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Correlations among Tree Quality, Stand Characteristics, and Site Characteristics in Plantation Teak in Mountainous Areas of Lao PDR

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Abstract: Teak (*Tectona grandis* Linn. f) is a globally valuable hardwood tree species whose growth performance and tree quality characteristics are controlled by various factors. Teak tree quality characteristics such as stem straightness, buttressing, and protuberant buds/knots are important in the sawing process, and directly affect timber yield, timber grade, recovery, and cost. In this study, we assessed the relationships among tree quality characteristics, stand characteristics, and site characteristics in plantation teak in the Luang Prabang province of the Lao PDR. We established 53 sample plots (20 × 20 m) and measured a total of 2149 sample trees. The stand-level tree age ranged from 10 to 31 years, and the trees were distributed in various modes of topography. The altitude ranged from 287 to 867 masl. The results of Spearman's partial rank correlation analysis among the parameters revealed the present condition of the teak plantation forest in the region. The altitude was related to stand age and was correlated with tree quality characteristics such as epicormic shoots, mode of branching, and branch size. The correlation results suggest that higher-density plantation at the higher altitude sites might be suitable for teak plantations in this area. In addition, we found that a longer rotation in forest management might degrade tree quality.

Keywords: Luang Prabang province; site characteristics; stem form; teak plantation; tree quality

1. Introduction

Teak (*Tectona grandis* Linn. f) is one of the most valuable hardwood tree species in the world and is planted in approximately 70 tropical countries [1] covering a total area of 6.89 million hectares. Teak wood exhibits a high timber quality owing to properties such as lightness with strength, stability, durability, malleability, resistance to termites and fungi, and high adaptability to environmental variations [2–4]. Hence, it is widely used in the building of both outdoor and indoor furniture, ships, decorative veneers, paneling, doors, and windows [5–7]. Due to these widespread applications, the production of high-quality timber with a high yield is essential for successful teak plantations.

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 [8,9]. Among them, stem straightness, buttressing, and protuberant buds/knots are important factors that directly alter the timber yield, grade, and price [7–9]. In general, tree quality depends on genetic properties [10,11]. In addition, Bouaphavong et al. [12] 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 such as climate (rainfall, temperature, and wind), edaphic factors (e.g., geology, topography, and soil), sunlight, and moisture [2,4,13]. Moreover, silvicultural practices of spacing density, thinning, and pruning are factors that affect teak quality. Stand density has a significative effect on crown diameter and the proportion of live and dead branches as a result of inter-tree competition [14]. However, the interaction among these factors and the mechanism of the effect are not yet fully understood.

In the Lao People's Democratic Republic (PDR), teak has been planted since 1942 [15,16]. In 1989, as part of its strategy for forest rehabilitation, the government declared teak as one of the first priority species of valuable timber, selecting it for the establishment of plantation forests across the country [17,18]. Recently, the total teak plantation area increased to 40,000 hectares [14]. Although the government's strategy promoted the increase in teak plantation, the international price of Lao's teak timber has been low [19], owing to the limited information available on the suitability of environmental conditions for teak plantation compared with Thailand [13,20] and Myanmar [21]. In addition, a supply system of seeds and seedlings under genetic management has not been established in Lao PDR, even though there are nurseries of teak seedlings, where the seeds originate from the teak forest with a relatively good quality. Luang Prabang province, a mountainous region in the Lao PDR, has 33.65% of its total land area under forest cover [22], including 15,000 hectares of teak plantation forests [23,24]. About 98% of the teak plantation forests belong to individual farmers and the private sector [6,24]. The farmers' teak plantations were established with a high stand density of 1100 to 2500 trees ha^{-1} [3], with the aim of promoting height growth during the early stage of stand development, but management operations such as thinning have not been carried out [7,18]. Therefore, considering the lack of control of genetic origin and stand density, we assumed that the teak tree quality might be affected by mainly tree age in this area. However, the relationship with the other site factors remains unclear.

The aim of this study is to provide guidelines for suitable site conditions of teak plantation in Lao PDR. In this paper, we focus on tree quality and aim to clarify the relationships among tree quality, stand characteristics, and site characteristics of teak plantation forests in Luang Prabang province of the Lao PDR.

2. Materials and Methods

2.1. Research Site

The research site was located in the southwestern part of Luang Prabang province, covering areas of both Luang Prabang and Xieng Ngern districts. 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) in the village of Thinxom in Luang Prabang district (altitude, 287 masl). 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 (altitude, 867 masl). 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; altitude, 297 masl), 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%) [25].

The mountainous terrain of this site comprises Paleozoic sedimentary rocks, limestone, and volcano-sedimentary rocks [26,27]. Acrisols and Alisols are the dominant soil types on the transect line, with Cambisols and Leptosols also present [28].

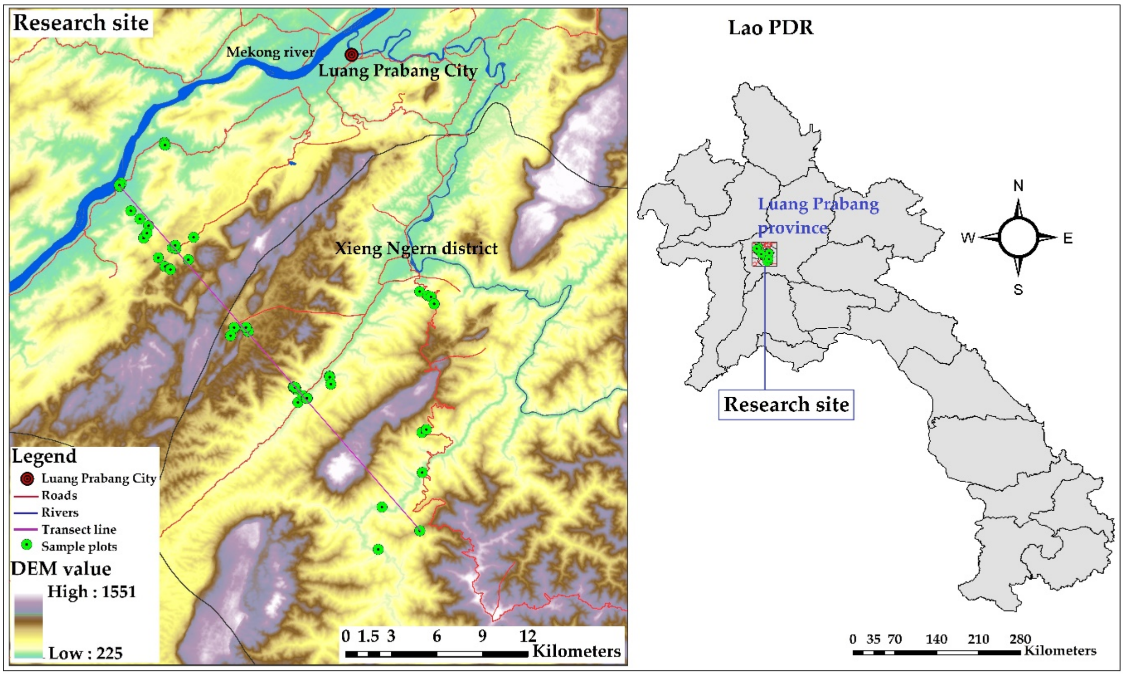

Figure 1. Map of the research site showing the transect line (pink) and the precise location within the Lao People's Democratic Republic (PDR). Source: Drawn by the authors based on Mekong Geographic Information Systems data. DEM, digital elevation model.

2.2. Plot Sampling and Site Description

In Luang Prabang province, teak plantations were established by replacing fallow land. The seedlings were bought from a private's nursery, and their origin was unknown. The teak seedlings were planted with a spacing of 2 × 2 m, 2 × 3 m, or 3 × 3 m. No active management such as thinning, pruning, and weeding has been carried out. Teak timber harvesting was sometimes conducted with a short rotation period of as little as 10 years [3,7,29]. In addition, teak is planted under various growing conditions [23]. Therefore, the sample plots used for this study were selected according to the following criteria: (1) Stand age (≥10 years), (2) site altitude (<900 masl), (3) type of landform (lowland, hill, or mountain), and (4) slope positions (bottom, lower, middle, upper, or crest). Based on these four criteria, we selected 53 sample plots (20 × 20 m) along the transect line (Figure 1), as shown in Table 1.

Table 1. Characteristics of sample plots and trees. North (N); east (E); south (S); west (W). Bottom (BO); lower slope (LS); middle slope (MS); upper slope (US); crest (CR). Slope gradient (SG). Basal area (BA). Stand density (SDE). Predominant height (PH).

Age Group (Years)	Slope Directions				Slope Positions					Altitude (m)	SG (%)	SDE (trees/ha)	BA (m^2/ha)	PH (m)
	N	E	S	W	BO	LS	MS	US	CR					
10 (n = 3)	1	–	1	1	–	3	–	–	–	702 ± 68	36 ± 10	1377 ± 292	19.3 ± 3.0	17.1 ± 1.1
11 (n = 6)	4	1	–	1	1	1	2	2	–	629 ± 142	39 ± 17	1394 ± 398	19.3 ± 5.0	15.4 ± 2.3
12 (n = 8)	1	4	1	2	–	4	2	–	2	581 ± 196	33 ± 24	1013 ± 398	16.2 ± 4.2	16.8 ± 1.4
13 (n = 6)	2	1	–	3	1	1	3	–	1	606 ± 203	24 ± 18	1336 ± 456	19.7 ± 4.2	16.8 ± 1.9
14 (n = 3)	3	–	–	–	1	–	2	–	–	506 ± 119	26 ± 21	821 ± 171	16.8 ± 2.5	17.3 ± 1.9
20 (n = 3)	1	1	1	–	1	2	–	–	–	511 ± 137	28 ± 28	793 ± 238	16.7 ± 3.2	18.8 ± 3.3
21 (n = 4)	1	3	–	–	–	2	–	1	1	587 ± 179	22 ± 16	987 ± 270	18.1 ± 6.8	17.2 ± 2.9
22 (n = 5)	3	–	2	–	1	1	2	1	–	402 ± 40	25 ± 14	1240 ± 121	22.6 ± 3.9	18.7 ± 1.5
23 (n = 8)	–	1	3	4	3	2	1	2	–	434 ± 146	19 ± 12	1080 ± 184	25.1 ± 5.3	20.9 ± 2.6
24 (n = 5)	1	1	1	2	–	3	2	–	–	443 ± 133	41 ± 17	1027 ± 380	22.9 ± 5.9	19.6 ± 3.6
25 (n = 1)	–	1	–	–	1	–	–	–	–	629	3	575	28.4	27.7 ± 2.2
31 (n = 1)	–	1	–	–	1	–	–	–	–	309	11	526	20.8	18.9 ± 2.9
Total	17	14	9	13	10	19	14	6	4	532 ± 167	28 ± 18	1103 ± 339	20.2 ± 5.3	18.9 ± 2.9

Mean ± standard deviation.

The total number of sample trees (diameter at the breast height [DBH] > 5 cm) was 2149 and the average number per plot was 40.6 trees. DBH was measured using a measuring tape, and bole and total heights were measured using a height measurer (Vertex IV, Haglöf, Sweden). Three trees (randomly selected from among the predominant trees) per plot were felled to estimate the actual stand age by counting the number of tree rings at the ground level, revealing that the stand age of sample plots ranged from 10 to 31 years (Tables 1 and A1).

Site characteristics of the sample plots including coordinates and altitudes were recorded with the aid of a global positioning system receiver (GPSMAP64, Garmin), and slope gradients (%) and slope directions were measured using a clinometer. The slope positions were scored as bottom (1), lower (2), middle (3), upper (4), and crest (5).

2.3. Assessment of Tree Quality Characteristics

The tree quality of all trees in each plot was assessed according to seven characteristics, based on Kjaer et al. [30] with modifications (Table 2 and Figure 2). For all assessment items (shown in Table 2), a score of "1" indicates the highest quality whereas higher numbers indicate the lower quality.

Table 2. Description of the appraised scores for tree quality.

Description	Interpretation of Appraised Scores
1. Stem Form (SF) Investigation of stem characters focuses on stem straightness, bends, and crooks. Scored in five classes (Figure 2a).	SF1: Straight SF2: Slightly wavering tree, few small bends SF3: Wavering tree, many small bends SF4: Crooked tree with one or two severed bends SF5: 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 2b).	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 2c).	BS1: Very light, less than 1/4 of the stem diameter BS2: Light, around 1/4 of the stem diameter BS3: Medium, between 1/4 and 1/2 of the stem diameter BS4: Heavy, around 1/2 of the stem diameter BS5: Very heavy, >1/2 to 3/4 of the stem diameter
4. Mode of branching (MB) Characteristics of tree branching. Scored in five classes (Figure 2d).	MB1: Regular, spreading branching MB2: Scattered branching-light MB3: Light forking MB4: Scattered branching-pronouncedMB5: 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 2e).	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 2f).	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 2g).	BU1: Nearly 100% of the area of the ideal stem BU2: About 3/4 of the area is the ideal stem BU3: About 1/2 of the area is the ideal stem BU4: About 1/3 of the area is the ideal stem

The relationships among tree quality characteristics, stand characteristics, and site characteristics were analyzed by non-parametric Spearman's partial rank correlation analysis using R version 4.0 [31] with the ppcor package [32]. We also visualized these relationships as a partial correlation network diagram by using the qgraph package [33] to evaluate the effect of stand characteristics and site characteristics on tree quality.

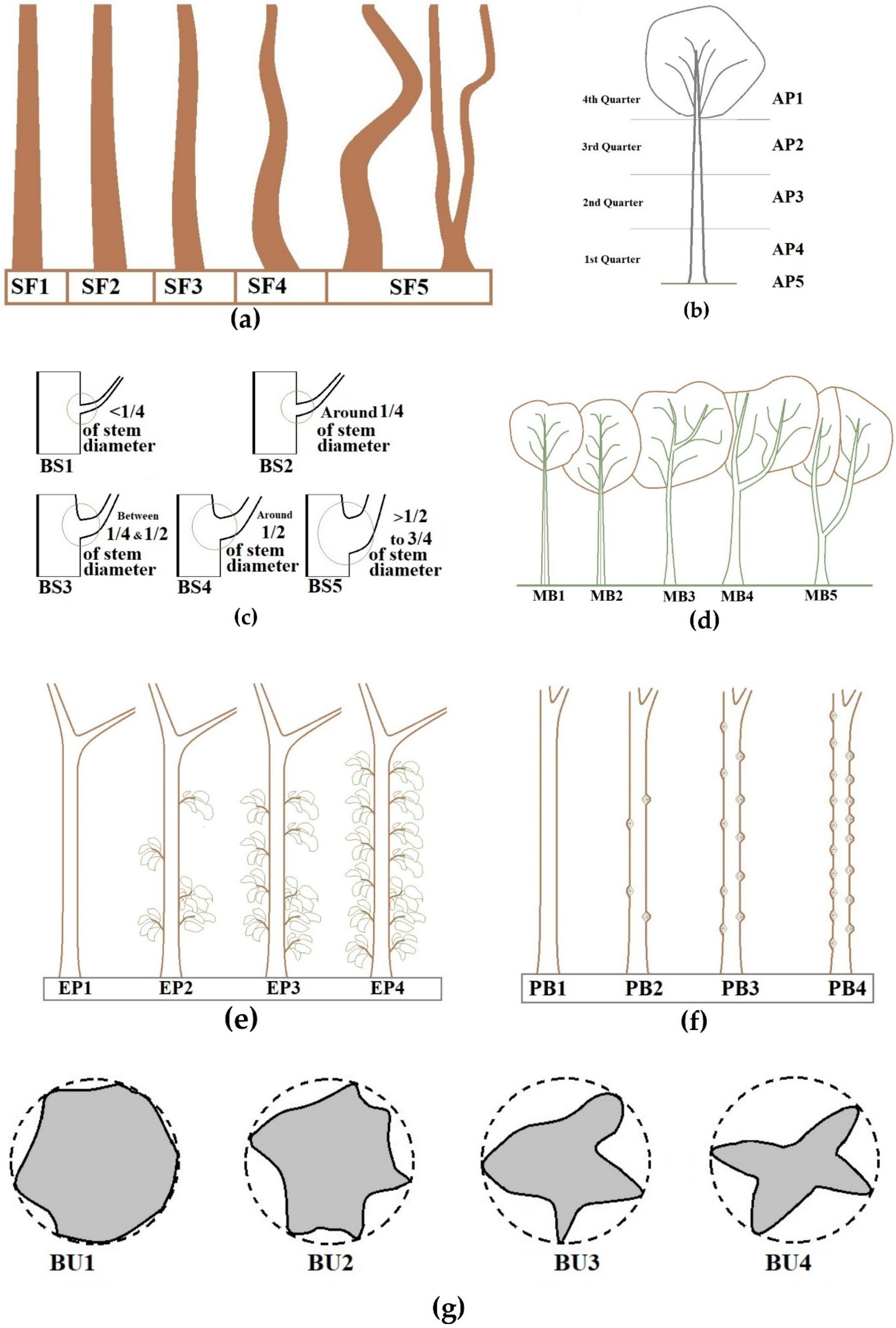

Figure 2. Scoring for tree quality assessment. (**a**) Stem form (SF) modified from Keiding et al. [34]. (**b**) Axis persistence (AP) modified from Kjaer et al. [30]. (**c**) Branch size (BS). (**d**) Mode of branching (MB) modified from Keiding et al. [34]. (**e**) Epicormic shoots (EP). (**f**) Protuberant buds (PB). (**g**) Buttressing (BU) modified from Kjaer et al. [30].

3. Results

The results of the Spearman's partial rank correlation analysis are shown as a network diagram in Figure 3. 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 3.

Four of the tree quality characteristics, namely, stem form (SF), axis persistence (AP), protuberant buds (PB), and buttressing severity (BU), were associated mainly with stand characteristics (Figure 3). The SF and AP scores had relatively stronger negative partial correlations with stand density ($p < 0.01$), but those of PB and BU had relatively stronger positive partial correlations with stand age ($p < 0.01$) (Figure 3 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 3). The BS scores had a relatively stronger positive partial correlation with altitude ($p < 0.01$), but those of MB and EP had relatively stronger negative partial correlations with altitude ($p < 0.01$) (Figure 3 and Table A2).

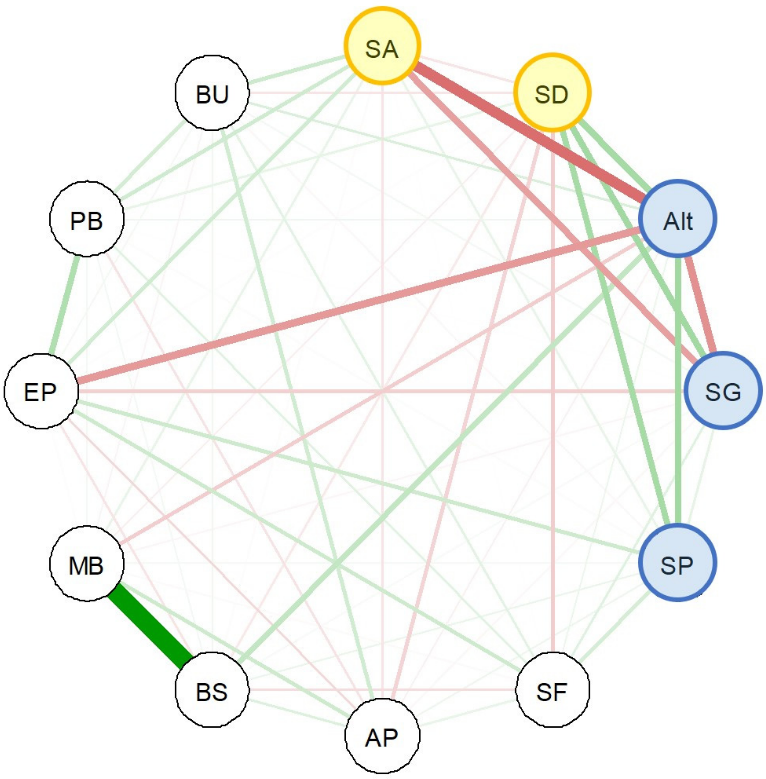

Figure 3. Partial correlation network among the tree quality characteristics, stand characteristics, and site characteristics. The green and red lines indicate positive and negative correlations, respectively. The line thickness indicates the strength of the partial correlation. Yellow, blue, and white circles indicate the stand characteristics, site characteristics, and tree quality characteristics, respectively. Stand age (SA); stand density (SD); altitude (Alt); slope gradient (SG); slope position (SP); stem form (SF); axis persistence (AP); branch size (BS); mode of branching (MB); epicormic shoots (EP); protuberant buds (PB); buttressing (BU).

4. Discussion

Forest management operations such as thinning are usually conducted as the forests age [19]. 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 (SD) (Figure 3 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, we 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 3).

One reason of the weak correlation between stand age and tree quality was the relatively strong negative partial correlation between stand age (SA) and altitude (Alt) ($p < 0.01$), as shown in Figure 3 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 [3]. The relatively strong negative partial correlation between stand age (SA) and altitude (Alt) 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 [7,18,24,35]. Since our research plantation 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.

Stand age (SA) showed weak positive partial correlations with mode of branching (MB), epicormic shoots (EP), protuberant buds (PB), and buttressing (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 number of protuberant buds [7,9,36]. Therefore, our results mean that younger teak plantations have higher value compared with older ones in terms of buttressing and number of protuberant buds. On the other hand, axis persistence (AP) had a weak negative correlation with stand age. This result might be attributable to stand growth with a high stand density.

Altitude had relatively stronger partial correlations with the scores of mode of branching (MB) and epicormic shoots (EP) ($p < 0.01$) (Figure 3 and Table A2). As shown in Figure 4, many epicormic shoots were visible on the stem from the riverside. Thus, less branching and fewer epicormic shoots might be due to the higher altitude. The stand density (SD) had negative partial correlations with the scores of stem form (SF) and axis persistence (AP) ($p < 0.01$) (Figure 3 and Table A2). Thus, the lower stand density might lower the stem form quality and the bole length [4,14,35]. Reflecting on the effect of site characteristics, stem form (SF) was positively correlated with slope gradient (SG) and slope position (SP). This means that the lower position of a gentle slope might produce a good straight shape of teak. Slope gradient (SG) and slope position (SP) also showed a partial correlation with epicormic shoots (EP) ($p < 0.01$) (Figure 3 and Table A2). Considering the observed partial correlation with stand age (SA) and altitude (Alt), epicormic shoots (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 [15] 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 altitude area. Although an infestation survey was not conducted as part of this study, our finding that higher altitude results in higher tree quality might reflect the effect of insects because few insects are found at higher altitude. Further studies investigating the effect of insects on teak plantation are therefore necessary.

In this study, the teak seedlings were generally provided by a private nursery and had an uncertain genetic background in Luang Prabang province. The genetics of plantation teak is one of the crucial factors in its growth and development [30,37]. Many countries pushing teak plantation have emphasized the importance of using appropriate clones to achieve high productivity [4]. However, in Luang Prabang province, because teak is not a native species [35] and a supply system for seeds and seedlings has not been established [38], the genetic origin of the planted teak is unknown [3]. 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 4. Photo of a teak tree with many epicormic shoots on its stems, taken from the riverside.

5. Conclusions

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 the Spearman's partial rank correlation analysis revealed that the higher-density plantation at higher altitude might be suitable for teak plantations, whereas the lower position of the gentle slope might produce a good straight shape of teak. In addition, the altitude was related to stand age and showed a correlation with the tree quality characteristics such as epicormic shoots, mode of branching, and branch size. Therefore, a longer rotation 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.

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Conflicts of Interest: The authors declare that they have no conflict of interest.

Appendix A

Table A1. Characteristics of selected plots and sample trees. 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). Stand age (SA). Stand density (SDE). Diameter at breast height (DBH).

Site	Altitude (m)	SD	SP	SG (%)	SA (Years)	SDE (trees/ha)	DBH (cm)	Bole Height (m)	Total Height (m)
P1	287	S	BO	17	23	811	18.0 ± 6.8	10.1 ± 5.1	16.6 ± 5.6
P2	308	W	BO	6	23	1005	18.8 ± 4.4	11.9 ± 3.0	18.6 ± 3.3
P3	309	E	BO	11	31	526	22.8 ± 6.8	7.6 ± 3.3	16.7 ± 4.6
P4	350	N	LS	17	13	837	15.2 ± 2.6	7.4 ± 2.0	14.2 ± 1.1
P5	376	W	MS	20	23	1096	15.8 ± 2.8	10.0 ± 2.6	15.6 ± 2.7
P6	407	N	US	30	11	731	16.3 ± 3.6	7.9 ± 1.7	13.9 ± 2.2
P7	445	E	CR	15	12	607	18.2 ± 4.6	6.0 ± 2.8	14.8 ± 2.8
P8	501	N	MS	19	12	967	17.4 ± 5.9	5.9 ± 2.3	13.1 ± 4.1
P9	511	N	MS	50	14	894	17.5 ± 5.4	7.0 ± 3.3	14.7 ± 4.0
P10	667	E	LS	17	23	1065	20.6 ± 5.8	11.1 ± 3.5	19.9 ± 3.9
P11	659	S	LS	17	20	980	15.7 ± 3.4	7.4 ± 2.0	14.3 ± 2.4
P12	671	S	MS	17	24	710	25.1 ± 7.0	10.5 ± 4.4	21.4 ± 4.7
P13	674	E	BO	12	11	1108	16.4 ± 3.6	8.6 ± 3.1	16.3 ± 2.8
P14	675	N	LS	27	10	1398	14.2 ± 3.2	8.3 ± 2.5	14.7 ± 2.6
P15	867	N	CR	17	13	2128	13.1 ± 3.3	7.2 ± 2.1	12.5 ± 2.1
P16	826	S	LS	20	12	1096	15.9 ± 5.8	8.0 ± 2.6	14.2 ± 3.5
P17	779	W	LS	47	10	1657	14.2 ± 3.7	9.1 ± 2.4	15.1 ± 2.5
P18	797	W	BO	3	13	1151	18.8 ± 2.9	10.1 ± 3.8	18.8 ± 1.7
P19	515	E	LS	43	21	898	16.6 ± 5.9	8.7 ± 3.3	13.9 ± 4.1
P20	485	E	LS	60	20	525	20.2 ± 4.8	10.9 ± 4.4	17.6 ± 4.5
P21	459	S	LS	15	23	1264	16.9 ± 3.4	12.5 ± 2.5	17.2 ± 2.4
P22	435	E	MS	24	12	1080	13.9 ± 3.4	8.9 ± 3.1	13.9 ± 3.2
P23	429	E	MS	40	13	1562	14.8 ± 2.8	9.5 ± 2.0	15.8 ± 1.5
P24	402	E	LS	33	24	737	21.6 ± 6.0	10.9 ± 3.3	17.9 ± 4.2
P25	412	W	MS	50	24	978	18.0 ± 4.3	9.6 ± 2.6	15.7 ± 2.1
P26	405	W	LS	62	24	1059	17.4 ± 3.1	11.3 ± 2.7	16.5 ± 2.6
P27	622	N	MS	20	14	943	15.8 ± 2.8	10.0 ± 2.1	15.1 ± 1.7
P28	648	W	MS	16	13	1063	16.2 ± 3.2	10.4 ± 2.1	15.5 ± 1.7
P29	389	N	BO	7	20	875	17.7 ± 3.8	12.4 ± 2.6	19.4 ± 3.7
P30	819	E	CR	10	12	980	14.6 ± 6.1	5.9 ± 2.6	11.3 ± 3.7
P31	292	W	BO	6	23	875	20.4 ± 5.7	14.3 ± 2.9	22.1 ± 4.0
P32	323	N	LS	45	24	1650	12.1 ± 2.6	9.2 ± 1.6	12.9 ± 2.2
P33	350	N	MS	40	22	1075	16.0 ± 3.5	11.4 ± 2.8	16.4 ± 3.5
P34	390	N	US	34	22	1350	14.1 ± 3.8	10.0 ± 2.3	14.2 ± 2.7
P35	432	S	LS	27	22	1150	17.2 ± 3.1	10.8 ± 2.3	17.6 ± 2.1
P36	452	S	MS	21	22	1300	16.4 ± 2.9	11.1 ± 2.9	17.2 ± 2.3
P37	473	S	US	23	23	1350	17.3 ± 2.8	10.9 ± 2.2	17.3 ± 1.7
P38	385	N	BO	9	14	625	19.5 ± 5.7	7.6 ± 3.0	17.1 ± 3.1
P39	401	E	LS	75	12	950	15.4 ± 5.4	8.2 ± 3.4	14.5 ± 4.2
P40	498	N	MS	40	11	1725	13.4 ± 3.0	8.5 ± 2.6	14.8 ± 2.3
P41	715	N	LS	40	11	1535	13.6 ± 3.1	7.0 ± 2.0	13.6 ± 2.1
P42	731	N	MS	56	11	1519	11.1 ± 2.4	4.7 ± 1.2	9.8 ± 1.5
P43	751	W	US	56	11	1748	13.1 ± 2.5	5.8 ± 1.5	12.6 ± 2.0
P44	629	E	BO	3	25	575	26.6 ± 8.0	11.3 ± 4.2	24.8 ± 6.1
P45	652	S	LS	35	10	1075	16.2 ± 3.7	6.4 ± 2.2	14.6 ± 1.7
P46	707	E	US	23	21	925	13.6 ± 3.7	4.2 ± 1.4	11.1 ± 1.9
P47	420	W	LS	65	12	1275	12.8 ± 3.3	7.1 ± 2.5	13.2 ± 2.8
P48	546	W	MS	53	13	1275	14.2 ± 4.1	7.5 ± 2.5	14.2 ± 1.9
P49	610	W	US	45	23	1175	17.6 ± 3.7	10.0 ± 2.9	16.7 ± 2.1
P50	758	E	CR	11	21	1375	16.2 ± 4.5	8.5 ± 2.9	16.6 ± 3.0
P51	802	W	LS	36	12	1150	16.3 ± 3.5	6.7 ± 2.1	16.9 ± 1.8
P52	386	N	BO	4	22	1325	14.3 ± 5.0	8.8 ± 3.2	14.5 ± 2.9
P53	369	N	LS	9	21	750	15.7 ± 4.9	9.5 ± 3.3	15.0 ± 4.6

Mean ± standard deviation.

Appendix B

Table A2. Partial correlation matrix among tree quality, stand characteristics, and site characteristics. Variables (VR). Stand age (SA). Stand density (SD). Altitude (Alt). Slope gradient (SG). Slope position (SP). Stem form (SF). Axis persistence (AP). Branch sizes (BS). Mode of branching (MB). Epicormic shoots (EP). Protuberant buds (PB). Buttressing (BU).

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

* Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed).

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