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Articles

Teak (*Tectona grandis*) silviculture and research: applications for smallholders in Lao PDR

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ABSTRACT

Teak is an important forest plantation species in Lao PDR (Laos), that has been planted extensively by smallholders, supplying domestic industries and international markets. There have been significant advances in the intensive silvicultural management of teak focused on the production of high-quality timber. Laos is not an exception. With support from the Australian Centre for International Agricultural Research, there have been advances in the understanding and knowledge of appropriate management practices for smallholder teak, as well as development of supporting technologies (i.e. *ex situ* conservation, genetic improvement, growth models, thinning and pruning prescriptions, and agroforestry systems). This paper summarises published information on the silviculture and management of teak, including improvement of genetic resources, stocking rate, thinning and agroforestry systems used in Asia, Africa, Latin America and Oceania, and relates this to the current situation in northern Laos. The challenge is

wledge to the teak smallholders, professionals, educators and policy

Introduction

Teak (*Tectona grandis* L. f.), a tropical hardwood, has a natural distribution which includes the Southeast Asian countries of Myanmar, Thailand, India and Lao PDR (Laos; Kaosa-Ard 1 Teak was introduced to Java around 400–600 years ago and now it is considered natur Indonesia (Simatupang 2000). Currently, natural teak forests are rapidly declining due to over-exploitation and uncontrolled deforestation in India and Southeast Asia (Kollert & Kleine 2017). Nevertheless, the area of planted teak in about 70 tropical countries around the world has reached an estimated area of between 4 350 000 and 6 800 000 ha, of which 80% is grown in Asia, 10% in Africa and 6% in the tropical countries of America (Kollert & Kleine 2017; Midgley et al. 2017).

Teak in Laos occurs naturally only in Sainyabuli and Bokeo provinces, which border northern Thailand and Myanmar. The Government of Laos (GoL) has restricted logging in natural forests and recently banned exportation of logs (both round logs and squared logs), in order to arrest the decline in natural forests, as reflected in the substantial decline in the native teak (Kollert & Cherubini 2012; Mounlamai & Midgley 2014). Teak is now regarded as a 'special species' which affords teak special protections under Lao law (Smith et al. 2017).

Teak is an important high-quality forest plantation resource in Laos; supplying domestic and international markets. The planting of teak has been promoted widely since around 1950 and has been successfully adopted by smallholders in northern Laos (mainly in Luang Prabang province) and to a lesser extent in southern Laos (Attapeu and Champasak provinces). The rate of teak plantation establishment peaked in the 1990s and early 2000s, and then declined, most probably due to restricted land availability and changed GoL policies relating to land tenure and incentives to plant teak, combined with emerging alternative employment opportunities. According to Hansen et al. (2007), the large adoption and expansion of teak plantations by Lao smallholders may also be attributed to political and socioeconomic factors of the 1990s such as an expanding road network, implementation of the land allocation processes, and/or access to credit (up to 40–60% of the estimated value of plantation). The total area of teak woodlots in Luang Prabang province was mapped using aerial photography, registering a total of 15 342 ha, with an average woodlot size of less than 1 ha, with 83% located less than 1 km from a road (Boer & Seneanachack 2016; Ozarska et al. 2017). Nevertheless, Smith et al. (2017) caution

homogeneous resource, owned by smallholders with a common

of teak planations in Laos is more poorly defined, but most probably there are up to 10 000 ha in both Sainyabuli and Champasak (Bolaven plateau) provinces (Hilary Smith pers. comm.), with perhaps a further 10 000 ha in the remainder of Laos.

Teak requires intensive silviculture management to maximise its yield potential and quality of merchantable logs. The productivity of planted teak is determined by the integration of silviculture management given during establishment (including selection of site, site preparation, quality of planting stock and the germplasm used) and the subsequent maintenance and protection of the woodlot (weed and fire control, thinning and pruni... through to harvest (Ugalde Arias 2013).

Recent reviews of the state of global teak genetic resources, silviculture practices and marketing of teak have been conducted by Ugalde Arias (2013) and by Kollert and Kleine (2017). These studies describe the information and scientific advances in silviculture practices such as the improvements in genetic resources, stocking rates, thinning regimes and agroforestry systems used in Asia, Africa, Latin America and Oceania. Midgley et al. (2007) and Midgley et al. (2012) carried out a review of teak smallholder farming systems in Luang Prabang; however, significant changes have since occurred. In this paper we aim to summarise the global information of silviculture and management of teak as it relates to research undertaken in Laos over the last ten years, and the current situation of planted teak in northern Laos.

Conservation and genetic improvement

The area of native teak forest has been drastically reduced worldwide during the last few decades due to logging (both legal and illegal), agricultural expansion, shifting cultivation and population pressures (Kollert & Kleine 2017). This has negatively impacted on the genetic resources of teak, nevertheless both, *in situ* and *ex situ* conservation strategies have played a critical role in the protection of the species. Over the last 60 years programs to genetically improve and conserve teak were initiated (Kedharnath & Mathews 1962; Kaosa-Ard 1981; Kedharnath 1984; Suangtho et al. 1999; Ugalde Arias 2013). These programs typically utilised seed selection and provenance trials, vegetative propagation (grafting, cutting and tissue culture techniques), selection of the elite trees for breeding, establishment of seed production areas (SPA), clonal banks (CB) and clonal seed orchards (CSO). For example, in Thailand the Teak Improvement Centre (TIC), established in 1965 as collaboration between the governments of Thailand and Denmark, focused on the conservation and improvement of teak germplasm (Keiding 1965). An evaluation of an international series of provenance trials comprising 75 provenances over 21 sites in eight countries was conducted by the DANIDA Forest Tree Seed

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...36). The TIC selected and maintained 450 plus trees in approximately ...ltiplication gardens (Graudal et al. 1999; Kurinobu 2008). India initiated selected, 5185 ha of SPA and 1022 ha of CSO were established (Katwal 2003; Sreekanth & Balasundaran 2013). Teak improvement in Indonesia started in the 1980s and more than 180 plus trees have been selected and 4000 ha SPA and 1300 ha of CSO established (Kurinobu 2008). In Malaysia, a teak improvement program was initiated in the early 1990s through a collaboration between Innoprise Corporation Sdn Bhd (ICSB), an investment subsidiary of the Sabah Foundation, and CIRAD-Foret. By the early 2000s this program had gathered tea germplasm from Thailand, India, Papua New Guinea, Solomon Islands, Indonesia, Tanz Ivory Coast and Peninsular Malaysia and established two provenance/progeny trials in East Sabah, Malaysia (Goh et al. 2003). As a result of this collaborative research, substantial advances have been made on genetic improvement, clonal selection, improvement of *in vitro* propagation techniques, the use of DNA molecular marker technologies (Goh et al. 2003; Goh et al. 2007). Teak breeding programs have also been established in Central (e.g. Costa Rica, Panama) and South America (e.g. Brazil, Colombia) as well as in Africa (e.g. Tanzania, Ivory Coast).

In Laos, teak genetic improvement efforts date to the 1990s as part of the Lao Tree Seed Project (LTSP), supported by the Danish government in collaboration with the Forestry Research Centre (FRC) of the National Agricultural and Forestry Research Institute (NAFRI). The LTSP had a significant role in both the *in situ* and *ex situ* genetic conservation of tree species of importance in Laos and the establishment of SPAs. For teak the LTSP established ten SPAs (totalling approx. 400 ha) in six provinces of Laos (Table 1, Fig. 1). However, most of these areas have now either been harvested or transferred to private ownership (Sirivongs 2006). Farmers have proven to be reluctant to pay a price premium for high-quality seed and resource limitations meant that relatively little seed was collected from these SPAs, although some was shared with planting programs in Cambodia.

Table 1. Teak seed production areas established by Lao Tree Seed Project (modified from Sirivongs 2006 ; Mounlamai & Midgley 2014)

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Figure 1. Location of the teak seed stands (▲) established by the Lao Tree Seed Project

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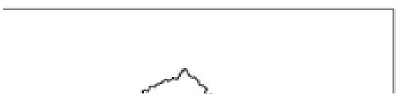

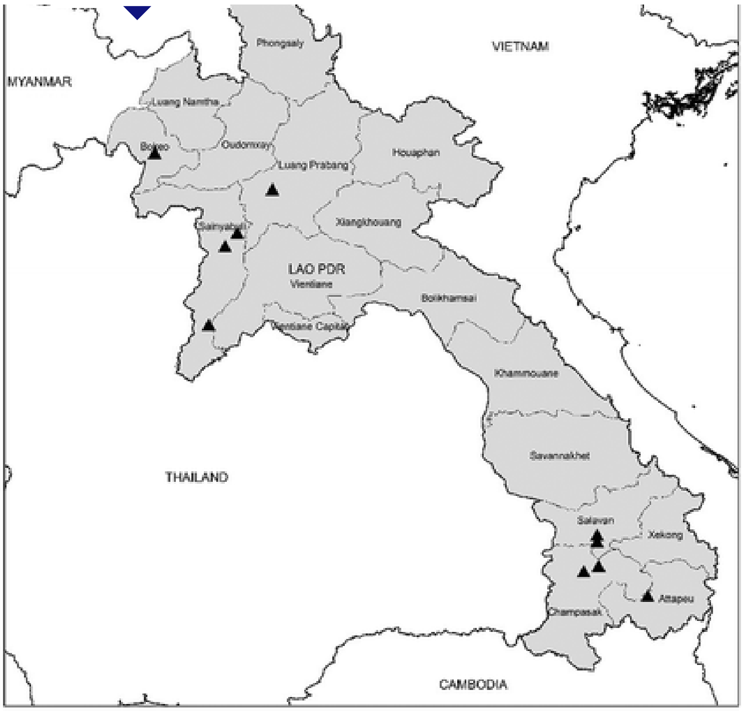

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Activities undertaken over the last ten years have had a significant impact on the teak improvement program in Laos, as part of projects (FST/2004/057 and FST/2012/041) supported by Australian Centre for International Agricultural Research (ACIAR) in collaboration with the University of Queensland (UQ, Australia) and Lao research partners NAFRI, Souphanouvong University (SU), the Rice Research Center (RRC) and the Upland Agriculture Research Center (UARC). Under these projects, over 200 elite teak trees were selected from smallholder woodlots through Luang Prabang province and from natural stands in Sainyabuli and Bokeo provinces. The selected trees were documented and propagated by grafting to establish three clone banks and one seed orchard at the Thong Khang Agroforestry Research Centre in Nan district of Luang Prabang in 2014 and 2015, and clonal hedge gardens at three locations in Laos (RRC at Napok, Vientiane; Souphanouvong University near Luang Prabang, and Houay Khot research station, Xieng-Nguen) and one in Vietnam (at the Research Center for Forest Tree Improvement, near Hanoi). One of these clone banks was subsequently destroyed by fire in 2017, and unfortunately all trees selected from the native forests in that clone bank were lost. The remaining 178 clones were re-grafted in 2018 and established in a clone bank at Houay Khot research station. Since selection and propagation of these plus trees, many of the original select trees have been cut from the woodlots, as a consequence of selective harvesting which removes the largest and best trees preferentially as sawlogs. Collection of improved open-pollinated seed from the selected trees themselves (ortets) was undertaken in 2014, and in 2016–2019 from ramets in

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in 2017–2019 from the CSO. Improved seedlings derived from
ırces have been distributed to farmers through collaborative trials, and

the District Agriculture and Forestry Offices (DAFO) commencing in 2019. Seed yields from the Laos clonal seed stands will continue to increase over the next 5–10 years but may not be sufficient to meet the long-term seed requirements, if all existing teak woodlots are replanted with teak.[1] Prabhu et al. (2013) estimate average seed yields from teak SPAs in Kerala varied from 2.3 kg ha^{-1} to 53.5 kg ha^{-1}, with an average of 13 kg ha^{-1}; although yields from more intensively managed clonal SPAs can be expected to be higher, therefore 5–10 ha will b required to produce 300 kg $year^{-1}$. The area of CSOs will be expanded in 2019 by grafti best 30 clones, as determined by the stem form and branching of the grafted ramets, w objective establishing a further three CSOs.

Over the last 10–15 years, there have been considerable improvements in cloning and mass propagation of teak via tissue culture enabling quick capture of genetic improvement; demonstrating significant and positive responses in growth compared to unimproved teak material (Goh et al. 2007; Ugalde Arias 2013; Kollert & Kleine 2017). In South American countries, clonal teak planting stock is widely used. For instance, in Brazil, the company Teak Resources Company (formerly-Floresteca), has established more than 40 000 ha of teak using clonal materials (Ugalde Arias 2013). In Malaysia (Goh et al. 2007), Thailand (Kijkar 2003) and Indonesia (Siswamartana 2003) teak propagation by tissue culture is well-developed.

As part of the teak genetic improvement program implement in Laos, dedicated tissue culture facilities were developed at three locations (the Rice Research Center near Vientiane, Souphanouvong University near Luang Prabang, and the Upland Agriculture Research Center in Xieng-Ngeun district of Luang Prabang province). It was anticipated that tissue culture would provide a means to rapidly multiply and deploy scarce improved teak germplasm. Methods were adapted from protocols for teak obtained from Thailand, Indonesia and Vietnam for the transfer shoots from grafted or seedling hedges into culture, and the subsequent multiplication of teak in culture. Multiplication cycles of 6–8 weeks are now being achieved, with a 2–3 times multiplication rate. Further protocols for the germination of teak seed in culture have also been developed, eliminating the requirement to decontaminate shoot material. Tissue culture efforts are currently directed at: (1) development of clonal lines either using shoots harvested from grafted hedges or from individual seeds (of maternal families, collected from the grafted seed orchard or clone banks) germinated and multiplied in culture; and (2) multiplication (in bulk) of the small quantities of improved seed collected from the orchard and clone banks from 2016 to 2018. The first teak produced by tissue culture in Laos were planted on 1 June 2017 as part of a tree planting ceremony and has demonstrated excellent growth potential (average of 6.3 m in total height at 1.6 years) and stem form (straight, round stems with little branching and taper). It

mately 5000 plants derived from tissue culture will be distributed to 019, and that the first clonal trials of teak will be planted in 2020.

Nevertheless, access by smallholders of Laos to improved teak planting stock is currently restricted to farmers working in collaboration with the ACIAR research project. Mechanisms to achieve the delivery of improved planting stock to smallholders at an affordable price and in sufficient quantity, remains a significant challenge that must be addressed if the impacts of genetic improvement are to be realised by smallholder tree farmers in Laos. Perdana and Roshetko (2015) similarly indicated that in Indonesia, smallholders rarely access improved germplasm of teak, which when combined with sub-optimal silviculture, results in slow growing and poorer quality teak compared to industrial teak plantations. In the earlier Harwood et al. (1999) indicated that access of smallholder farmers to improved planting stock was typically low across a range of species in Southeast Asia.

Site selection

Teak grows well and is adapted to a wide range of environmental conditions (Street 1962; Kadambi 1972; Kaosa-Ard 1981). Although the natural distribution of teak is characterised by a monsoon climate with rainfall ranging from 1300 to 2500 mm year^{-1} and a 3–5 month dry season (Kaosa-Ard 1981), successful teak plantations can be found in environments without a dry season such as in Mato Grosso and Para Brazil (Ugalde Arias 2013). The most favourable conditions for the growth of teak are between 22°C and 27°C, where the maximum monthly temperature is below 40°C and the minimum monthly temperature is above 13°C (Kaosa-Ard 1981). The species is frost-sensitive although tolerates light freezing (Louppe et al. 2008); in northern Laos, this typically restricts planting to elevations below 800 m a.s.l. Optimal performance of teak is achieved in fertile, deep and well-drained soils with neutral or slightly acid pH, but the performance of teak is limited by water logging, soil compaction, high elevation and low temperatures (Kolmert 2001).

Teak is a major component of the landscape in Luang Prabang province; however, sites were planted to teak with little respect to site quality. Historically, teak woodlots in Laos have been established primarily within 1 km of the existing road networks or along rivers, on fertile alluvial soils, usually following a long (10–15 years) fallow period. More recently, competition with other land uses, has meant that teak has been planted mainly in upland fields located further from existing infrastructure, with companion crops such as maize (*Zea mays* L.), upland rice (*Oryza sativa* L.) or Job's tears (*Coix lacryma-jobi* L.) in the first one or two years. Shortening of fallow periods in upland fields as a consequence of the GoL land allocation processes and increasing population pressure is expected to result in reduced fertility of sites available for future woodlots or agroforestry plantings in Laos. Recent infrastructure development in Laos

...ing of roads, construction of hydroelectric dams, railway and electricity ...cted adversely on the planted teak resource in Laos. Consequently, the

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approximately 15 000 ha reported by Boer and Seneanachack (2016).

Initial spacing

The initial stocking rates used for teak woodlots varied greatly worldwide from as many as 3000 trees ha^{-1} (1.8 × 1.8 m spacing) to around 1100 trees ha^{-1} (3 × 3 m spacing). Current planting configurations for the production of sawlogs typically range from 3 × 3 m (1111 trees ha^{-1}) to 3.5 × 3.5 m (816 trees ha^{-1}). If teak is established using an agrofore intercropping approach, wider spacing is typically left between trees rows for the production of agriculture crops (Kollert & Kleine 2017). For instance, Passos et al. (2006) and Ugalde Arias (2013) indicate common initial planting configurations of either 6 × 2 m (833 trees ha^{-1}) or 8 × 2 m (625 trees ha^{-1}).

In Laos, initial stocking rates historically range from 1111 (3 × 3 m) to over 2500 trees ha^{-1} (2 × 2 m). Although much higher rates have been used, most probably resulting from a view that more trees equate to more value, misunderstanding of the concepts of horizontal versus slope distances and/or an inability of farmers to correctly estimate plant requirements (i.e. all trees purchased are planted). The currently recommended initial spacing for teak is 3 × 3 m (Kolmert 2001), a requirement to meet the definition for a tree plantation under the current Lao forest regulations.

The research experience with planted teak of the Lao and Australian research partners, ACIAR (2017) recommended maximum initial stocking rates for teak woodlots of 1111 (3 × 3 m) trees ha^{-1} on flat land (<10% slope) and 1000 trees ha^{-1} (5 × 2 m) on steep lands (≥10% slopes). Further, the project has developed simple extension materials in the Lao language, supported the training of district staff in teak silviculture, provided assistance to incorporate appropriate teak silviculture into the curriculum of the local forestry college, and provided district officials with resources to conduct teak silvicultural training in villages across Luang Prabang province. In addition, the smallholder teak manual from Indonesia (Pramono et al. 2011) has been revised to better suit the Lao context, and a version in the Lao language has now been printed and available online (www.latarp.wordpress.com).

Weed control

To maximise the growth of teak, adequate weed control is required in the early stages of plantation establishment, and preferably through the first and second years after planting (Anoop & Mohan Kumar 1992; Kolmert 2001; Ugalde Arias 2013). Overall, the frequency and

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uired will depend on the environmental conditions (temperature and rowth stage of the plantation. Young teak needs good weed control to is generally not necessary. Tools used for weeding vary from manual to mechanised slashing, with chemical control being widely used and recommended in many countries. The correct use of chemical control will reduce the frequency of weeding and minimises the cost and labour requirements (Rance et al. 2013). Nevertheless, although weed control is required to maximise the growth of teak, and prevent damage to trees from vines, teak will persist and eventually grow through fairly intensive weed competition. Unfortunately, in Laos this has led to a perception that weed control is not necessary.

In Laos, manual slashing is the common practice for controlling weeds in teak woodlots. Successful weed control is achieved when teak is intercropped with annual crops (*Taungya* systems) during the first 1–2 years of the plantation. Currently, the GoL through the national research organisations and provincial and district agriculture and forestry offices, does not support chemical control of weeds in teak woodlots by smallholders. This is due to the risks associated with the inappropriate use of herbicides and insecticides experienced in other crops such as banana. Over the last 5–8 years (2010–2018), low-cost motorised brush-cutters manufactured in China have become a common sight in rural areas of Laos. Prior to this, there was little knowledge amongst Lao farmers of this technology. Farmers commonly report significant labour savings; achieving in one day with a motorised brush-cutter what would have previously taken up to ten days for a single person working with a machete. Motorised brush-cutters are expected to enable Lao farmers to now achieve higher levels of weed control in teak woodlots, once they stop companion cropping.

Site index

A knowledge of the site productivity is imperative for estimation of the timber production and for managing the silvicultural decisions. Site Index (SI), which refers to the height of the dominant trees in a stand at a specific reference age, is considered one of the most useful and practical methods for measuring potential site productivity in even-age forestry plantations (Burkhart & Tennent 1977). A higher SI (a larger height at the nominated base age) indicates a more productive site and has the advantage of being independent of stocking rate (Kollert & Kleine 2017). Given the significance of this measure, SI curves have been developed in several regions of the world for teak and can be used to compare teak growth and productivity between countries (Table 2). In Laos, the first SI (based age of 15 years) was developed by Dieters et al. (2014) using data from a set of 64 permanent plots of teak in Luang Prabang province. Two equations were developed for estimating SI_{15} using either the mean height (R^2 = 0.68) or predominant height (R^2 = 0.65). A comparison with other regions suggests site quality in Laos of

…ɪan many other countries where teak is grown (Table 2), possibly …ason.

Table 2. Summary of Site Index (SI) in Asia, Africa and Central and South America countries

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Singling and pruning

Under some conditions, teak can develop multiple and/or forked stems and large branches. Multiple stems can compromise the straightness of the bottom log and reduce the value of the log. Form pruning seeks to remove large branches that may lead to a forked stem. Reducing each tree to a single dominant stem (singling) and form pruning are recommended silvicultural practices which enhance the productivity and performance of teak woodlots.

The quality of teak timber is based on an appearance grade, which depends on visual assessment of knots in the timber (size, number, and diameter) and the presence of heartwood. Knot-free ('clear') teak timber can achieve the maximum price in the market (Pérez Cordero 2005). Natural (self) pruning occurs in teak plantations, particularly when teak is grown at high stockings; however, this does not guarantee sufficient clear timber volume (Viquez & Pérez 2005), as there is a risk of occlusion of dead branches, leading to dead or loose knots and/or decay, which will significantly reduce timber values. Consequently, pruning is typically required to maximise the production of high-quality teak timber. A generally accepted recommendation is to prune young teak up to 50% of the tree total height at the first thinning (Pérez & Kanninen 2003a; Ugalde Arias 2013). The pruning height should also take account of the merchantable log lengths, with the aim of complete (full) pruning of one, two or three full logs. Typically, a partially pruned log has no more value than an unpruned log. In Central America, Pérez and Kanninen (2003a) recommended a pruning scheme for teak related to stand development rather than stand age. According to their study, the first pruning should be carried out when the stand reaches a total height of 4–5 m, pruning the lower branches to a height of 2–3 m (approx. 40–50% pruning intensity). A second pruning should be applied when the stand reaches 9–10 m in height; removing the branches up to 4–5 m height. Finally, the last pruning should be done when the stand reaches 12 m of total height; removing branches up to a height of 7 m. Viquez and Pérez (2005) also found that initial pruning up to 3 m height (42% pruning intensity) of 2.2 years teak plantation (average diameter at breast height (DBH) of 7.6 cm) produced trees with high individual growth and heartwood formation; however, more intensive pruning intervention (i.e. pruning >50% of tree height) reduced diameter and height growth.

knowledge and low adoption of pruning in teak woodlots. Newby et al. than 40% of the households interviewed (127 households) had done practice in Xieng Nguen and Luang Prabang districts, with only 13% of teak farmers interviewed reporting that they did some pruning. Keonakhone (2005) evaluated the effect of pruning and thinning intensities in an eight-year-old plantation and reported that pruning had a positive impact on tree growth. The current recommendation for teak smallholders in Luang Prabang (Dieters et al. 2018) is pruning all trees after the fourth or fifth growing season (approx. 5 or 6 years of age) to 2.4 m height with the aim of obtaining a pruned log of 2.3 m. After th[e first] pruning, the lower branches should be removed annually, avoiding pruning more than [...] the branches, until a pruned height of either 4.8 m or 7.2 m is attained. Pruning to a he[ight of] more than 7.2 m is not recommended as most of the timber volume and value is achieved in the lower part of the tree. For smallholder farmers, a pruning strategy which involves annual pruning of the lower branches combined with removal of any large branches which may affect stem form (i.e. form pruning), is able to be achieved more readily by farmers with restricted labour.

Thinning

Silvicultural thinning to manage inter-tree competition is recognised as a key component of intensive plantation management to produce high-quality timber. In this paper, unless otherwise stated explicitly, 'thinning' refers to the progressive removal of small, forked, damaged or otherwise low-value trees from the stand with the aim of enhancing the growth of the retained trees, and improving stand health and quality. Thinning is arguably more important in teak than many other forest tree species, as teak is highly intolerant of competition from neighbouring trees (Ugalde Arias 2013). Crowns of teak trees become abraded where they overlap, and overtopped trees become suppressed, cease to grow and the stem form progressively deteriorates as the suppressed tree attempts to 'move' away from its larger neighbours.

The adoption of intensive management practices in teak plantations have shown that high-intensity thinning has a large advantage (e.g. shorter rotation, high-quality timber) compared to low-intensity thinning practices (Pérez Cordero 2005). In addition, it has been demonstrated that the timing and intensity of thinning depends on stocking rate (determined primarily by initial spacing) and the site quality (Pérez & Kanninen 2003a; Pérez Cordero 2005; Ugalde Arias 2013). For instance, teak planted at narrow spacing will reach canopy closure sooner and require an earlier thinning intervention to manage competition compared to teak planted at a wider initial spacing or on a poor site (Kollert & Kleine 2017). Thinning is recommended in young teak plantation with the aim of maximising the growth rate of young trees. In contrast, if

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an advanced age, the growth response may be limited (Ugalde Arias

Several indices of stand competition have been evaluated in teak plantations to help elucidate the timing and intensity of thinning interventions, including: stand basal area (BA), stand density index (SDI), total height of dominant trees (i.e. predominant height), crown closure (CC) and age of plantation (Lowe 1976; Pérez & Kanninen 2003a; Kanninen et al. 2004; Pérez Cordero 2005). The most common criterion is BA. According to several authors thinning intervention is recommended when the plantation reaches a threshold 20–22 m^2 ha^{-1}; however, this depends on the site quality (Kollert & Kleine 2017). For instance, for medium-quality sites in Cos[ta Rica,] Vásquez and Ugalde Arias (1995) recommend that teak stands should be managed to h[ave BA] between 15 m^2 ha^{-1} and 20 m^2 ha^{-1}, but in high-quality sites, BA should be reduced from 20–26 m^2 ha^{-1} to 8–15 m^2 ha^{-1} (Centeno 1997; Bermejo et al. 2004; Pérez & Kanninen 2005). In Venezuela, Torres (1982) recommends BA should be reduced to 17 m^2 ha^{-1} when the teak plantation reaches 24 m^2 ha^{-1}. While the actual values vary slightly, in general, the maximum recommended standing BA is in the range of 18–24 m^2 ha^{-1}, and thinning should aim to remove 25–50% of the standing BA.

Stand density index, also known as Reineke's Stand Density Index (Reineke 1933) is another measure used for planning thinning schedules. In India, Kumar et al. (1995) suggested that thinning management, focused on the production of poles and large diameter logs, should be carried out when the SDI reaches 420 (35% of maximum SDI) and reduced to a SDI of 240 (20% of maximum SDI) by thinning. These values are similar to those reported by Jayaraman and Zeide (2007) who found an optimal density index of 475. In Costa Rica, Arias (2004) obtained a lower value of maximum SDI, reporting 368 as the optimal SDI (35% of maximum SDI) for teak and recommend that SDI should be managed through thinning to keep the stand between 263 (25% of maximum SDI) and the optimal SDI.

Based on the use of several indices of competition, several authors have recommended thinning prescriptions in different countries around the world, that on average suggest 4–5 interventions (range 2–8 interventions), aiming for a final stocking of 230 trees ha^{-1} (range 87–500 trees ha^{-1}) and final harvest at 35 years old (range 20–74 years; Table 3). However, thinning prescriptions based on concepts such as BA or SDI, are too complicated and labour intensive for adoption by smallholder farmers.

Table 3. Summary of thinning prescription for teak plantation in different countries around the world. Remnant trees are expressed in trees ha^{-1} and timing in years

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in Laos, responses to thinning demonstrate substantial increases in diameter (Keonakhone 2005; Dieters et al. 2014); leading to the conclusion that thinning should aim to remove approximately one half of the standing trees or one third of the standing BA, in order to have a positive impact on the BA and volume increments post-thinning. This is particularly so when the stand has been overstocked for many years and contains a high proportion of small and suppressed trees. Lighter thinning regimes retain a high proportion of suppressed trees, which show no response to thinning (Dieters et al. 2014). Nevertheless, it is uncommon for te smallholders in Laos to thin their stands as part of regular management, and farmers a reluctant to remove any trees which are close to the minimum commercial diameter limits for sawlogs (i.e. trees 10–15 cm in diameter), even when these trees are highly suppressed. Newby et al. (2012) reported that only 9% of the households interviewed had thinned any of their teak woodlots, and although farmers had attended training events on thinning, they were still not confident about the benefits from thinning, particularly when the trees removed were too small to sell into the local sawlog markets. A similar finding was previously reported by Midgley et al. (2007), where none of those interviewed reported that they had undertaken any thinning activity. Additionally, there is a misunderstanding of the concept of silvicultural thinning compared to harvesting; Lao farmers typically understand 'thinning' to be selective harvesting of the largest trees as they reach a merchantable size (i.e. thinning from 'above'). Therefore, it is possible that some responses in the survey by Newby et al. (2012), may have indicated selective harvesting of the largest trees from their woodlots, rather than application of thinning from below to allow more space of the largest trees to continue growing to rotation age. As a consequence of high initial stockings, and a reluctance to apply pre-commercial thinning, most teak woodlots in Luang Prabang poorly managed, overstocked and characterised by small tree diameter and long rotations. Further, the practice of repeated selective harvesting of the best trees, means that many older teak woodlots are degraded, and stocked primarily with poorly formed, suppressed trees of low value, that are growing only very slowly. Yet farmers are still reluctant to cut the remaining trees and start a new woodlot.

Demonstration sites, training and extension activities are required to overcome these misunderstandings and assist farmers to adopt better management practices. Farmers must be convinced of the long-term benefits of investing labour today to manage a woodlot, for a return/benefit that will not be realised for many years in the future. Where labour is limited, farmers must choose between applying silvicultural management to their teak or undertaking other activities which will return (perhaps lower) benefits in a shorter timeframe with less/no risk. Further, thinning regimes must be presented in a way that is easy to understand and implement by farmers. As teak is intolerant of competition between the crowns of adjacent

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ns have been developed around the concept of maintaining space for
; need big crowns.

farmers to produce high-quality timber is to reduce the initial stocking to approximately 600 trees ha^{-1} using a planting configuration of 4 × 4 m or a paired teak row of 2 × 2 × 12 m in an agroforestry plot. Results of a ten-year study of the initial stand density of teak in a Nelder wheel experiment in Luang Prabang found that an initial stocking of around 600 trees ha^{-1} provided a good balance between promoting individual diameter growth and achieving high merchantable log volume (Pachas et al. 2019).

Agroforestry systems with teak

Agroforestry systems with teak have been practiced for a long time (Nair 1989). Systems such as *taungya* (Myanmar) or *tumpangsari* (Indonesia) that involve intercropping teak with annual crops are common practices adopted by farmers (Weersum 1982; Nair 1989; Hansen et al. 2007; Roshetko et al. 2013). These systems consist of intercropping teak with annual and perennial crops have the advantages of providing early cash-income to farmers and off-setting the cost of weed control. In Indonesia, most teak smallholders cultivate annual crops such as rice, maize or soybean (*Glycine max* L.) with teak, where the tree crop benefits from fertilisation of the food crops (Perdana et al. 2012). Khasanah et al. (2015) reported that maize intercropping in the early stage of teak growth provides a clear advantage compared to monoculture of teak, which may be attributed to the use of the fertiliser in the cropping years. Perennial species such as leucaena (*Leucaena leucocephala* (Lam.) de Wit), banana (*Musa paradisiaca* L.), pineapple (*Ananas comosus* (L.) Merr.) are also recommended as good companion crops for teak. In India, Kumar et al. (1998) found that leucaena was a highly desirable species in combination with teak; enhancing soil properties (e.g. N) with teak growth improving with an increasing proportion of leucaena in the mixture. In Thailand, Tanasombat et al. (2007) reported that intercropping teak with paper mulberry (*Broussonetia papyrifera* (L.) L'Hér. ex Vent.) or banana benefited the tree growth as well as the yield of the companion crops and provided a satisfactory income to the smallholders. Djagbletey and Adu-Bredu (2007) carried out a survey about the adoption of agroforestry systems in Ghana and found that teak was adopted as the main tree species for *taungya* systems, and was intercropped with several agriculture crops such as maize, yam (*Dioscorea alata* L.), tomatoes (*Solanum lycopersicum* L.), cassava (*Manihot esculenta* Crantz) and groundnuts (*Arachis hypogaea* L.). Most of the farmers they interviewed (82%) reported to have grown two or more different crops on the same land in mixture with teak and the main reason for intercropping was the weed control. Farmers reported that the high cost for weed control can be alleviated by the economic return from intercropped species during the period before total canopy closure.

erica, *taungya* systems in teak plantation have been successfully Passos et al. 2006; Ugalde Arias 2013; Escalante & Guerra 2015).

such as living fences, teak and cacao (*Theobroma cacao* L.), teak and coffee (*Coffea arabica* L.) or silvopastoral systems, have been adopted by smallholders to maintain long-term crop production. For instance, living fences with teak have been adopted by farmers in Colombia (Ugalde Arias 2013) and Venezuela (Escalante & Guerra 2015), and it can be found along the main roads or internal roadways. In Ecuador, Cunuhay et al. (2009) evaluated four forest species associated with coffee and compared the agroforestry systems and monoculture in bo[...] and coffee. They found that after five years, teak intercropped with coffee had the best growth performance (average 26.5 cm in DBH) compared to a teak monoculture contro[...] (average 16.9 cm of DBH) and coffee trees reached an average yield of 2094 kg ha^{-1}. Farmers in Colombia (Murgueitio et al. 2016) and Brazil (Maneschy et al. 2009) have adopted silvopastoral systems with teak to obtain short-term economic and financial benefits from beef production and improved long-term benefits from the production of high-quality timber while offering additional benefits of shade and shelter for livestock, reduction of erosion and increased biodiversity. In these countries, silvopastoral systems with teak are promoted using double or triple rows of teak with alleys between of 8 m and 28 m wide. In Colombia, teak is one of tree species recommended for using in what are called intensive silvopastoral systems (iSPS), that combine trees species at densities of 100–600 trees ha^{-1} with wide alleys that allow high-density cultivation of fodder shrubs such as leucaena (4000–40 000 plants ha^{-1}) that grow together with improved tropical grasses (Murgueitio et al. 2011; Calle et al. 2013). Additionally, Calle et al. (2012) reported that the fallen leaves of teak did not affect the pasture due to the trampling and urine that accelerated the decomposition/breakdown of the leaves and that the cattle eat some green leaves. Maneschy et al. (2009) reported that silvopastoral systems in Para (Brazil) with teak are economically attractive, having a better net present value and internal rate of return compared to open pasture. Their study was based on data from trials with an initial stocking rate of 625 trees ha^{-1} with two thinnings scheduled at 7 and 11 years, respectively, and final harvest at 15 years. In Alta Floresta Mato Grosso, Brazil, Ugalde Arias (2013) reported that more than 300 ha of silvopastoral systems with teak (clones) have been established in combination with *Brachiaria* sp. pastures and beef cattle by the Fazenda Becaeri company. These silvopastoral arrangements consisted of approximately 200 trees ha^{-1} in single teak rows with alleys 15, 17 or 20 m wide. In the same region, Ângelo et al. (2008) evaluated the economic and financial outcomes of teak plantation and concluded that due to the high growth performance of teak in this environment it is a profitable and attractive investment option for Brazilian farmers.

[...]h teak in Laos, date from 1950, when a large area of teak plantation [...] Department of Forestry and Water and promoted by the French

1980s and 1990s teak was the perennial tree species most commonly planted in the uplands regions of Luang Prabang and during the first years after planting, intercropping with annual crops was a common practice. Most, if not all, of the teak woodlots established in Luang Prabang were established in combination with companion crops such as rice and maize during the first 1–2 years. Midgley et al. (2007) reported that smallholders are attracted to companion cropping, however due to the high levels of shade under closely spaced teak the yield of companion crops is low after the first one or two years. To evaluate the potential of alley cropping systems, ten agroforestry trials were established in collaboration with smallholders in the village of Phonsavang, Xieng-Ngeun district of Luang Prabang province (Dieters et al. 2014). These agroforestry trials were established using a paired-row configuration with alleys of 8 m or 10 m wide (i.e. 2.1 × 1.8 × 8 m or 2.1 × 1.8 × 10 m), and demonstrated that the wider alleys allowed intercropping with rice, banana and broom grass (*Thysanolaena latifolia* (Roxb. ex Hornem.) Honda) beyond four years, with banana successfully harvested for up to seven years, and obtain higher teak growth compared to nearby teak woodlots planted in a traditional configuration (3 × 3 m). Under the ACIAR project FST/2012/041, four initial planting densities of 1100, 918, 788 and 650 trees ha^{-1} using paired-rows of teak established with alleys of 8, 10, 12 and 15 m wide respectively, were evaluated in over 80 trials established in collaboration with farmers in 2014 and 2015 in four district of Luang Prabang. Early results indicate optimum alley widths of 10–12 m. These new systems have allowed the smallholders to extend the period of intercropping annuals and perennials crops as well as enhancing the teak growth.

Discussion

Significant advances have been achieved in the understanding of the intensive silvicultural management of teak focused on the production of high-quality timber. Breeding and propagation programs have demonstrated improved growth and returns; however, the ability of smallholders to access improved germplasm is limited. Support from NGOs, extension organisations and government, both in Laos and elsewhere, is necessary to support the delivery of improved planting stock to smallholders; nevertheless, new models for germplasm delivery may be required. According to Harwood et al. (1999), farmers in Southeast Asia are willing to pay a premium for seeds or seedlings of high genetic quality and suggest that the establishment of on-farm demonstration trials can enhance links between farmers and improved germplasm.

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better understanding of the growth and management of planted teak
dels and SI equations have been developed and published for several

et al. 2017; Tewari et al. 2013; Ugalde Arias 2013; Dieters et al. 2014). Further, the benefits of intensive silvicultural management of planted teak have been well-documented. South and Central American countries are characterised by the use of more intensive land preparation that involves the use of tractors, fertilisation and chemical weed control compared to Asian and Africa countries. Differences are attributable to the socio-economic context, government policies and support, land tenure and woodlot size, but also by smallholder views of tre planting and teak, in particular. The typical Lao smallholder growing teak views teak as term investment, requiring little/no inputs or management once the trees are establish

Several countries have independently developed protocols for intensive teak management, which include thinning and pruning prescriptions focused on producing high-quality timber over rotations of 15–25 years (depending on site quality), compared to traditional management of teak in India and Indonesia (usually in government-owned plantations) which involve rotations of 50 or more years. Under these intensive protocols, the initial planting densities are consistently around 1000–1100 trees ha^{-1}, allowing for some mortality and pre-commercial thinning, and the harvest of at least 400–600 trees ha^{-1} at maturity. The availability of improved planting stock (i.e. seedlings from clonal SPAs, or clonal plants from tissue culture or cuttings) will allow further reductions in the initial stocking rates, and potentially direct regimes (e.g. plant and harvest 600 trees ha^{-1} without thinning). Thinning studies have demonstrated the importance of the early management of inter-tree competition, with stands left at high stockings for more than 10–15 years responding poorly to thinning. Early thinning intervention in young teak plantations and relatively intensive thinning (30% of BA) is better than light thinning (10–15% of BA), and studies generally indicated teak woodlots should not exceed standing BAs of 20–26 m^2 ha^{-1} prior to the next thinning. The smallholders of Laos are reluctant to remove teak trees from their woodlots without a financial return from the sale of the timber, and pre-commercial thinning is perceived as a waste of time and timber. The Luang Prabang Teak Program (an initiative of the Provincial Forest Service) and Earthworm foundation (formerly The Forest Trust), assisted farmers to achieve plantation registration as an incentive to form grower groups (Ling et al. 2018). Groups were also seen to provide training and extension, and improve management of teak woodlots. Yet, they concluded that these grower groups, and the associated group certification schemes, largely failed to deliver the anticipated benefits of increased market access, higher price and greater bargaining power, and state 'Ironically, the bargaining power of poorer farmers is enhanced when collective selling is not enforced, since, if they don't like the price offered or don't need the money, they can simply leave the tree standing' (Ling et al. 2018, p. 375).

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nore intensive silviculture by Lao smallholders, as a starting point :hanges are required to support greater adoption of lower initial plantings). Current Lao law provides no opportunity to register forest plantations that have not been established according to the departmental instructions (Smith et al. 2017), but this may change under current revisions to Lao forestry law. Plantation registration, while not commonly adopted by Lao smallholders due to costs and complexities, has become the default requirement of legality throughout the teak value chain in Laos (Smith et al. 2017). Therefore, without the opportunity for plantation registration there is currently no pathway for le[gal] harvesting of timber from woodlots or agroforestry plots established at lower than the recommended initial stocking levels for teak in Laos (i.e. 3 × 3 m).

Lao farmers require information and extension support to facilitate the adoption of more appropriate management strategies, and to promote the wider adoption of tree planting to achieve the GoL objectives for afforestation. This information should be independent and verifiable: Gebert (2010, p. 18) remarks, 'There are far too many cases in Laos where farmers have been fed a diet of totally incorrect information on likely incomes'. Research for development such as that outlined here and supported by ACIAR can provide this independent evidence to underpin changes in practice.

Conclusions

Over the last decade in Laos there have been significant advances in the knowledge of intensive silvicultural management of teak and supporting technologies. The *ex situ* conservation program has preserved the genetic diversity from teak plantations in Laos that otherwise would have been lost through the common practice of thinning from above. Seed production from grafted seed orchards are being expanded to meet long-term seed requirements in Luang Prabang Province, with additional genetic gains captured quickly using tissue culture and deployment of selected clones. Yet collaborative efforts of GoL agencies, NGOs, extension organisations and the private sector are imperative to ensure access to improved germplasm by Lao smallholders. Adoption of thinning and pruning silviculture practices remains low in Laos, therefore efforts on training and the establishment of demonstrative plots need to continue with the aim of increasing high-quality timber and reducing rotation age of teak. Initial stocking rates of 1000 trees ha^{-1} or higher will require early management of competition to maintain the standing BA below 20 m^3 ha^{-1}. However, simple management regimes which do not require thinning may be more appropriate for smallholders. Intercropping teak with perennial crops is recommended for farmers with limited land and sufficient labour, in order to maintain annual cash incomes for a longer period (up to 5–8 years) and to produce high-quality teak. The next challenge is to

[...]and technology generated by research to the teak smallholders, [...]and policy decision makers of Laos.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes

1 Estimated seed requirement of 320 kg year^{-1}–15 000 ha on 25-year rotation, initial stocking of 1000 trees ha^{-1}, 1250 fruits kg^{-1} and average of 1.5 plants per fruit.

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