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**Centralblatt**  
für das gesamte  
Forstwesen**Branch development of eight-year-old *Mytilaria laosensis* plantations in response to planting density****Zweigentwicklung in achtjährigen *Mytilaria laosensis* Plantagen als Reaktion auf die Pflanzdichte**Zhi-hai Wang<sup>1,2</sup>, Niu Yu<sup>1</sup>, Rong-sheng Li<sup>\*</sup>, Wen-tao Zou<sup>1</sup>, Jin-chang Yang<sup>1</sup>, Guang-tian Yin<sup>1</sup>, Tai-lai Peng<sup>2</sup>**Keywords:** natural pruning, allometry, allocation patterns, branch characteristics, branch distribution, high-quality timber**Schlüsselbegriffe:** natürliche Astreinigung, Allometrie, Allokationsmuster, Eigenschaften von Zweigen, Verteilung der Zweig, astfreies Holz**Abstract**

Branch development is related to the formation of wood knots and affects timber quality and future market value of plantations and native forests alike. This study provides a theoretical basis and reference for knot-free timber production in a *Mytilaria laosensis* plantation. The branch diameter, length, angle, status (alive or dead), azimuth, and branch height under 12 m were measured for 60 dominant or co-dominant trees in response to five planting density treatments (625, 833, 1111, 1667, and 2500 stems ha<sup>-1</sup>). With increasing planting density from 625 to 2500 stems ha<sup>-1</sup>, the mean branch diameter and branch length decreased by 7.09% and 8.70% respectively. Dead and live branch angle decreased by 10.54% and 9.66% respectively, while number of living branches increased by 31.67% from 625 to 2500 stems ha<sup>-1</sup>. Analyzing the spatial distribution using branch azimuth, we discovered that branches pointing north were more abundant and had larger diameter, larger branch length,

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and higher branch angle than branches pointing south. Branch diameter, length, and number were positively related to the relative branch height. Our results underline that increasing the planting density from 625 to 2500 stems ha<sup>-1</sup> considerably affect branch growth. Thus, optimizing planting density when establishing *Mytilaria laosensis* plantations according to the forest management targets and future pruning can improve the timber quality and future value.

## Zusammenfassung

Die Zweigentwicklung hängt mit der Bildung von Astlöchern und Knoten zusammen, die sich wiederum auf die Holzqualität und den zukünftigen Marktwert eines Bestandes auswirken. Ziel dieser Studie war es, eine theoretische Grundlage und Referenz für astfreie Holzproduktion einer *Mytilaria laosensis* Plantage zu erarbeiten. Wir untersuchten den Astdurchmesser, die Astlänge, der Astwinkel, den Status (lebendig oder tot) der Äste, die Orientierung der Äste sowie die Asthöhe unter 12 m für 60 dominante oder kodominante Bäume in fünf Pflanzdichtevarianten (625, 833, 1111, 1667 und 2500 Stämme pro Hektar). Mit zunehmender Pflanzdichte von 625 auf 2500 Stämme ha<sup>-1</sup> nahm der mittlere Astdurchmesser und die Astlänge ab (-7.09 % bzw. -8.70 %). Der Winkel wurde zunehmend spitzer sowohl für lebende als auch tote Äste (-10.54 % bzw. -9.66 %) und die Anzahl der lebenden Äste wurde um 31.67 % größer mit zunehmender Pflanzdichte. Hinsichtlich der räumlichen Verteilung der Äste zeigt sich, dass Äste in nördlicher Richtung höhere Astdurchmesser und Astlänge und geringere Astwinkel aufwiesen als Äste in südlicher Richtung. Durchmesser, Länge und Anzahl der Äste standen in positivem Zusammenhang mit der relativen Asthöhe. Diese Ergebnisse legen nahe, dass eine Erhöhung der Pflanzdichte von 625 auf 2500 Stämme ha<sup>-1</sup> das Zweigwachstum deutlich beeinflusst. Die Wahl einer geeigneten Pflanzdichte beim Anlegen von *Mytilaria laosensis* Plantagen entsprechend den waldbaulichen Zielen und der Möglichkeit eines Astschnitts kann daher die Holzqualität und den Marktwert erhöhen.

## Introduction

*Mytilaria laosensis* Lecomte is a fast-growing, broad-leaved tree species that has straight stem form and growing in China's South Subtropical Region (Guo *et al.* 2006). This species has been widely used for forestry transformation and timber production (Lin *et al.* 2000; Chen *et al.* 2012). High-quality and large-diameter *M. laosensis* timber is becoming increasingly popular on the markets. However, the low natural pruning capacity of *M. laosensis* results in the formation of many knots negatively affecting wood development and utilization.

Branches are a vital part of the canopy and support the leaves and reproductive structures. Tree vitality, growth, and stem form are determined by the distribution and size of the branches (Biging and Dobbertin 1992), which in turn affects tree growth and the forest stand volume (Wang *et al.* 2007). The quality and value of timber depend

largely on the branches, as the diameter and number of branches along the stem are closely related to knot development (Hein 2008; Wang *et al.* 2016b). Dead branches, that are not shed, are gradually wrapped by the trunk cambium. Artificial pruning is a traditional forest management method critical for cultivating timber without knots, as it can reduce not only water and nutrient consumption (O'Hara 1991), but also the dead-knot defects of wood (Hein and Spiecker 2007). However, this method is time-consuming and costly. Therefore, studies of branch characteristics and distributions are critical to understand the growth characteristics and natural pruning. Stand density can control branch development and reduce costs for pruning and improve the quality of timber (Kellomäki *et al.* 1989).

Numerous factors influence branch development, including stand density (Mäkinen 1999a; Neilsen and Gerrand 1999; Alcorn *et al.* 2007), water and nutrient allocation to branches (Mäkinen *et al.* 2001), genotype (Alcorn *et al.* 2007; Gort *et al.* 2010), and other factors. For timber species, the lower part of stem below 6-8 m accounts for 90% of the future tree value (Kint *et al.* 2010). Thus, branch development in this region is essential for the early growth of trees and later utilization of the wood (Wang *et al.* 2018). Density control is an integral part of plantation management. Branch death and the speed of wound healing can be accelerated by high-density planting (Johansson 1992; Mäkinen 1999a). Although wide spacing is beneficial for the development of large-diameter wood, it can prolong branch death (Mäkinen 2002).

We previously investigated the effect of different planting densities on branch development in 'standard trees' of a six-year-old *M. laosensis* plantation (Wang *et al.* 2019). The definition of standard trees are trees with average diameter and tree height within the forest. Standard trees are representative for an unthinned forest. Selective target tree management and thinning has gained more attention from national and international forest researchers (e.g. De Freitas, 2004; David C, 2007; Liao SX, 2009). Dominant or co-dominant trees are the main crop trees for future harvesting, and suppressed trees may be removed by thinning. This approach can result in high-quality, large-diameter wood for the market, support sustainable forest management, and maximize the stability of forest ecosystems. We measured branch number, status (alive-dead), branch diameter, branch length, branch angle, azimuth, and height of first-order branches under 12 m of 60 dominant or co-dominant trees *M. laosensis* trees at different planting densities. We then tested the effect of five planting densities on branch development in this eight-year-old *M. laosensis* plantation. The results of the present study can provide an appropriate planting density for producing high-quality *M. laosensis* timber and reduce costs for artificial pruning.

## Materials and Methods

### Experimental Site

The spacing trial was located at the SanKeng experimental base, XiJiang Forest Farm, Yunfu City, Guangdong Province, China (23°07'N, 111°51'E, Figure 1). The site is approximately 150–270 m above sea level and lies on a north slope with lateritic soil (pH 4.0). The study area has a south subtropical monsoon climate with an average annual temperature of 21.2°C and mean annual rainfall of 1600 mm. The mean annual air humidity is approximately 82%. Five planting densities (2500 ha<sup>-1</sup> [2 × 2 m spacing], 1667 ha<sup>-1</sup> [2 × 3 m], 1111 ha<sup>-1</sup> [3 × 3 m], 833 ha<sup>-1</sup> [3 × 4 m], 625 ha<sup>-1</sup> [4 × 4 m]) were arranged in a randomized complete block design with four replicates in August 2010. The afforestation costs for five planting densities are shown in Table 1. Each plot was about 0.05 hectare. All trees in the experimental site were from the same provenance. One or two rows of trees of *M. laosensis* were planted around each plot for protection, so subject trees at plot edges were not influenced by neighboring plot circumstances.

Table 1: Plantation costs for five planting density treatments.

Tabelle 1: Plantagenkosten für fünf Pflanzdichteverarianten.

Planting density(stems ha <sup>-1</sup> )	Seedling cost (EUR ha <sup>-1</sup> )	Land clearing costs (EUR ha <sup>-1</sup> )	Digging plant holes (EUR ha <sup>-1</sup> )	Fertilizer application (EUR ha <sup>-1</sup> )	Phosphate fertilizer (EUR ha <sup>-1</sup> )	Planting fees (EUR ha <sup>-1</sup> )	Total afforestation cost (EUR ha <sup>-1</sup> )
625	93.6	280.8	171.6	34.3	39.1	74.1	693.4
833	124.8	280.8	228.7	45.8	52.0	93.6	825.6
1111	166.4	374.4	291.2	58.3	69.4	117.8	1077.4
1667	249.6	374.4	416.1	87.4	104.1	166.5	1397.9
2500	374.4	561.6	624.0	124.8	156.0	234.0	2074.8

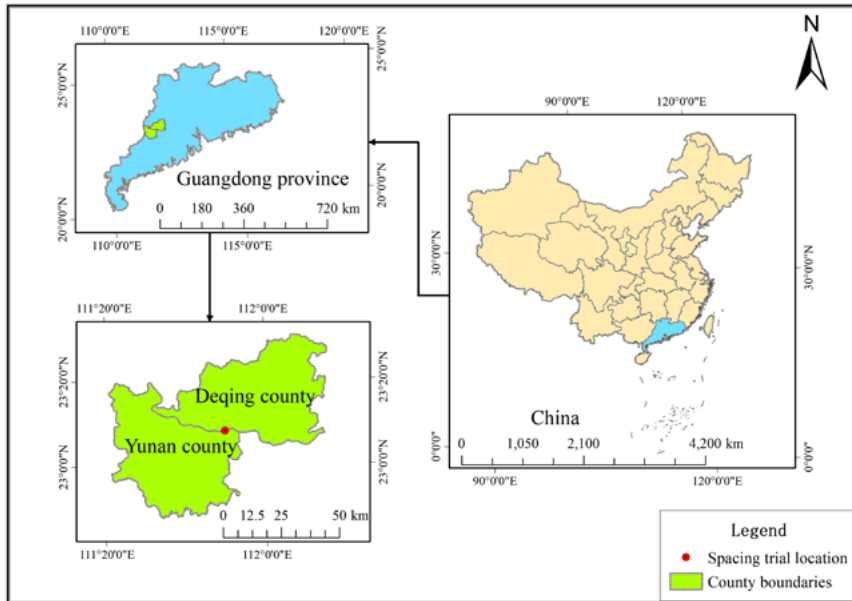


Figure 1: Location of *M. laosensis* spacing trial in Yunan County, Guangdong Province.

Abbildung 1: Die Lage des *M. laosensis* Pflanzdichteversuchs im Bezirk Yunan der Provinz Guangdong.

## Measurements

Between July 13 and September 17, 2018 we measured diameter at breast height, tree height, height of the first live branch, and height of the first dead branch. Branch quantity (number, proportion), morphology (diameter, length, and angle), position (height and azimuth), and status (dead or alive) under 12 m of tree height were investigated in 60 dominant or co-dominant trees at five planting densities. Four plots were established for each of the five planting densities (in total 20 plots). Three dominant or co-dominant trees per plot were sampled for branch measurement. All sample trees were surrounded by healthy neighboring trees in all directions and only had a single leader; the trees were disease-free and had no broken tops. For each branch along the stem of the sample trees, the following variables were measured: branch diameter (30 mm from the base of each branch), branch length (length of primary branches), branch angle (from the branch base to the stem; a value of  $0^\circ$  indicates a perpendicular branch), relative branch height, and branch azimuth ( $0$ – $360^\circ$ ). The azimuth was divided into eight intervals ( $0$ – $45^\circ$ ,  $46$ – $90^\circ$ ,  $91$ – $135^\circ$ ,  $136$ – $180^\circ$ ,  $181$ – $225^\circ$ ,  $226$ – $270^\circ$ ,  $271$ – $315^\circ$ , and  $316$ – $360^\circ$ ). The status of each branch (dead or alive) was recorded and the numbers of live and dead branches were counted from the ground to the top of the sample tree. Live branches were defined as branches with green leaves;

dead branches were defined as branches with no green leaves.

Researchers used an extendable ladder to measure all branches on each tree in situ. The branch height and branch length were measured with a steel tape after using chalk to mark the stem at every 1 m, branch diameter was measured with an electronic Vernier caliper, and branch angle was measured with an electronic protractor. In total, 4363 branches (3312 dead branches and 1051 live branches) were measured from 60 dominant or co-dominant trees (3 trees per plot  $\times$  4 plots per treatment  $\times$  5 treatments).

### Data Analysis

One-way analysis of variance (ANOVA) and Duncan's multiple range tests were performed to explore the differences in branch diameter, branch length, branch angle, number of live branches, and number of dead branches on stems below 12 m height among the five planting density treatments. The height of 12 m was used as the timber portion between the base of the stem up to a height of 6–8 m constitutes 90% of the future trees of commercial value (Kint *et al.* 2010). We used SPSS 20.0 (SPSS, Inc., Chicago, IL, USA) to determine the differences in height of first live branch, height of first dead branch, number of dead branches, number of live branches, number of total branches, and share of dead branches (ratio of dead branch quantity to total branches) among different treatments. We then analysed differences in branch diameter, branch length, branch angle, and branch numbers at different azimuth and heights by planting density.

## Results

### Tree growth and height of branches

Planting density significantly affected the stem diameter at breast height as well as height of first living branch for dominant or co-dominant trees in the *M. laosensis* plantation (Fig. 2). The stem diameter at breast height was negatively correlated with planting density from 22.0 to 18.0 cm, and stem diameter at breast height of 625 and 833 stems  $\text{ha}^{-1}$  treatment was significantly higher than those of other treatments ( $P < 0.01$ ). The height of first living branch increased with the increasing planting density from 6.8 to 9.4 m. The treatment of 1667 stems  $\text{ha}^{-1}$  was not significantly (6.8%) higher than that of 2500 stems  $\text{ha}^{-1}$  ( $P > 0.05$ ). Thus, our results indicated that planting density did not significantly affect the height of first dead branch and tree height of dominant or co-dominant trees.

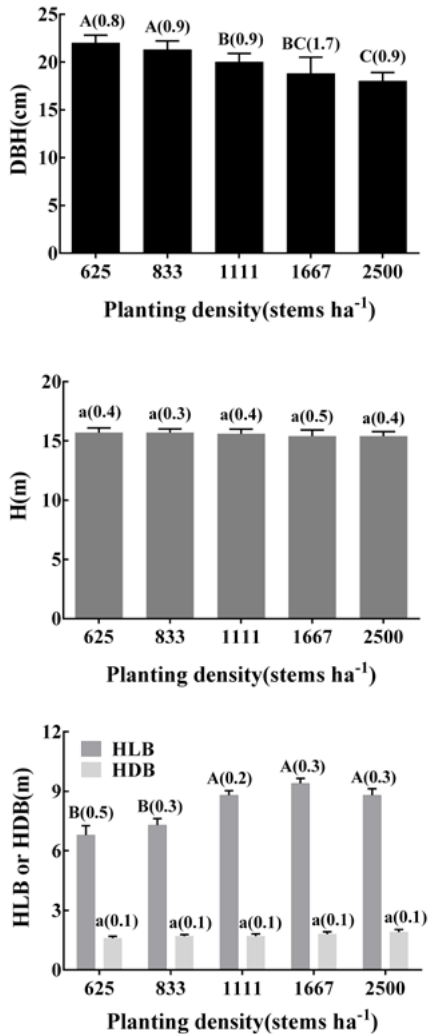


Figure 2: Diameter at breast height (DBH), tree height (H), height to first living branch (HLB) and height to dead branch (HDB) and associated analysis of variance of planting densities on dominant and co-dominant tree in a 8-year-old *M. laosensis* plantation. Standard error is shown in parentheses; different letters in the same column indicate significant differences between planting density treatments at the 0.01 level.

Abbildung 2: Brusthöhendurchmesser (DBH), Baumhöhe (H), Höhe des ersten lebenden Astes (HLB) und Höhe des ersten toten Astes (HDB) und deren Varianzanalyse bei unterschiedlichen Pflanzdichten von dominanten und kodominanten Bäumen einer 8-jährigen *M. laosensis* Plantage. Standardfehler in Klammer, unterschiedliche Buchstaben zeigen signifikante Unterschiede zwischen den Pflanzdichten bei 0.01 Signifikanzniveau.

### Branch quantity

Planting density had no significant effect on the number of total branches, number of dead branches, and number of dead branches under 12 m among the five density treatments ( $P > 0.05$ ). The number of live branches and number of live branches below 12 m were negatively correlated with planting density. The share of dead branches was positively correlated with increasing planting density. The highest density of dead branches was observed in the 2500 stems  $\text{ha}^{-1}$  treatment (Table 2), whereas there were no significant differences between the 1111, 1667, and 2500 stems  $\text{ha}^{-1}$  treatments.

Table 2: The main effect from analysis of variance of planting densities on branch number and share of dead branches of sample dominant or co-dominant trees of *M. laosensis* plantation. For details, we refer to table 1.

Tabelle 2: Der Haupteffekt der Varianzanalyse der Pflanzdichten auf die Anzahl der Äste und des Anteils abgestorbener Äste von dominanten und kodominanten Bäumen der *M. laosensis* Plantage. Für Details verweisen wir auf Tabelle 1.

		Planting density (stems $\text{ha}^{-1}$ )				
		625	833	1111	1667	2500
Branch number (tree <sup>-1</sup> )	Total	124(6)a	125(5)a	107(6)a	111(7)a	111(7)a
	Dead	65(6)a	65(4)a	62(6)a	67(5)a	70(7)a
	Live	59(4)A	60(3)A	45(2)B	44(2)B	41(3)B
Branch number below 12 meters	Total	91(5)a	88(5)a	75(4)a	80(5)a	83(5)a
	Dead	64(5)a	64(5)a	59(4)a	66(5)a	65(6)a
	Live	27(3)A	24(3)AB	16(2)B	14(2)B	18(3)AB
Share of dead branches (%)		51.93(2.95)B	51.43(2.01)B	57.46(2.58)AB	59.64(1.50)AB	62.49(2.77)A

### Branch diameter, length, and angle

Planting density significantly affected the mean branch diameter and branch length of dead branches under 12 m of the stem for *M. laosensis* ( $P < 0.01$ ). The mean branch diameter and branch length ranged from 17.95 to 19.32 mm and 1.47 to 1.61 m, respectively, and both showed a decrease with increased planting density. There were no significant differences in the mean dead branch diameter and branch length between 1667 and 2500 stems  $\text{ha}^{-1}$  treatments, and the branch diameter and branch length of the 1667 stems  $\text{ha}^{-1}$  treatment were only 2.1% and 1.4%, respectively, which were greater than those of the 2500 stems  $\text{ha}^{-1}$  treatment. However, the mean branch diameter and branch length of living branches were not significantly affected by



planting density. In addition, there was a significant linear positive relationship between branch diameter and branch length (Fig. 3).

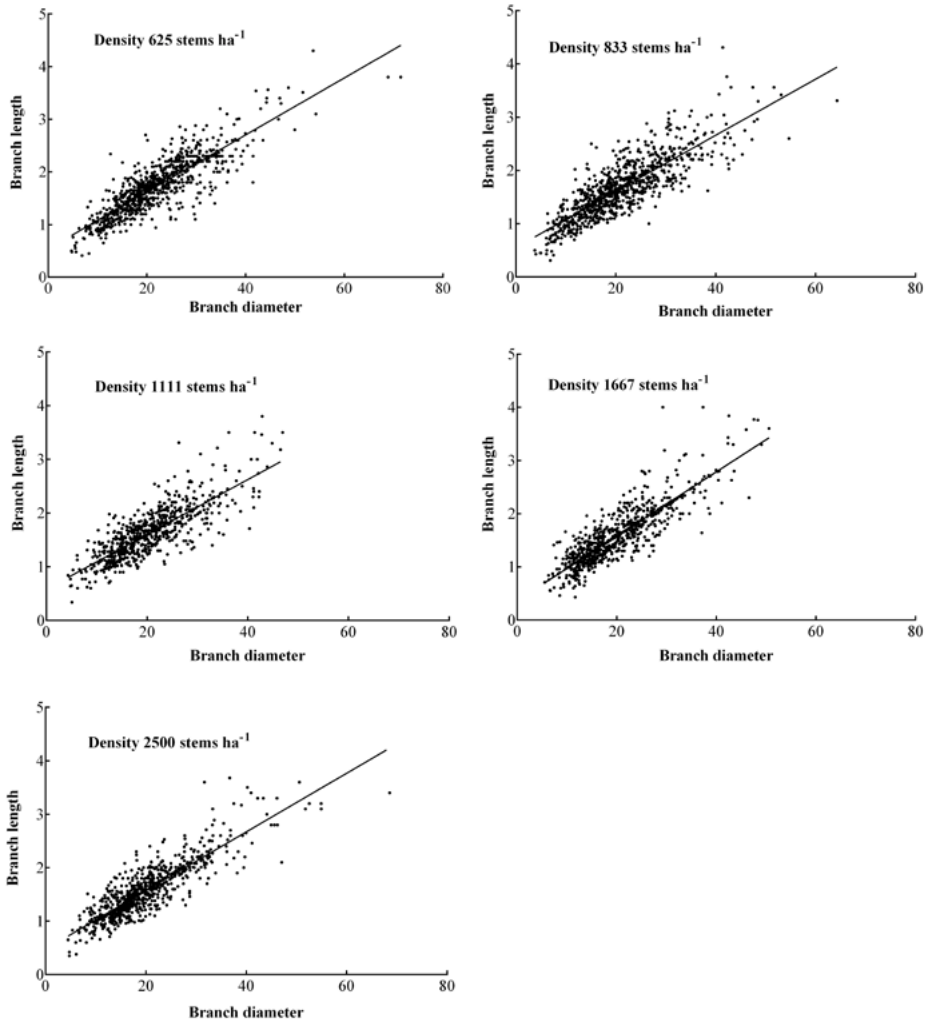


Figure 3: The positive correlation between branch diameter and branch length.

Abbildung 3: Die positive Korrelation zwischen Astdurchmesser und Astlänge.

The mean branch angles of both dead and living branches under 12 m were negatively correlated with planting density. The angles ranged from 50.85° to 56.84° and

45.91° to 50.82°, respectively. The branch angle at the lower density (625 and 833 stems ha<sup>-1</sup>) was significantly larger than that in the other treatments, indicating that competition limits horizontal space available for branch growth with increasing planting density. The branch angle of living branches was more acute than that of dead branches at the same planting density (Fig. 4).

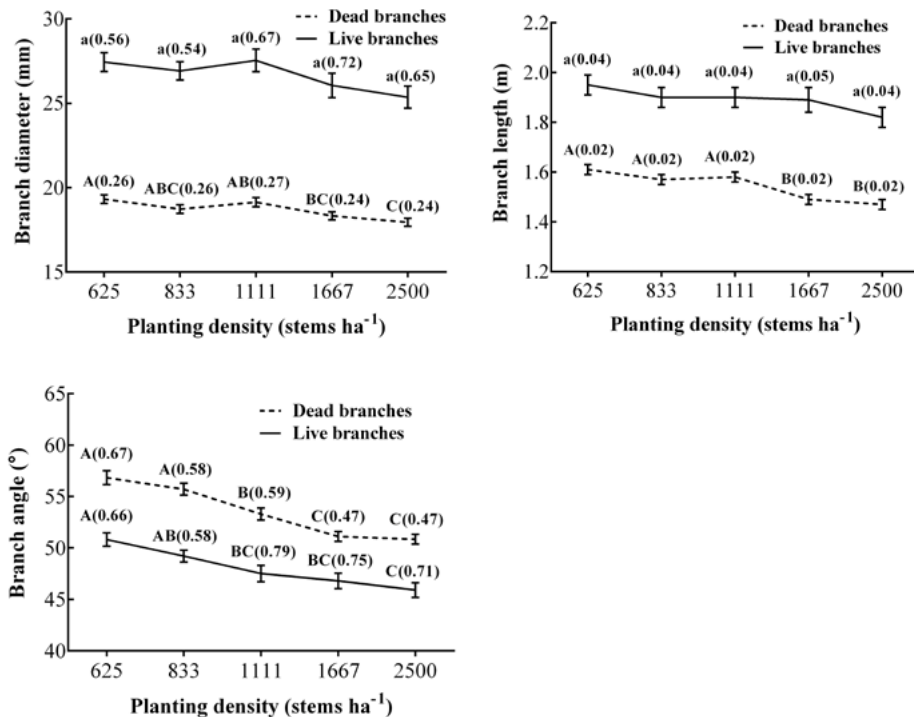


Figure 4: The main effect from analysis of variance of planting densities on branch diameter, length, and angle of dominant or co-dominant trees in the *M. laosensis* plantation. For details, we refer to table 1.

Abbildung 4: Der Haupteffekt aus der Varianzanalyse der Pflanzdichten auf Durchmesser, Länge und Winkel der Äste von dominanten oder kodominanten Bäume in der *M. laosensis* Plantage. Für Details verweisen wir auf Tabelle 1.

The proportions of branch number on the lower stem ( $\leq 12$  m height) of the *M. laosensis* plantation first increased and then decreased with an increasing range of branch diameter at the same planting density. The branch number at the same planting density decreased in the order 10–19.9 > 20–29.9 > 30–39.9 > 0–9.9 mm. The proportion of branches with a branch diameter greater than 40 mm was lowest, showing a value

of only 1–4% among the five planting density treatments. The proportion of branch number in the range of 10–19.9 mm was significantly different from that of 20–29.9 mm at medium and high densities (1111, 1667, and 2500 stems ha<sup>-1</sup>,  $P < 0.01$ ). We noted no significant difference at low densities (625 and 833 stems ha<sup>-1</sup>), indicating that the frequency of the number of larger branches increased with decreasing planting density (Table 3). In contrast, the number of branches with diameters of 20–29.9 mm and 30–39.9 mm tended to decrease with increasing planting density. However, the number of branches with a diameter of 10–19.9 mm increased with increasing planting density and reached a maximum in the 1667 stems ha<sup>-1</sup> planting density treatment.

Table 3: The main effect from analysis of variance of planting densities on proportion of branch number for different ranges of branch diameters of dominant or co-dominant trees in the *M. laosensis* plantation. For details, we refer to table 1.

Tabelle 3: Der Haupteffekt der Varianzanalyse der Pflanzdichte auf den Astanteil für verschiedene Astdurchmesserbereiche von dominanten oder kodominanten Bäume in der *M. laosensis* Plantage. Für Details verweisen wir auf Tabelle 1.

Range of branch diameter (mm)		Planting density(stems ha <sup>-1</sup> )				
		625	833	1111	1667	2500
Proportion of branch number (%)	0~9.9	4.79(1.13)B	7.92(0.57)BC	5.18(1.07)C	4.17(1.14)C	6.52(1.53)C
	10~19.9	40.55(3.96)A	41.4(2.11)A	45.38(3.29)A	52.28(4.72)A	51.94(4.62)A
	20~29.9	39.49(3.24)A	35.89(1.87)A	36.22(1.28)B	33.74(4.01)B	31.34(2.73)B
	30~39.9	12.4(1.96)B	11.46(1.61)B	10.01(1.67)C	8.04(1.45)C	8.15(1.79)C
	>40	2.78(1.03)B	3.34(1.44)C	3.22(0.68)C	1.77(0.35)C	2.05(0.87)C

### Branch Distribution

By analyzing the distribution of branch diameter, branch length, branch angle, and branch quantity with a different azimuth at the same planting density, we found that branches pointing towards the north had a larger diameter, longer branches, higher branch angle, and a higher number of branches than those pointing towards the south. The branch diameter and branch length of the five planting density treatments first decreased and then increased with an increasing azimuth angle. They reached a maximum value in the interval of 0–45° or 46–90° with good light conditions and decreased to a minimum value in the interval of 136–180° or 181–225°. Variance analysis showed no significant difference between the branch diameter and branch

length in azimuth intervals 0–45°, 46–90°, 91–135°, and 316–360°. The branch angle reached a maximum value in the interval of 0–45° or 316–360° and decreased to a minimum value in the interval of 136–180°. The influence of different azimuth on branch number was not significant for the five planting density treatments (Table 4). Although branch number was not significantly affected by planting density, this value first decreased and then increased with increasing azimuth.

The branch diameter and branch length under the same planting density increased with increasing relative branch height, after which there was no significant change. The branch diameter reached a maximum at 8–10 or 10–12 m and decreased to a minimum at 0–2 or 2–4 m. The extreme difference in the vertical direction of branch diameter between the five planting density treatments was 5.68–7.31 mm. The branch length reached a maximum at 6–8, 8–10, or 10–12 m and decreased to a minimum at 0–2 or 2–4 m. The variation amplitude of branch length at each density in the vertical direction was 0.16–0.38 m. The branch angle and branch number for the same density treatment increased with increasing relative branch height (Table 5).

Table 4: The main effect from analysis of variance of different azimuth on branch characteristics for *M. laosensis* under the same planting density. For details, we refer to table 1.

Tabelle 4: Der Haupteffekt aus der Varianzanalyse verschiedener Azimutwinkel auf die Asteigenschaften von *M. laosensis* unter der selben Pflanzdichte. Für Details verweisen wir auf Tabelle 1.

	Density (stems ha <sup>-1</sup> )	Azimuth range							
		0–45°	46–90°	91–135°	136–180°	181–225°	226–270°	271–315°	316–360°
Branch diameter (mm)	625	23.15(0.68)AB	22.88(0.77)AB	23.52(0.95)A	19.52(0.86)C	19.62(0.58)C	20.26(0.69)BC	21.47(0.77)ABC	22.09(0.82)ABC
	833	22.77(0.70)A	23.45(0.82)A	23.62(0.80)A	19.59(0.67)BC	17.88(0.65)C	18.48(0.52)C	19.55(0.78)BC	21.77(0.88)AB
	1 111	24.21(0.85)A	22.46(0.80)ABC	19.53(0.69)CDE	18.15(0.75)DE	16.95(0.66)E	20.23(0.73)BCD	21.25(0.75)ABC	22.94(0.80)AB
	1 667	20.08(0.62)ABC	22.31(0.81)A	21.03(0.86)AB	18.72(0.72)BC	17.96(0.70)C	17.52(0.55)C	19.8(0.73)ABC	19.77(0.60)ABC
2 500	22.02(0.69)A	21.32(0.69)AB	21.8(0.93)AB	19.12(0.73)BC	15.46(0.46)D	18.12(0.71)C	19.03(0.60)BC	20.18(0.78)ABC	
Branch length (m)	625	1.79(0.04)A	1.77(0.05)AB	1.83(0.06)A	1.59(0.05)B	1.59(0.04)B	1.63(0.04)AB	1.66(0.05)AB	1.77(0.05)AB
	833	1.75(0.04)AB	1.83(0.05)A	1.81(0.05)A	1.56(0.05)CD	1.48(0.04)D	1.52(0.04)CD	1.58(0.05)BCD	1.7(0.06)ABC
	1 111	1.87(0.05)A	1.73(0.05)AB	1.58(0.05)B	1.55(0.04)BC	1.39(0.05)C	1.59(0.05)B	1.7(0.05)AB	1.7(0.05)AB
	1 667	1.56(0.04)AB	1.71(0.06)A	1.69(0.07)A	1.47(0.04)B	1.45(0.05)B	1.44(0.04)B	1.55(0.05)AB	1.57(0.04)AB
2 500	1.71(0.04)A	1.67(0.04)AB	1.69(0.06)A	1.5(0.04)BC	1.28(0.03)D	1.44(0.04)CD	1.5(0.04)BC	1.61(0.05)ABC	
Branch angle (°)	625	61.7(1.16)AB	57.44(1.31)B	51.29(1.29)C	47.38(1.38)CD	45.79(1.38)D	47.66(1.15)CD	59.01(1.59)AB	62.99(1.22)A
	833	60.61(0.98)AB	56.22(1.22)B	50.11(1.2)C	43.69(1.32)D	47(1.26)CD	50.32(1.07)C	57.43(1.13)AB	61.06(1.24)A
	1 111	57.64(1.03)A	50.66(1.21)BC	45.86(1.27)CD	41.67(1.48)D	46.6(1.3)BC	51.49(1.56)B	57.63(1.17)A	59.53(1.28)A
	1 667	56.11(0.94)A	53.12(1.06)AB	47.56(0.98)CD	44.92(1.15)D	46.14(1.22)D	45.87(1.03)D	51.36(1.12)BC	56.41(1.14)A
2 500	54.43(0.86)A	48.4(1.01)B	46.62(1.14)BC	43.66(1.18)C	45.57(1.22)BC	45.55(0.9)BC	53.74(1.22)A	55.74(1.03)A	
Branch number	625	14(1)a	12(1)a	11(1)a	11(1)a	10(1)a	11(1)a	12(1)a	12(1)a
	833	13(1)a	12(1)a	10(1)a	10(1)a	11(1)a	10(1)a	11(1)a	11(1)a
	1 111	10(1)a	10(0)a	8(1)a	9(1)a	9(1)a	9(1)a	10(1)a	10(1)a
	1 667	11(1)a	10(1)a	10(1)a	9(1)a	8(1)a	11(1)a	10(1)a	11(1)a
	2 500	12(1)a	11(1)a	10(1)a	8(1)a	9(1)a	10(1)a	11(1)a	12(1)a

Table 5: The main effect from analysis of variance of different height on branch characteristics for *M. laosensis* under the same planting density. For details, we refer to table 1.

Tabelle 5: Der Haupteffekt aus der Varianzanalyse unterschiedlicher Höhe auf Asteigenschaften für *M. laosensis* unter der gleichen Pflanzdichte. Für Details verweisen wir auf Tabelle 1.

Branch characteristics	Planting densities (stems ha <sup>-2</sup> )	Height range (m)					
		0-2	2-4	4-6	6-8	8-10	10-12
Branch diameter (mm)	625	16.4(1.2)C	18.88(0.62)BC	20.77(0.62)AB	22.14(0.48)AB	22.79(0.61)A	22.75(0.67)A
	833	16.8(1.21)C	17.24(0.63)C	18.55(0.5)BC	21.31(0.56)AB	21.92(0.58)A	24.11(0.6)A
	1 111	17.93(1.23)BC	17.54(0.53)C	19.22(0.61)BC	20.8(0.62)ABC	21.18(0.55)AB	23.85(0.67)A
	1 667	15.98(1.12)C	17.15(0.55)BC	17.59(0.5)BC	18.77(0.45)BC	20.19(0.53)AB	23.15(0.6)A
	2 500	16.22(1.12)C	17.24(0.78)BC	17.06(0.47)BC	19.8(0.56)AB	21.9(0.64)A	21.47(0.47)A
Branch length (m)	625	1.44(0.1)B	1.6(0.05)AB	1.68(0.04)A	1.82(0.03)A	1.77(0.04)A	1.66(0.04)AB
	833	1.47(0.09)B	1.47(0.05)B	1.53(0.04)B	1.73(0.04)A	1.72(0.04)A	1.74(0.04)A
	1 111	1.53(0.06)b	1.54(0.04)b	1.59(0.04)ab	1.63(0.04)ab	1.69(0.04)ab	1.73(0.04)a
	1 667	1.38(0.09)B	1.46(0.04)B	1.46(0.04)B	1.53(0.03)AB	1.56(0.04)AB	1.72(0.04)A
	2 500	1.41(0.09)B	1.51(0.05)AB	1.43(0.03)B	1.58(0.04)AB	1.67(0.04)A	1.58(0.03)AB
Branch angle (°)	625	74.71(6.6)A	69.03(1.94)A	60.81(1.33)B	54(0.87)C	52.22(0.78)C	47.77(0.77)C
	833	78.26(2.47)A	68.08(1.57)B	60.85(1.06)C	51.59(0.79)D	49.75(0.64)DE	46.60(0.71)E
	1 111	63.94(3.19)A	63.61(1.65)A	53.69(1.41)B	53.2(0.99)B	49.53(0.79)BC	45.65(0.81)C
	1 667	59.22(2.98)A	55.77(1.36)AB	51.62(1.15)BC	48.6(0.87)C	49.4(0.74)C	48.18(0.68)C
	2 500	62.76(2.76)A	56.92(1.45)B	50.64(0.83)C	47.56(0.87)C	47.5(0.77)C	47.68(0.67)C
Branch number	625	2(0)D	11(1)C	15(2)BC	19(1)AB	23(1)A	21(1)A
	833	3(1)D	10(1)C	15(2)B	18(2)AB	22(1)A	20(1)AB
	1 111	2(1)C	9(1)B	11(1)B	17(1)A	18(1)A	18(1)A
	1 667	2(0)D	11(1)C	13(2)BC	16(2)AB	20(2)A	18(1)A
	2 500	2(1)C	10(2)B	15(2)AB	17(2)A	20(2)A	19(1)A

## Discussion

### Height of first branch

Planting density had a significant effect on the stem diameter at breast height of the sampled dominant or co-dominant trees. Our results indicate that tree growth in the horizontal direction was inhibited by competition. Tree height was not significantly affected by planting density. This result is consistent with those of studies of planting or initial density and spacing for tree species such as *Eucalyptus pilularis* and *E. cloeziana* (Alcorn *et al.* 2007), *Betula alnoides* (Wang *et al.* 2018), six-year-old *M. laosensis* (Zhang *et al.* 2018), and young *Pseudotsuga menziesii* (Mirbel) Franco (Li *et al.* 2007). However, analysis of *Pinus taeda* L. by Antón-Fernández (2011) revealed differences between the dominant height and spacing, and these differences did not disappear with age. This may be because of the different characteristics of the tree species. Zhang (2018) found that dominant height was significantly affected in the first six years of *M. laosensis* growth.

There was no significant relation between planting densities and height of first dead branch, whereas height of first living branch was significantly increased with increasing planting density. This confirmed the results of Sun's study (2014) of *Cunninghamia lanceolata*, Mäkinen's study (1999b) of *Pinus sylvestris*, and Alcorn's study (2007)

on *E. pilularis* and *E. cloeziana*, demonstrating that the mortality of branches on the lower stem increased with increasing stand density. However, the self-pruning ability of *M. laosensis* was lower than that of other tree species. Most dead branches on the lower stem were dry but not easily detached from the stem. Therefore, the capacity for self-pruning cannot be determined by the single indicator of the height of the first living branch but should also be comprehensively evaluated with multiple indicators, such as the height of the first dead branch and numbers of dead branches, living branches, and total branches.

### Branch quantity

Branch quantity, particularly the number of dead branches hanging on the stem was closely related to wood quality. The number of total branches and number of dead branches in the 8-year old *M. laosensis* plantation did not differ significantly between the five planting density treatments. This result agreed with those of previous studies on planting density for some broad-leaf tree species such as 8-year old and 14-year-old *B. alnoides* (Wang *et al.* 2016b, 2018) and *Fagus sylvatica* (Kint *et al.* 2010). Our previous study of standard trees of an 8-year old *M. laosensis* plantation, Mäkinen and Hein's study (2006) of *Picea abies* (L.) Karst, and Hein's study (2008) of *Pseudotsuga menziesii* also showed that the branch number was mainly controlled by genes and a low correlation with environmental factors. Therefore, cultivating non-knot or lower-knot timber of *M. laosensis* by using density to control the branch number cannot be considered.

The number of live branches decreased significantly with increasing planting density. This result agreed with those of studies of *E. pilularis* and *E. cloeziana* (Alcorn *et al.* 2007), and *B. alnoides* (Wang *et al.* 2018), indicating that the forest environment affected the preservation of living branches. Light conditions at low density are better than those in higher density forests. Branches in the lower density groups have a wider growth space and longer survival time.

### Branch characteristics

The branch diameter and branch length of dead branches were directly related to the formation of dead-knots. The branch diameter and branch length of dead branches of *M. laosensis* on the lower stem ( $\leq 12$  m height) decreased with increasing planting densities, whereas those of living branches were not significantly affected by planting densities. This result is consistent with those of studies of 10-year-old *B. alnoides* (Wang *et al.* 2016a), 20-year-old *Pinus sylvestris* (Gort *et al.* 2010), young *Pseudotsuga menziesii* (Mirbel) Franco (Newton *et al.* 2012), and 4-year-old *Eucalyptus robusta* (Alcorn *et al.* 2007). Our previous study of standard trees of *M. laosensis* also showed that branch diameter and branch length were negatively correlated with planting density. However, the difference in branch diameter and branch length of standard trees at different planting densities was mainly reflected in the lower density (625, 833 stems

ha<sup>-1</sup>), medium density (1111, 1667 stems ha<sup>-1</sup>), and higher density (2500 stems ha<sup>-1</sup>), whereas the difference in dominant or co-dominant trees was reflected at lower density (625, 833 and 1111 stems ha<sup>-1</sup>) and higher density (1667 and 2500 stems ha<sup>-1</sup>). Because branch size was significantly positively correlated with the size of dead-knots in the timber, afforestation at high density may inhibit increases in branch diameter and reduce dead-knot wood problems in *M. laosensis*. Low density was conducive to cultivation of large-diameter timber, whereas higher density inhibited increases in branch size. The differences in branch diameter and branch length between the two higher planting density treatments (1667 and 2500 stems ha<sup>-1</sup>) was not significant, whereas the afforestation cost of 1667 stems ha<sup>-1</sup> density treatment was 32.62% lower than that at the 2500 stems ha<sup>-1</sup> density.

The branch angle of both dead branches and living branches significantly increased with decreasing planting density. This may be because the reduction in planting density resulted in a larger space for growth and lowered the competition among branches in the horizontal direction. For *M. laosensis*, larger branches were heavier than smaller branches because of their larger number of leaves. Hence, the vertical pull of gravity may increase branch angle. Branch diameter was negatively related to planting density. Branches in the low-density forest were subjected to gravity in the vertical direction, which can also increase the angle between the branches and stem. In contrast, a larger branch angle made it easier for leaves to absorb sunlight. This result partly agrees with our study of standard trees of *M. laosensis* and Alcorn *et al.* (2007) and Henskens *et al.* (2001) studies of some eucalyptus species. However, Gort *et al.* (2010) evaluated *Pinus sylvestris* and found that branch angle was controlled by genes and not significantly affected by density. Wang *et al.* (2018) found in *B. alnoides* that although the branch angle was not significantly affected by planting density, lower planting density increased the branch angle.

### Branch Distribution

In the horizontal direction, the branch diameter, branch length, and branch angle of *M. laosensis* on the side exposed to higher levels of sun at the same planting density and different azimuth were larger than those in the shade. The branch number was not significantly affected by the different azimuth range. Wang *et al.* (2018) evaluated 5-year-old *B. alnoides* and Xiao *et al.* (2006) evaluated *Pinus sylvestris* L. var. *mongolica* Litv. and found that the azimuth had no discernible effect on the number of primary branches. This result differs from our previous study of standard trees of an 6-year old *M. laosensis* plantation, in which the branch number of standard trees first decreased and then increased significantly in the horizontal direction with increasing azimuth. The dominant or co-dominant trees were taller than the rest, enabling the capture of more sunlight. For the large trees, the distribution of branches around the trunk was affected by the prevailing light conditions but not significantly. These branch indicators generally reached a maximum value in the azimuth angle of 0–45° but the maximum value of some densities were observed in the azimuth of 316–360° inter-



val. This is because the slope of the test location is not an absolute north slope; there were subtle changes in the slope, which slowly changed the northeast slope into a northwest slope.

In the vertical direction, the branch number first increased gradually and then stabilized with increasing relative branch height. This result is consistent with that of Liu and Li (2007) for *Pinus sylvestris* L. var. *mongolica* Litv., where branches on the lower stems withered more than those in the crown. The branch diameter and branch length were significantly affected by the relative branch height. This finding partly agrees with those of studies of *Betula alnoides* (Wang *et al.* 2016b) and *E. pilularis* and *E. grandis* (Kearney *et al.* 2007), in which branch diameter and branch length increased significantly and branch angle decreased with increasing relative branch height. This also agrees with our previous study of standard trees of *M. laosensis*. For *Pseudotsuga menziesii* (Mirbel) Franco, Weiskittel *et al.* (2007) found that the branch angle was significantly negatively correlated with branch height.

### Economic implications

Our results suggest that planting density should be determined according to the purpose of forest management or forest density should be adjusted by intermediate felling to control the branch size. Artificial pruning should be performed in young *M. laosensis* plantation when the branch diameter is low and the branches are rapidly growing. At this stage, the wound heals quickly and is less likely to be infected after pruning. Afforestation at a density of 1667 stems ha<sup>-1</sup> can produce only approximately 2.1% larger branches than at 2500 stems ha<sup>-1</sup>, but 32.62% of the cost could be saved on afforestation compared to that at 2500 stems ha<sup>-1</sup>. Our findings provide a reference for density control, intensive management, and artificial pruning of *M. laosensis* plantations to enable production of high-quality and large-diameter timber. However, this was a static study of branch development in an 8-year-old *M. laosensis* plantation. As the fundamental aim of our study was to cultivate non-knot timber and improve timber quality, further studies of the relationship between phenotype features and knot formation are necessary. Additionally, the dynamic growth process of branch development with age should be evaluated.

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## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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