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Initial spacing of teak (*Tectona grandis*) in northern Lao PDR: Impacts on the growth of teak and companion crops

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Abstract

Teak (*Tectona grandis*) has been planted extensively by smallholder farmers in Luang Prabang province of northern Laos, primarily in small woodlots established at high initial stocking rates with little/no management until the largest trees are harvested selectively, commencing at 15–20 years after planting. This study used a Nelder wheel experiment planted in 2008, and measured annually after the end of the first 10 growing seasons, to evaluate the effects of the initial planting density on the growth of teak. The potential for intercropping established teak was also evaluated using this Nelder wheel, when the trees were 5–6 years of age, to emulate what might be achievable from companion cropping under an agroforestry system with teak. Individual tree diameter was maximised at the lowest initial stocking, but tree height showed optimum development between 637 and 1,020 trees ha^{-1}. While standing volume (m^3 ha^{-1}) was maximised at the highest initial stocking (2,424 trees ha^{-1}), merchantable volume maximised at initial stocking rates between 423 and 637 trees ha^{-1}. Companion cropping demonstrated that modest yields of maize, cassava and pigeon pea are possible under established teak, where the spacing between trees exceeds 8 m. Both maize and cassava achieved yields of over 2 t ha^{-1} with a spacing of 8 m between trees, while pigeon pea achieved 3 t ha^{-1} at 10 m spacing between trees. These results demonstrate that the adoption of reduced initial stocking rates for teak (i.e. below 1000 trees ha^{-1}) can significantly increase the growth rates of teak, improving individual tree volumes, and potentially reducing time to commercial harvest. Further, where row spacing is at least 8–10 m, these results suggest that extended periods of companion cropping (2–6 years after planting) may be possible. Finally, given that Lao farmers are reluctant to adopt pre-commercial thinning, serious consideration should be given to the promotion of simple, regimes for teak woodlots using an initial stocking rate of around 600 trees ha^{-1}. Alleys widths of 10 m are recommended for farmers wishing to establish grow teak in an agroforestry system and extend the period for companion cropping. Nevertheless, revision of Government of Lao policy frameworks are required to support the adoption of more appropriate initial spacing in teak woodlots and agroforestry systems by smallholders.

Keywords: Agroforestry systems; Competition; High-quality timber; Intercropping; Smallholders

1 Introduction

Teak (*Tectona grandis* L. f) is a tropical hardwood, with a natural distribution which includes the south-east Asian countries of Myanmar, Thailand and Lao Peoples Democratic Republic (Kaosa-ard, 1981). In Lao PDR (or Laos), teak occurs naturally only in the provinces of Sayabouli and Bokeo bordering Thailand and Myanmar, but has been planted extensively in the provinces of Luang Prabang, Sayabouli, and Champasak. With the exception of rubber, teak is currently the most important plantation forest tree species in Laos, with strong domestic and international markets for the timber. The planting of teak has been promoted in Laos since the early 1950s; however, the greatest adoption has occurred during the last 35 years (Midgley et al., 2007). In 1976, there was only 1~~,~~140 ha of teak plantation, and this reached 6~~,~~250 ha in 1991 (Hansen et al., 1997; Kolmert, 2001). The current total area of planted teak in Laos is not well defined, but is most likely to be between 30,000 and 40,000 ha: approximately 15,000 ha in Luang Prabang province (Smith et al., 2017), with up to 10,000 ha in both Sayabouli and Champasak provinces (Bolaven plateau) (Hilary Smith, *pers. comm.*) with perhaps 3~~,~~000 ~~to~~ –5~~,~~000 ha of teak in the remainder of Laos. These teak woodlands are frequently less than one hectare in size, and were mostly planted by smallholders in conjunction with the cultivation of upland fields following a long fallow.

Teak woodlots in Laos have been established at relatively high initial stand densities, e.g. 2 × 2 m (2~~,~~500 trees ha^{-1}) was commonly used, and more recently 3 × 3 m (1100 tree ha^{-1}) has been the recommended initial spacing. Once planted, farmers are reluctant to remove trees unless the timber can be sold. This means that woodlots are frequently left at high stocking levels through to least 15 years after planting, and then only thinned from above, by the progressive removal of the largest trees as they reach a size that can be sold as sawlogs. These high stocking rates reflect a poor understanding of teak siliviculture and the absence of reliable information available to smallholders in the Lao language. There is prevailing view amongst Lao farmers that all teak trees are potentially marketable, with woodlot value based on the number of standing trees rather than the standing volume, the current value of the timber, or the future growth potential of the woodlot. Failure to implement appropriate silvicultural practices has been identified as a major constraint to the growth potential and quality of teak in Laos (Hansen et al., 2007; Midgley et al., 2007).

The planting period for teak corresponds to the beginning of the annual wet season, with stumps (i.e. bare-root planting stock produced from seedlings raised in nursery beds) planted in late April/early May, and seedlings raised in polybags planted in late May/early June. It is a common practice to intercrop teak with annual crops such as upland rice (*Oriza sativa*), maize (*Zea maize*), or Job's tears (*Coix lacryma-jobi*) during the first one or two years of the teak woodlot. These companion crops generate income and off-set the cost of weed control. However, Lao farmers will usually not grow annual crops with teak after the second growing season due to a lack of labour and reduced crop yield associated with the shade generated by the teak canopy at conventional stocking rates of 1~~,~~100 or more trees per hectare. Recently, Lao smallholders have been attracted to growing teak in alley cropping systems to extend the period during which companion crops can be grown successfully. However, evidence-based, extension and training is required to support adoption.

Regarding the trade of teak trees, smallholders most commonly sell individual standing trees to middlemen on an *ad hoc* basis as needs arise. These middlemen can be acting independently or as agents of sawmills. The middleman covers all costs associated with felling, transport of logs from the forest to the road-side and then to the mill. Farmers are paid prior to harvest in cash, but the price can be low, and is negotiated depending on tree size, the relative ease/difficulty of access, and the distance of the trees the from road-side. Typically, the minimum merchantable size is 50–60 cm in girth at approximately 2 m above ground, thereby achieving a minimum small-end diameter of 12–15 cm under bark in the first 2.3 m log. However, such trees have relatively low timber values ($ m^{-3}) as well as having small log volumes. The value of individual trees increases significantly with girth, with larger logs attracting a higher price per cubic metre. As a result of the prevalance of high initial stocking rates and no pre-commercial thinning, harvesting ~~usally~~usually does not commence until at least 15 years after planting, with younger woodlots having few trees of merchantable diameter (Kolmert, 2001). Few teak woodlots are retained past 35 years of age in Laos.

In contrast to the 'boom' years of the 1990s and early 2000s, relatively few new areas are currently being planted with teak in northern Laos. As such the current area of planted teak is not expected to increase in the short term, and may be declining. To make the growing of teak more attractive to Lao smallholders, better planting stock, improved genetic material and appropriate silvicultural methods are required to improve the yield and value of teak woodlots, reduce or eliminate the production of small-dimension/low-value trees, and to reduce the time from planting to the first commercial harvest. Agroforestry (alley cropping) systems involving the cultivation of teak with fodder production (for cattle, buffalo or goats) and/or high-value perennial crops (e.g. banana, pineapple, fruit trees, coffee, nuts, etc.), may also make teak cultivation more attractive to smallholders in Laos by extending the period where companion cropping is viable. However, these agroforestry systems have higher labour inputs and supporting information is required.

Focused on enhancing on-farm incomes through improved teak production systems, the Australian Centre for International Agriculture Research (ACIAR) funded silviculture and agroforestry teak-based projects between 2008 and 2018. As part of these projects, the effects of initial planting density on the growth of teak and the interaction with companion crops were evaluated using a Nelder wheel experiment (Nelder, 1962).

The objectives of this manuscript are to: (i) present data on the productivity of teak across the first ten growing seasons and the yields of companion crops over a two-year period in this Nelder wheel; and, (ii) in the light of these results, discuss teak silviculture that may be more appropriate for smallholders in Laos.

2 Materials and methods

2.1 Experiment site

The experiment was conducted at the Northern Agriculture and Forestry College (NAFC) in Luang Prabang district, Luang Prabang province, Lao PDR (19.98983°N, 102.24369°E). The site forms part of the alluvial floodplain of the Mekong River characterized as a black clay loam. The climate is tropical with an average rainfall of 1~~,~~615 mm per annum and distributed following a monsoon pattern, with >90% occurring in the six-month period from May to October. The highest average maximum and minimum temperatures of 36.6 and 22.4 °C occur in April, while the lowest are 26.7 and 12.7 °C in January (Lao Statistics Bureau, 2017).

2.2 Site preparation and planting material

Prior to planting, the site was prepared by hand slashing of weeds, followed by ploughing using a 4WD tractor and a seven disc offset plough. Teak was planted on 29 July 2008 using stumps (15-month-old bare-root seedlings) produced from seeds sourced locally of two provenances; one 'Luang Prabang' collected in nearby plantations of teak, and the second 'Myanmar' from a small plantation of this provenance established at the Kengben Teak Improvement Research Station.

2.3 Experimental design

Teak was planted using a Nelder Wheel design (Nelder, 1962) in the same configuration as used by Lamb and Borschmann (1998). Ten concentric rings of trees were planted with radii of 6, 7.9, 10, 12.5, 16, 20, 25, 32, 40 and 50 m. Each ring contained 24 trees located equidistantly around the circumference, giving approximately square spacings between trees, ranging in stocking from 106 to 2~~,~~424 trees ha^{-1} (Table 1, Fig. 1, Photo 1 and Video 1). In this design, the angles between spokes were set at 15° (0.2617 rad) generating 24 spokes. Each quadrant contained six spokes, and each provenance was planted along alternate spokes (Figs. 1 and 2). The Nelder experiment occupied an area of 0.78 ha with a total 240 trees, including the inner and outermost rings which were used as guard (or isolation) trees ~~(see Photo 2)~~.

Table 1 Radial length (spoke), ring tree spacing, equivalent tree stocking and potential growing space in the Nelder wheel experiment.

Radius	Radius length (m)	Stocking rate (trees ha^{-1})	Growing space (m^2 tree^{-1})	Spacing between rings (m)	Spacing between spokes (m)
1†	6	–	–	–	–
2	7.9	2424	4.1	2.1	2.1
3	10	1659	6	2.5	2.6
4	12.5	1020	9.8	3.5	3.3
5	16	637	15.7	4	4.2
6	20	423	23.6	5	5.2
7	25	255	39.2	7	6.5
8	32	159	62.8	8	8.4
9	40	106	94.5	10	10.4
10†	50	–	–	–	–

† Inner and outer rings are guard rows.

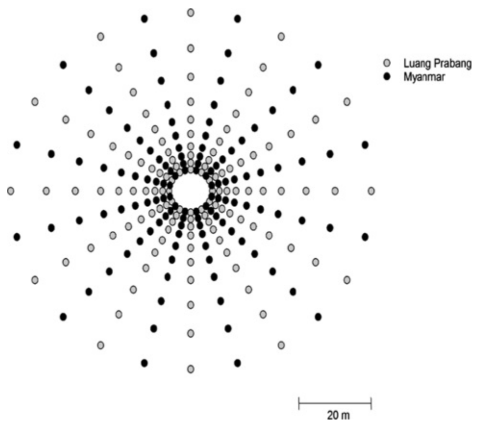

Fig. 1 Schematic representation of the Nelder wheel experiment established at the Northern Agriculture and Forestry College at Luang Prabang, Laos. Teak trees of provenances are shown in different colours: Luang Prabang (grey dots) and Myanmar (black dots).

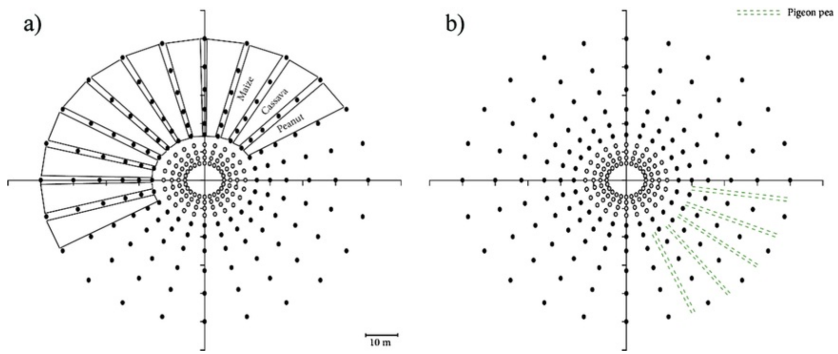

Fig. 2 Schematic representation of the intercropping experiments conducted in the Nelder wheel in 2013 with maize, cassava and peanut (a), and with pigeon pea during 2014–2015 (b).

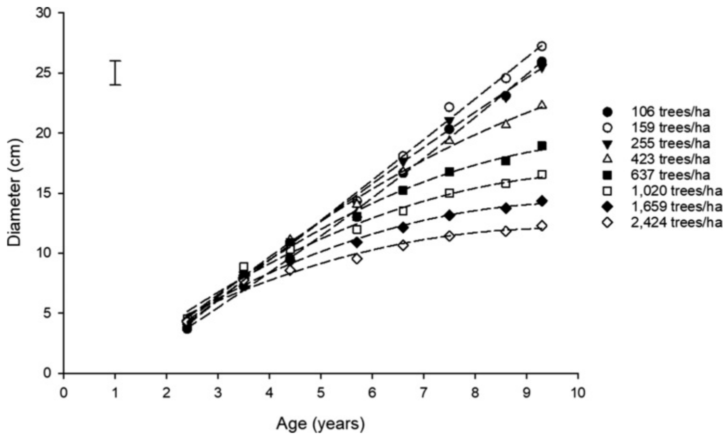

Fig. 3 Average diameter ($n = 4$) of teak grown at different ~~intial~~initial densities. Regression equations were fitted for each density ($n = 32$, dash lines). The regression models and their coefficients of determination (R^2) are summarised in Appendix B. The error bar indicates LSD ($P = 0.05$) based on the analysis of all density treatments at 9.3 years.

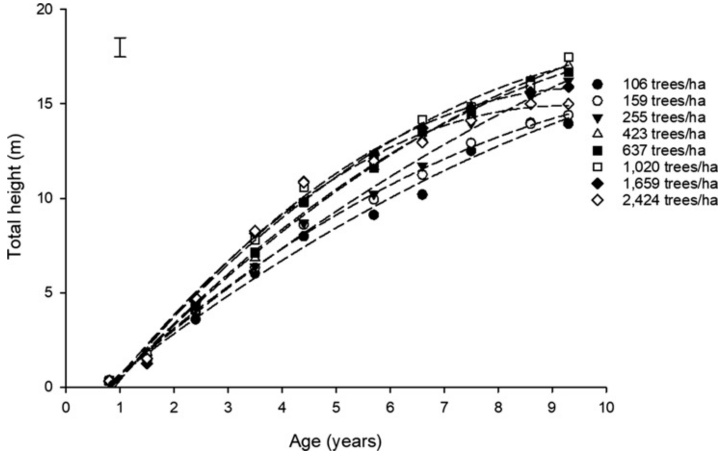

Fig. 4 Average individual total height ($n = 4$) of teak grown at different initial densities. Regression equations were fitted for each density ($n = 40$, dash lines). The regression models and their coefficients of determination (R^2) are summarised in Appendix C. The error bar indicates LSD ($P = 0.05$) based on the analysis of all density treatments at 9.3 years.

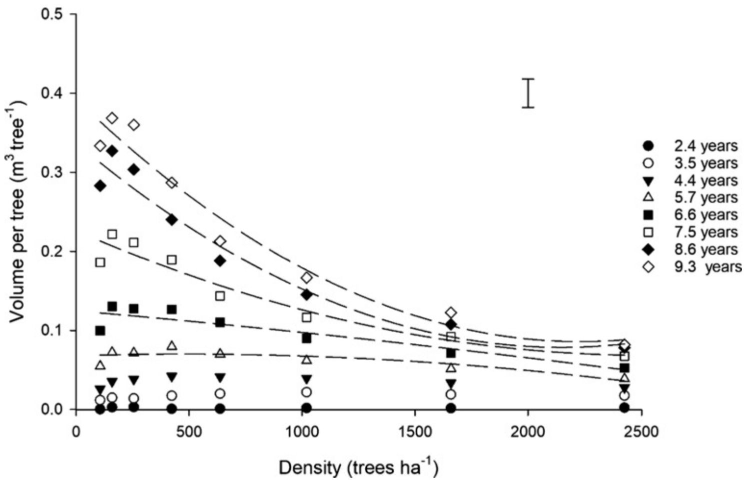

Fig. 5 Average volume per tree (m^3 $tree^{-1}$; $n = 4$) of teak grown at different initial densities. Regression equations were fitted for each density ($n = 32$, ≥ 5.7 years; dash lines). The models and regression statistics are summarised in Appendix D. The error bar indicates the LSD ($P = 0.05$) based on the analysis of all stocking treatments at 9.3 years.

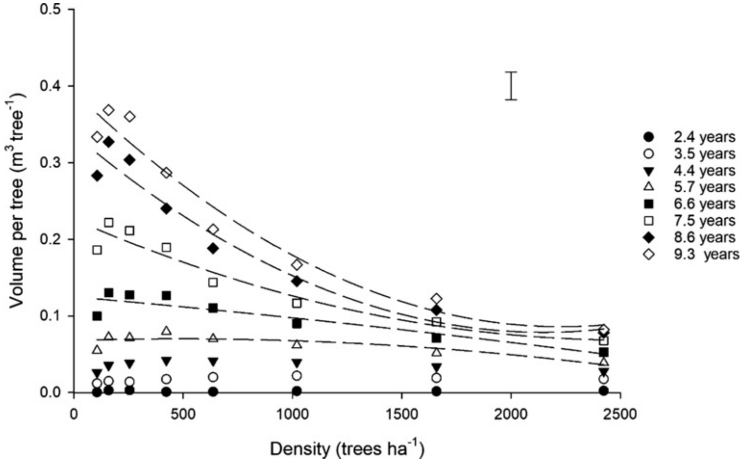

Fig. 6 Average total volume (m^3 ha^{-1}; $n = 4$) of teak grown at different tree initial densities. Regression equations were fitted for each density ($n = 32$; dash lines). All models and regression statistics are shown in Appendix E. The error bar indicates the LSD ($P = 0.05$) based on the analysis of all stocking treatments at 9.3 years.

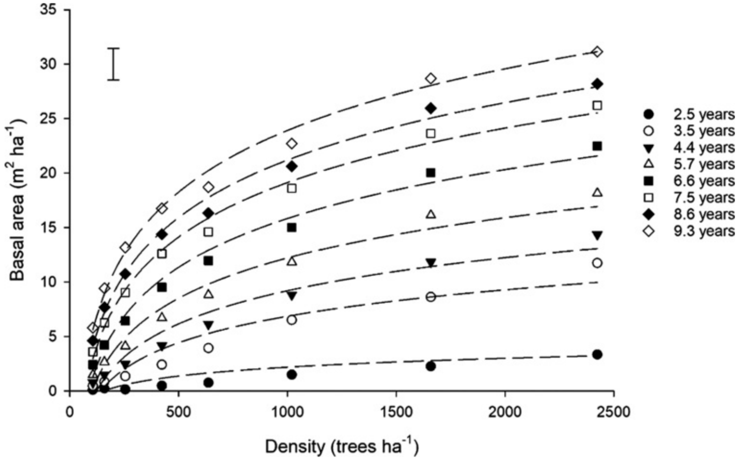

Fig. 7 Average base area (m^2 ha^{-1}; $n = 4$) of teak grown at different tree initial densities. Regression equations were fitted for each density ($n = 32$; dashed lines), and the estimated regression model and their coefficient of determination (R^2) are shown only for trees of 9.3 years-old (solid line). All models and regression statistics are shown in Appendix F. The error bar indicates LSD ($P = 0.05$) based on the analysis of all stocking treatments at 9.3 years.

Photo 1 Aerial view of the Nelder wheel experiment (6 November 2017) at 9.3 years-old.

Photo 2 Maize intercropped in the Nelder wheel experiment (5/07/2013).

Form pruning was applied during the first and second growing season. Stem pruning was applied at year 6 and 7, removing branches up to 4 and 6 m respectively. During the establishment of the experiment, any dead trees were replaced with stumps of the same provenance raised in polybags, thereby achieving 100% survival at the end of the first year. Tree mortality was observed at 5.7 years of age at 106 trees ha^{-1} (1 tree); 8.6 years of age at 2,424 trees ha^{-1} (1 tree); and, at 9.3 years of age at 106, 637, 1020 and 2,424 trees ha^{-1} (1 tree at each density).

2.4 Intercropping experiments

Maize (*Zea mays*), cassava (*Manihot esculenta*) and peanut (*Arachis hypogaea*) were planted in June 2013, five years after planting the teak. Due to the high level of shade in the inner rings of the Nelder experiment, the crops were grown between the spokes starting from radius five through to radius ten, therefore the crops were established in alleys from 4 to 10 m apart (Table 1, Fig. 2a, Photo 2). The area between twelve tree spokes were planted on 27 June 2013 using the recommended plant density for maize (0.5 × 0.5 m), cassava (1 × 1 m) and peanut (0.3 × 0.3 m) with four-time replication. Pigeon pea (*Cajanus cajan*), was planted in double rows (1.5 × 1.5 m) along the spokes on 5 May 2014 (Fig. 2b). The double-row was replicated in nine spokes, from radii six to ten along spokes of the experiment.

2.5 Tree measurement

Total height (Ht, m) and the diameter at breast height (DBH, cm) over bark, of each tree were measured annually at 0.8 (2/05/2009), 1.5 (25/01/2010), 2.4 (12/12/2010), 3.5 (10/01/2012), 4.4 (29/12/2012), 5.7 (2/04/2014), 6.6

(20/02/2015), 7.5 (18/01/2016), 8.6 (20/02/2017) and 9.3 (6/11/2017) years after planting. Due to the marked wet/dry seasons, these measurements correspond to the growth achieved after the first through to the tenth growing seasons respectively. Height was measured using a measuring pole in the first and second years and a ultrasonic hypsometer (Haglof Vertex III) in the following years. The DBH was measured using a diameter tape.

The volume per tree (Vol, m^3) was estimated using equation developed for teak in Luang Prabang province (Dieters et al., 2014):

$$\text{Vol} = \frac{0.4320\pi(DBH)^2 Ht}{40,000} \quad (1)$$

The volume per unit area ($m^3\,ha^{-1}$) and basal area ($m^2\,ha^{-1}$) were calculated by multiplying the average individual tree volume ($m^3\,tree^{-1}$) or basal area ($m^2\,tree^{-1}$) at each stocking level by the equivalent stand density (trees ha^{-1}).

Merchantable timber volume (Vol_m, m^3) was estimated using the Eq. (2) suggested by Pérez and Kanninen (2003):

$$\text{Vol}_m = \text{Vol}\left(1 - 0.7839\left(d_m\right)^{2.4149}(\text{DBH})^{-2.4175}\right) \quad (2)$$

where; Vol_m is the merchantable volume per stem (m^3), Vol is the total stem volume estimated using Eq. (1), d_m is the upper stem merchantability limit expressed as a minimum diameter in cm (i.e. 15 cm over bark in Laos), and all other variables as defined above. The merchantable volume per unit area ($m^3\,ha^{-1}$) was estimated by multiplying the average merchantable volume per stem by the equivalent stand density (trees ha^{-1}).

To characterise the individual crown size, the crown diameter (CD) and crown base height (CBH) were measured on 18 August 2017, as described below:

- CD was obtained by measuring the horizontal distance using a tape measure from the maximum vertical projection of the edges of the canopy in two perpendicular directions.
- CBH was defined as the height above the soil surface to the first green branch in the crown and was measured using a height pole.

Stem straightness and stem roundness were also assessed at this time; however, as these traits did not vary significantly with stocking, results are not reported.

2.6 Yield of the companion crops

Maize, cassava and peanut were harvested in 2013, at 92, 110 and 98 days after sowing (DAS), at a time optimal for each crop. Sample plots were harvested mid-way between trees in adjacent spokes, at each spacing. The yield per unit area was estimated by harvesting subplots of 2 × 2 m (4 m^2) on each treatment and replication. On each replicate and for each density treatment, the total yield was recorded and expressed by unit area (kg m^{-2}). Similarly, the pigeon pea was harvested in 2015 after 346 DAS.

2.7 Statistical analysis

Spatial analysis was used to examine the effect of stocking on growth traits at different periods of measurement. This method was used to account for spatial correlation of the observations due to the spatial proximity (Affleck, 2001; Parrott et al. 2012). A 2-dimensional irregular grid of rows and columns was obtained by calculating the X and Y coordinates for each tree using the spoke angles and radius lengths (Table 1). Spatial analyses were undertaken for DBH, total height, basal area, individual tree and stand volume, crown diameter and crown base height, at each period of measurement using a mixed model where the X/Y grid is fitted as random effects, and *Block*, *Spacing*, *Provenance* and *Spacing*. *Provenance* fitted as fixed effects. *Block* refers to each quadrant of the experiment, *Spacing* refers to the initial planting density and *Provenance* refers to germplasm material. Least squares means for each block obtained from the spatial analysis were used to fit regression models (n = 32, i.e. 4 blocks × 8 spacings) to model the effect of initial planting density on individual tree volume ($m^3\,tree^{-1}$), stand volume ($m^3\,ha^{-1}$) and basal area ($m^2\,ha^{-1}$) for each year of measurement. A similar approach was used to fit regression models to determine the effect of age on DBH (cm) and total height (m) for each spacing (n = 40, i.e. 4 blocks × 10 measurement dates). Models with linear and quadratic terms (trees ha^{-1}) were tested and the most appropriate model selected (R^2 and root-mean-square error).

The yield of the companion crops across tree spacing were analysed using regression analyses. Individual regression models were fitted for each crop, and best fitting model selected.

All statistical analyses were carried out using GenStat 18, and the significance of the fixed effects were tested using F and Wald statistics (Payne et al., 2015). Figures were developed in SigmaPlot 13.0 (Systat Software, San Jose, CA).

3 Results

3.1 Tree growth

Trees from Myanmar and Luang Prabang provenance had similar diameter and total height growth across all ages evaluated, except for total height at the end of the second and third growing seasons were trees of Myanmar provenance were taller ($P < 0.01$). However, differences between provenances were not significant in subsequent years.

The average diameter per tree varied significantly according to tree density ($P < 0.001$). DBH decreased with an increment of stocking. During the second and third years, there were no significant differences ($P > 0.05$) in diameter according to stocking (Appendix A). However, in the following years, trees growing at lower stocking rates had significantly larger diameters compared to teak trees growing at high stocking (Fig. 3). The maximum mean annual increment (MAI) in diameter when calculated over the 10 growing seasons, occurred at 106 and159 trees ha^{-1} (3.36 cm year^{-1}), followed by 255, and 423 trees ha^{-1} that registered increments over 2 cm year^{-1}. The MAI of trees growing at 637, 1~~,~~020, 1~~,~~659 and 2~~,~~424 were 1.64, 1.27 and 1.02 and 0.76 cm year^{-1} respectively. Trees grown at stocking levels of 637 trees ha^{-1} and lower, achieved mean tree diameters exceeding 15 cm by 9.3 years (Fig. 3).

Significant differences ($P < 0.05$) in total height between stocking levels were observed from the second year, where trees growing at high densities were taller than trees at lower densities (Fig. 4 and Appendix A). At 9.3 years after planting, trees growing at stockings of 106, 159 and 423 trees ha^{-1} were significatively shorter than teak growing at higher densities. The maximum average tree height of 17.3 m was registered at a stocking of 1~~,~~020 trees ha^{-1} at 9.3 years after planting (Fig. 4).

There were no ~~signficiant~~significant differences in volume until after the fourth growing season. In all subsequent years, the volume per tree was significantly larger for trees grown at lower stocking levels (Fig. 5), following a similar pattern to that observed for tree diameter. Trees growing at 106 trees ha^{-1} had a threefold greater volume per tree compared to trees growing at 2~~,~~424 trees ha^{-1}. However, the inverse relationship was observed when the volume was expressed per unit area (m^3 ha^{-1}); while volume per tree decreased, the total volume per ha increased (Fig. 6).

The basal area (m^2 ha^{-1}) displayed similar patterns to that for volume per unit area (Fig. 7), which increased with the increment of tree stocking and age ($P < 0.05$).

The crown ~~diamter~~diameter measured at 2~~,~~424 trees ha^{-1} was 60% less than that of trees grown at 106 trees ha^{-1}. Conversely, the crown base height was greater at high tree density and it was least at low tree stocking (Table 2).

Table 2 Average crown diameter (CD) and crown base height (CBH) at eight different initial planting density measured at 9.1 years after planting.

Stocking rate (trees ha^{-1})	CD (m)	CBH (m)
2424	2.31 ± 0.18	8.91 ± 0.32
1659	2.65 ± 0.22	8.35 ± 0.32
1020	2.98 ± 0.24	8.45 ± 0.34
637	3.73 ± 0.29	7.27 ± 0.43
423	4.35 ± 0.27	7.32 ± 0.32
255	5.26 ± 0.31	6.91 ± 0.17
159	6.26 ± 0.15	6.20 ± 0.18
106	5.87 ± 0.25	5.84 ± 0.24

The estimated merchantable volumes per unit area (m^3 ha^{-1}) are shown in Table 3. At 9.3 years of age, the highest merchantable volume per hectare was obtained at 423 trees ha^{-1} (85.6 m^3 ha^{-1}), followed by 637 and 255 trees ha^{-1} which reached 77.9 and 72.5 m^3 ha^{-1} respectively. However, trees growing at 2424 trees ha^{-1} had zero merchantable volume (Table 3).

Table 3 Average estimated average merchantable volume per tree (m^3 tree^{-1}) and per hectare (m^3 ha^{-1}) of teak growing at 9.3 years-old.

Stocking (trees ha^{-1})	Merchantable volume (m^3 tree^{-1})	Merchantable volume (m^3 ha^{-1})
106	0.25	26.6
159	0.30	47.0
255	0.28	71.6
423	0.20	85.3
[illegible]	[illegible]	[illegible]

637	0.11	71.7
1020	0.04	40.8
1659	0.01	16.6
2424	0	0

3.2 Yield of companion crops

Regression models for the yield of the four species intercropped with teak in the Nelder wheel are summarised in Table 4. The yield of cassava demonstrated a continuous improvement as spacing between trees increased, achieving a yield of over 4.2 t ha^{-1} at the largest distance between trees (10 m), meanwhile at 4 m spacing the yield was drastically reduced by 72% (Table 4). A similar result was observed for pigeon pea, where the highest yield of 2.6 t ha^{-1} was achieved at 10 m spacing and reduced by 76% at the 5 m spacing (Table 4). Maximum yield of maize was reached at 8 m spacing and reduced by 26% and 38% when grown at 10 and 4 m spacing respectively (Table 4). The overall yield of peanuts (i.e. ground nuts) was poor; observations of the crop indicated that the local variety used was highly susceptible to foliar diseases, and this most probably resulted in the very low yield and limited response to tree spacing that was observed here.

Table 4 Average yield of companion crops grown at different spacing between trees in the Nelder wheel experiment. Range (max. and min. yield) is presented in parenthesis based on the analysis of all treatments. Coefficient of determination (R^2), Root Mean Square Error (RMSE) and level of significance with * and ** indicating p-values of 0.01 and 0.001 respectively.

Crop yield	Spacing between trees (m)					R^2	RMSE	Sig
(t ha^{-1})	4 *m*	5 *m*	7 *m*	8 *m*	10 *m*			
Cassava	1.73	2.63	3.65	3.4	4.28	0.86	1.98	**
	(0.5–4.4)	(1.2–3.7)	(1.8–5.1)	(1.7–4.7)	(2.3–5.7)			
Maize	1.94	3.1	3.05	3.15	2.3	0.86	1.29	**
	(1.4–2.4)	(2.1–4.4)	(2.4–3.7)	(2.7–3.6)	(2.1–2.7)_			
Peanut	0.14	0.16	0.15	0.18	0.07	0.62	0.01	**
	(0.1–0.2)	(0.1–0.3)	(0.1 –0.2)	(0.1–0.3)	(0.1–0.1)			
Pigeon pea	–	0.7	0.21	0.77	2.63	0.45	1.81	*
		(0.1–0.2)	(0.1–0.5)	(0.3–1.5)	(0.5–5)			

4 Discussion and conclusions

4.1 Diameter and height

This Nelder wheel experiment clearly demonstrated the impact of stocking on the diameter and height growth of *Tectona grandis*. Trees grown at lower stocking (i.e. wider spacing) had larger diameter compared to those grown at the higher initial stocking rates, a trend that starting after the fourth year of growth. The experiment confirmed that the diameter of teak is adversely affected by high stocking rates, in common with other tree species, as a result of increasing competition for light and water and to a lesser extent nutrients (Cameron et al., 1989; Eastham and Rose, 1990; Lamb and Borschmann, 1998; Kuehne et al., 2013; Pachas et al., 2018). There is relatively little information in the published literature about the diameter response of *Tectona grandis* grown at initial stocking rates of 600 trees ha^{-1} and lower, with most studies established at initial stockings of 833 ~~to~~ –2~~,~~000 trees ha^{-1} (Ola-Adams, 1990; Kanninen et al., 2004; Passos et al., 2006, Zahabu et al., 2015; Noda and Himmapan, 2014). For example, Ola-Adams (1990) reported the influence of spacing on the diameter of teak in Nigeria, when established at initial spacing regimes equivalent to approximately 5~~,~~100, 2500, 1~~,~~190 and 640 trees ha^{-1}, with observed diameter increments of 0.99, 1.07, 1.3 and 1.47 cm year^{-1} respectively. Kollert and Kleine (2017) reported that diameter increments peaked between 3 and 5 cm year^{-1} in juvenile teak plantations of 3–6 years of age. In our experiment, increments >2 cm year^{-1} were obtained regardless of the stocking rates during the 4th and 5th growing seasons, but subsequently the average diameter increment was clearly affected by initial stand density. The maximum average increment (MAI) of 2.9 cm year^{-1} was observed in trees growing at 159 trees ha^{-1} after the 7.5 year measurement.

The total height of the teak was also significantly affected by the initial stocking. During the first growing season the average total height was similar regardless of the initial stocking. However, from the 2nd to 5th growing season the observed tree height increased with increasing stand density. The effect of stand density to promote height growth during the early stages of stand development has previously been reported and was associated with physiological responses that induce stem elongation to increase the chance of overtopping neighbouring trees (Telewski and Jaffe, 1986; Riley and Nixon, 1993, Kuehne et al., 2013).

From the 6th growing season, the effect of stand density on height was more evident, and at 9.3 years (after 10 growing seasons) the tallest trees (average of 17 m) were found at the intermediate stand densities (423–1020 trees ha^{-1}), while the shortest trees (average 14.8 m) were registered at lowest stockings (106–255 trees ha^{-1}). The lower mean height observed at the highest stocking levels reflects a higher proportion of suppressed and sub-dominant trees.

The average total height obtained in this Nelder experiment suggests that the experiment is located on a very productive site, with a site index (SI) of between 17 and 19 (at a base age of 15 years), while the maximum site index registered in smallholder woodlots of Luang Prabang province by Dieters et al. (2014) was 19. Nonetheless, similar patterns relating to the impact of initial stocking on the height and diameter of teak can be expected on sites with lower site index, but achieved at later ages. Where trees are growing slower, on sites with lower fertility, inter-tree competition will commence at a later age.

4.2 Crown size and stem form

Stand density had a significative effect on the crown diameter as a result of inter-tree competition. By the end of the tenth growing season, full canopy closure was observed at stockings equal and over 423 trees ha^{-1}, reflecting high levels of competition. Trees grown at the lowest stocking (106 trees ha^{-1}) had greater crown diameter (~6 m), but also thicker and larger live branches (data not reported). Increasing stand density reduced the crown diameter to 2.3 m (at 2424 trees ha^{-1}), and increased the proportion of dead branches on the main stem and the consequent increase in the height to the first live branches (over ~9 m). These results and observations confirmed that teak is intolerant of inter-tree competition and crowns of adjacent trees do not intermingle substantially. Pérez and Kanninen (2003) studied the above ground biomass of 16 plantation *T. grandis* (8–47 year-old) in Costa Rica, and found a positive and strong relationship between crown diameter and DBH. Conversely, Ola-Adams (1990) did not find that the initial spacing affected the crown diameter in 18-year-old teak in south-western Nigeria, although the crown diameter at 3.96 × 3.96 m was slightly larger than at 1.37 × 1.37 m (i.e. 4.3 and 3.6 m respectively). A comparison of the crown diameters (Table 2) and the distance between trees in adjacent spokes (Table 1) in this Nelder wheel experiment, suggests that crown expansion was constrained by inter-tree competition in all density levels from 637 trees ha^{-1} and higher. Only at the lower density levels was the crown diameter 1 m or more less than the spacing between trees in adjacent spokes of the Nelder wheel (i.e. indicating space for continued crown expansion).

4.3 Basal area and volume

Basal area (m^2 ha^{-1}) was highly dependent on stand density. The maximum basal area of 31 m^2 ha^{-1} was observed at 2424 trees ha^{-1} at 9.3 years-old. Several authors have suggested a basal area threshold for teak plantations of between 15–20 m^2 ha^{-1}; over this limit inter-tree competition increases and the individual tree size is drastically compromised (Lowe, 1976, Perez, 2005). In our experiment, if we consider 18 m^2 ha^{-1} as the threshold of critical competition, at the last measurement (9.3 years after planting), only densities equal or <423 trees ha^{-1} were growing without limitation as they had not yet reached this basal area. However, initial planting densities of 2424, 1659, 1020 and 637 trees ha^{-1} reached the threshold of critical competition (18 m^2 ha^{-1}) at 5, 6, 7 and 9 years of age respectively. This reflects observations of crown diameter relative to tree spacing noted previously, and suggests the need for pre-commercial thinning at 5–7 years after planting where teak is planted at initial densities greater than or equal to 1000 trees ha^{-1}.

Standing volumes were maximised at high initial densities; however, where silviculture aims to produce high-value sawlogs, tree size must be considered in addition to stand volumes. In order to maximise the value of timber production, teak silviculture must manage stand density to provide the appropriate balance between individual tree growth (to obtain high-value logs) and total volumes. The market for teak in Luang Prabang is based on log size, with a requirement for a minimum small-end diameter of 12–15 cm (the actual value varies slightly between mills) and a minimum log length of 2.3 m. The results presented here indicate that by 9.3 years 70 m^3 ha^{-1} of merchantable volume can be achieved at initial planting densities between 255 and 637 trees ha^{-1}. However, these calculations of merchantable volume (using Pérez and Kanninen's, 2003 equation), do not take account of log length or differences in taper that may result from changes in stand density. The increased stem diameter and reduced height observed at the lowest initial planting densities (i.e. those below 637 tree ha^{-1}), indicate a marked increase in taper and so volume equations developed for trees grown at higher stocking rates (600 tree ha^{-1} or more; i.e. Dieters et al., 2014) may not be applicable, possibly leading to the over-estimation of tree volumes at these stocking levels. Further, visual observations indicate that trees grown at the lowest densities will yield only one or two 2.3 m logs after the 10th growing season, while trees grown at 637 stems ha^{-1} may be expected to yield at least three 2.3 m logs at the same age. Likewise, if we consider the merchantable volume (40.8 m^3 ha^{-1}) estimated for an initial planting density of 1020 trees ha^{-1} and a mean diameter of 16.5 cm at the last measurement, many trees will produce only a single small sawlog of low value, and so the actual merchantable volume may be less than that estimated.

4.4 Effect of spacing on crop yield

The initial planting spacing of teak had a significant effect on the yield of companion crops. There is a shortage of published data on the yield of maize, cassava, peanut and pigeon pea growing in either monoculture and in agroforestry systems in the uplands of northern Laos. Asai and Soisouvanh (2017) report that the yield of monoculture hybrid maize varied from 1.2 to 4.9 t ha^{-1} depending on the fertility of the soil. Meanwhile, Roder et al. (1996) reported mean yields of 1.8 and 7.3 t ha^{-1} for upland maize and cassava respectively. The intercropping annual and perennials crops during the first 2–3 years after establishment of trees (i.e. the *Taungya* systems) has been a common practice in Asia more than a century (Nair, 1987). However, several silviculture management practices such as thinning, pruning or species selection have been suggested to extend the intercropping period (Nair, 1991). The successful association of annual crops with teak during the first years of a tree plantation has been reported by several authors (Weersum, 1982; Watanabe et al., 1988; Hansen et al., 1997; Roshetko et al., 2013; Ugalde, 2013). However, few studies have evaluated wider teak spacing in Laos (or elsewhere) with the aim of extending the intercropping period beyond the first 2–3 years after planting teak. Results reported above indicate that viable crops of cassava, maize and pigeon pea can be grown 5–6 years after planting teak, where the spacing between trees is 6 m or more for maize or cassava (producing over approximately 3 t ha^{-1}) and at least 10 m for pigeon pea. Surprisingly, there was a substantial drop in yield of maize at the widest tree spacing. The reason for this is unknown, but may reflect damage from birds, or perhaps theft at the peripheries of experiment. At the closer tree spacing, the yields of all crops were significantly impacted, most probably by the shade generated by the teak. This indicates that teak agroforestry systems involving alley widths of at least 8~~ to ~~–10 m will be required to enable cultivation of companion crops for at least 6 years after planting teak. Intercropping of teak with annual or perennial crops will provide food and non-food products for self-consumption or income generation, having substantial additional benefits over tree growing alone. Similarly, the cultivation of companion crops, particularly legumes such as pigeon pea, may improve the growth of the tree crop through control of woody weeds and vines, and the fixation of nitrogen. Alley cropping may also reduce the potential for soil erosion on steep slopes, particularly compared to teak woodlots grown at initial planting densities of 1~~,~~000 trees ha^{-1} or more. Nevertheless, it should be remembered that in order to achieve the benefits from intercropping, higher inputs are also required in comparison to a teak woodlot and this labour may not be available.

4.5 Management implications

Several planting systems are appropriate for teak, but those of most importance in Laos are a woodlot (teak only) with companion crops in first 1–2 years (i.e. the *Taungya* system) or an agroforestry system (i.e. an alley cropping system with teak plus agricultural or perennial crops). In both systems, the initial stocking and spacing should aim to produce a homogenous stand with large trees for the final harvest, using genetically improved planting stock and following the best practice of soil preparation and weed control during the establishment of the tree crop. In Laos, there are currently no markets for small diameter teak logs, and given the relatively small plantation estate, distributed in small blocks across the landscape, investment in processing plants to produce engineered wood products that can utilise small diameter, low value timber is unlikely. Spindle-less lathe technology is widely used in southern China, and can use small diameter logs, nevertheless large diameter logs are still preferred and of higher value. Therefore, teak silviculture in Laos should focus on producing high-quality sawlogs (large diameter logs free of knots), and eliminate the production of low-value/small-diameter trees. Further, there is no question that thinning (from below) and pruning will increase profitability and reduce the rotation age of teak (Ugalde, 2013; Noda and Himmapan, 2014; Kollert and Kleine, 2017). However, it needs to be recognised that silvicultural thinning is not a common practice of smallholders in Luang Prabang (Midgley et al., 2007), rarely if ever implemented. Newby et al. (2012) reported that only 9% of the farmers who had had training on thinning have adopted this practice, and most also did not perceived any benefit from thinning their teak. There is a general perception that all trees potentially have value and pre-commercial (silvicultural) thinning is seen as a waste, therefore farmers typically only cut trees when they can be sold as sawlogs (almost invariably selectively harvesting the largest tree) as trees reach a merchantable size, with the sale of trees prompted by household needs household cash needs (Midgley et al., 2007) rather than any silvicultural purpose.

Although the benefits of pre-commercial thinning can be demonstrated, it is expected that adoption by smallholders in Laos will continue to be low. Smallholders are risk adverse, and are reluctant to invest resources (e.g. labour) where the benefit is significantly delayed. Particularly, where labour is limited, and farmers have no off-farm source of income, farmers are more likely to invest labour in an activity which will provide an immediate (or short term) benefit, even though this benefit may be lower than that potentially achievable from thinning or pruning of their teak. Consequently, we believe that silvicultural systems recommended for teak in Laos should, where possible, not require pre-commercial thinning and be as simple as possible.

The results presented here demonstrate that both high and low initial stand density constrain the potential growth, value and quality of teak. For instance, initial stocking rates of 1~~,~~000 trees ha^{-1} or higher, require early management of competition (i.e. pre-commercial thinning) to prevent high levels of inter-tree competition and the consequent reduction in tree size. Stands left un-thinned will demonstrated reduced growth rates compared to trees grown at a lower initial stocking, extended the time to first commercial harvest, and leading to reductions in merchantable volume and tree value. Conversely, low initial stocking (i.e. 400 trees ha^{-1} or less) promote diameter growth, but lead to reductions in tree height, and consequent increase in stem taper and branch size. Trees grown at these low stocking rates also appear to be more susceptible to wind damage (stem breakage).

Taking all factors into consideration, initial planting densities of between 600 and 1~~,~~000 trees ha^{-1}, are most likely to achieve the optimal balance providing sufficient space to maximise early growth while providing sufficient inter-tree competition to promote early height growth thereby minimising taper. Initial planting densities of 1000 trees ha^{-1} or higher, will require pre-commercial thinning to maintain the standing basal area below 20 m^2 ha^{-1}, while initial planting densities of around 600 trees ha^{-1} may provide a 'direct' regime (Fenton ~~et al., ~~and Sutton 19~~72~~68), whereby almost every tree planted can be harvested commercially. A reduction of the initial planting densities will also reduce the cost of establishment and reduce labour inputs due to the lower number of trees planted and reduce the time from planting to commercial harvest. Future research should focus on evaluating the economics of reduced initial planting densities (e.g. 600 trees ha^{-1}) compared to the current practice (i.e. 1100 trees ha^{-1} without any pre-commercial thinning) and evaluation of impacts on wood quality from fast grown shorter rotation teak.

In conclusion, initial planting density is a critical factor impacting on individual tree growth and stand productivity of teak. Simple management regimes are recommended for teak-smallholders in Laos interested in producing high-quality timber in a teak woodlot or agroforestry system. For woodlots initial planting densities around 600 trees ha^{-1} (e.g. 4 × 4 m or 8 × 2 m) are recommended for smallholders under *Taungya* systems for up to least two years. If farmers are seeking to intercrop teak for longer periods (i.e. 5–8 years) an agroforestry planting configuration with alley widths of at least 8–10 m is recommend (e.g. paired row configuration 2 × 2 × 10 m, or 833 trees ha^{-1} at planting) that will allow production of high quality teak in conjunction with companion crops.

Uncited references

ACIAR (2017), Bhat (1995), Erkan (2016), Holbrook and Putz (1989), Kokutse et al. (2004), Laming and Van der Zee (2008), Polato and Laming (2003), VSN International (2018).

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Appendix A

Result of the spatial statistical analysis for all traits evaluated at different ages at the Nelder wheel experiment for the Block (B), spacing (S), provenance (P) and interaction spacing × provenance (S × P). *P*-values > 0.05 is presented as number, ∗*P*-value < 0.05, ∗∗P-values < 0.01 and ∗∗∗*P*-values < 0.001.

Years after planting	Traits	B	S	P	S × P
0.8	Total height (m)	*	0.866	0.059	0.159
1.5	Total height (m)	8	0.336	**	0.435
2.4	Total height (m)	**	**	**	0.591
	DBH (cm)	*	*	0.056	0.606
3.5	Total height (m)	**	**	0.241	0.888
	DBH	*	**	0.067	0.096
	Total height (m)	***	***	0.747	0.534
	DBH (cm)	*	***	0.349	0.331
4.4	Basal area (m^2/ha)	0.349	***	0.44	*
	Volume per tree (m^3/tree)	**	***	0.52	0.419
	Stand volume (m^3/ha)	0.107	***	0.47	*
	Merchantable volume (m^3/ha)	0.186	0.059	0.446	0.761
	Total height (m)	***	***	0.083	0.173
	DBH (cm)	0.083	***	0.35	0.174
5.7	Basal area (m^2/ha)	0.733	***	0.334	*
	Volume per tree (m^3/tree)	*	***	0.922	0.163

	Stand volume (m³/ha)	0.286	***	0.707	*
	Merchantable volume (m³/ha)	*	***	0.834	0.574
	Total height (m)	***	***	0.067	0.242
	DBH (cm)	*	***	0.097	0.171
6.6	Basal area (m²/ha)	0.893	***	0.268	0.056
	Volume per tree (m³/tree)	***	***	0.918	0.228
	Stand volume (m³/ha)	0.438	***	0.78	*
	Merchantable volume (m³/ha)	**	***	0.509	0.752
	Total height (m)	***	***	0.444	*
	DBH (cm)	*	***	0.168	0.155
7.5	Basal area (m²/ha)	0.898	***	0.357	0.118
	Volume per tree (m³/tree)	***	***	0.461	0.103
	Stand volume (m³/ha)	0.775	***	0.624	0.121
	Merchantable volume (m³/ha)	***	***	0.462	0.198
	Total height (m)	0.235	***	0.745	*
	DBH (cm)	0.185	***	0.128	0.154
8.6	Basal area (m²/ha)	0.957	***	0.216	0.144
	Volume per tree (m³/tree)	*	***	0.174	*
	Stand volume (m³/ha)	0.92	***	0.422	0.196
	Merchantable volume (m³/ha)	**	***	0.182	0.333
	Total height (m)	0.091	***	0.467	0.244
	DBH (cm)	0.364	***	0.211	0.094
	Basal area (m²/ha)	0.996	***	0.329	0.106
9.3	Volume per tree (m³/tree)	0.151	***	0.273	0.327
	Stand volume (m³/ha)	0.151	***	0.273	0.327
	Merchantable volume (m³/ha)	0.088	***	0.348	0.38
	Crown diameter (m)	***	***	0.156	0.17
	Crown base height (m)	0.471	***	0.737	0.403

Appendix B

Models and regression statistic developed in this study between D.B.H (cm) and age of tree (years) for each initial planting density (trees ha^{-1}).

Density	N. obs.	Model	*a**	*b**	R^2	RMSE
106	40	$y = ax + bx^2$	1.59	0.13	0.93	5.03
159	40	$y = ax + bx^2$	1.90	0.12	0.93	5.34
255	40	$y = ax + bx^2$	2.13	0.07	0.96	2.01
423	40	$y = ax + bx^2$	2.44	0.001	0.95	2.04
637	40	$y = ax + bx^2$	2.62	−0.06	0.95	1.26
1020	40	$y = ax + bx^2$	2.69	−0.10	0.97	0.42
1659	40	$y = ax + bx^2$	2.53	−0.11	0.92	0.89
2424	40	$y = ax + bx^2$	2.39	−0.11	0.88	0.98

Appendix C

Models and regression statistic developed in this study between total height (m) and age of tree (years) for each initial planting density (trees ha^{-1}).

Density	N. obs.	Model	*a**	*b**	R^2	RMSE
106	40	$y = ax + bx^2$	1.68	−0.011	0.97	1.08
159	40	$y = ax + bx^2$	1.92	−0.034	0.95	1.22
255	40	$y = ax + bx^2$	1.78	−0.009	0.96	1.16
423	40	$y = ax + bx^2$	2.06	−0.018	0.96	1.07
637	40	$y = ax + bx^2$	2.15	−0.003	0.96	1.30
1020	40	$y = ax + bx^2$	2.37	−0.05	0.96	1.09
1659	40	$y = ax + bx^2$	2.53	−0.08	0.95	1.67
2424	40	$y = ax + bx^2$	2.59	−0.098	0.94	1.73

Appendix D

Models and regression statistics developed in this study between volume per tree (m^3 $tree^{-1}$) and stand density (trees ha^{-1}) according to age after planted.

Age	N. obs.	Model	*Intercept(y0)*	*a**	*b**	R^2	RMSE
2.4	32	N/A	N/A	N/A	N/A	N/A	N/A
3.5	32	$y = y0 + ax + bx^2$	N/A	N/A	N/A	N/A	N/A
4.4	32	$y = y0 + ax + bx^2$	N/A	N/A	N/A	N/A	N/A
5.7	32	$y = y0 + ax + bx^2$	0.068	6E−06	−8E−09	0.36	0.0002
6.6	32	$y = y0 + ax + bx^2$	0.1266	−3E−05	−1E−09	0.49	0.0006
7.5	32	$y = y0 + ax + bx^2$	0.2274	−0.0001	3E−08	0.68	0.0014
8.6	32	$y = y0 + ax + bx^2$	0.3394	−0.0002	6E−08	0.79	0.0021
9.3	32	$y = y0 + ax + bx^2$	0.3931	−0.0003	6E−08	0.78	0.0032

Appendix E

Models and regression statistics developed in this study between stand volume (m^3 ha^{-1}) and stand density (trees ha^{-1}) according to age after planted.

Age	N. obs.	Model	*Intercept (y0)*	*a**	R^2	RMSE
2.4	32	y = y0 + a ∗ ln(x)	−12.95	2.54	0.79	1.4
3.5	32	y = y0 + a ∗ ln(x)	−63.68	12.67	0.85	5.66
4.4	32	y = y0 + a ∗ ln(x)	−102.42	20.93	0.88	8.17
5.7	32	y = y0 + a ∗ ln(x)	−135.65	28.77	0.90	10.25
6.6	32	y = y0 + a ∗ ln(x)	−178.96	39.19	0.91	12.64
7.5	32	y = y0 + a ∗ ln(x)	−204.28	47.07	0.9	16.1
8.6	32	y = y0 + a ∗ ln(x)	−213.1	52.18	0.88	20.47
9.3	32	y = y0 + a ∗ ln(x)	−224.19	56.4151	0.85	24.64

Appendix F

Models and regression statistics developed in this study between basal area (m^2 ha^{-1}) and stand density (trees ha^{-1}) according to age after planted.

Age	N. obs.	Model	*Intercept (y0)*	*a**	R^2	RMSE
2.4	32	y = y0 + a ∗ ln(x)	−5.95	1.17	0.82	0.58
3.5	32	y = y0 + a ∗ ln(x)	−17.35	3.51	0.87	1.43
4.4	32	y = y0 + a ∗ ln(x)	−21.1	4.38	0.91	1.47
5.7	32	y = y0 + a ∗ ln(x)	−24.72	5.34	0.92	1.66
6.6	32	y = y0 + a ∗ ln(x)	−28.94	6.48	0.93	1.87
7.5	32	y = y0 + a ∗ ln(x)	−30.72	7.21	0.92	2.18
8.6	32	y = y0 + a ∗ ln(x)	−31.30	7.6	0.91	2.64
9.3	32	y = y0 + a ∗ ln(x)	-32.39	8.16	0.91	2.77

Appendix G. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.foreco.2018.12.031.

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Appendix G. Supplementary material

Multimedia Component 1

Supplementary data 1

Multimedia Component 2 

Supplementary video 1

Highlights

- Diameter and height of teak are impacted significantly by the initial stand density.
- Initial stocking of >1000 trees ha^{-1} require pre-commercial thinning by 5 years.
- Initial stocking rates between 600 and 1000 trees ha^{-1} are likely to maximise growth and value of teak woodlots in Laos.
- Inter-row spacing of at least 10 m allows crop yields over 2 t ha-1, 5–6 years after planting teak.

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