.02	1.00									
DBH	-0.08	-0.45**	1.00								
HT	0.39**	0.13	0.43**	1.00							
HCB	-0.02	0.00	0.36**	0.18*	1.00						
HCV	0.28**	0.01	-0.29**	-0.16	0.90**	1.00					
EV	-0.13	0.28**	0.17*	-0.10	0.14	-0.21*	1.00				
SG	0.14	0.02	-0.06	-0.19*	0.03	-0.12	-0.15	1.00			
SD	0.11	0.10	-0.02	0.09	0.07	-0.05	0.16	0.17	1.00		
SF	-0.30**	0.27**	0.06	0.26**	-0.03	0.13	-0.11	0.40**	-0.11	1.00	
SP	0.04	0.09	0.06	-0.31**	-0.12	0.22**	0.35**	0.24**	-0.08	-0.08	1.00

Note: Variables (VR). Tree Age (TA). Stand density (SDe). Diameter at breast height (DBH). Total height (HT). Heartwood Content of Basal area (HCB). Heartwood Content of commercial Volume (HCV). Elevation (EV), Slope gradient (SG), Slope direction (SD), Slope form (SF), Slope position (SP). * Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed).

Table A6. Spearman's partial rank correlation matrix between heartwood properties and topographic conditions.

VR	TA	SDe	DBH	HT	BD	TS	RS	EV	SG	SD	SF	SP
TA	1.00											
SDe	-0.07	1.00										
DBH	-0.08	-0.52**	1.00									
HT	0.50**	0.17*	0.55**	1.00								
BD	0.30**	0.15	0.03	-0.10	1.00							
TS	-0.17*	-0.01	-0.07	0.07	-0.20*	1.00						
RS	0.09	-0.21*	-0.20*	0.06	0.14	0.59**	1.00					
EV	-0.27**	0.31**	0.23*	-0.09	-0.15	-0.19*	0.20*	1.00				
SG	-0.03	0.03	-0.07	-0.17*	-0.04	-0.24**	0.17*	-0.15	1.00			
SD	0.16	0.10	0.01	0.10	0.01	0.05	-0.03	0.17*	0.18*	1.00		
SF	-0.16	0.17*	-0.02	0.28**	0.01	0.09	-0.32**	-0.11	0.37**	-0.10	1.00	
SP	0.18*	0.06	0.01	-0.31**	0.09	-0.04	-0.04	0.31**	0.19*	-0.08	-0.03	1.00

Note: Variables (VR). Tree Age (TA). Stand density (SDe). Diameter at breast height (DBH). Total height (HT). Basic density (BD). Tangential shrinkage (TS). Radial shrinkage (RS). Elevation (EV), Slope gradient (SG), Slope direction (SD), Slope form (SF), Slope position (SP). * Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed).

Table A7. Spearman's partial rank correlation matrix between heartwood color and topographic conditions.

VR	TA	SDe	DBH	HT	L*	a*	b*	EV	SG	SD	SF	SP
TA	1.00											
SDe	-0.03	1.00										
DBH	-0.05	-0.43**	1.00									
HT	0.47**	0.08	0.55**	1.00								
L*	-0.07	0.14	-0.04	0.12	1.00							
a*	0.08	0.08	0.00	0.07	-0.73**	1.00						
b*	-0.16	-0.21*	0.08	-0.13	0.55**	0.72**	1.00					
EV	-0.29**	0.22**	0.24**	-0.11	0.20*	0.13	-0.17*	1.00				
SG	0.01	-0.01	-0.06	-0.21**	0.17*	0.15	-0.14	-0.14	1.00			
SD	0.14	0.15	-0.01	0.14	-0.26**	-0.18*	0.19*	0.21**	0.21**	1.00		
SF	-0.19*	0.24**	0.09	0.25**	-0.15	-0.23**	0.04	-0.15	0.37**	-0.12	1.00	
SP	0.18*	0.09	0.04	-0.34**	-0.05	0.05	-0.09	0.30**	0.20*	-0.08	-0.02	1.00

Note: Variables (VR). Tree Age (TA). Stand density (SDe). Diameter at breast height (DBH). Total height (HT). Heartwood color; Lightness (L*), Redness (a*), Yellowness (b*). Site characteristics; Elevation (EV), Slope gradient (SG), Slope direction (SD), Slope form (SF), Slope position (SP). * Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed).