Resources

Silvicultural systems to optimise value from northern Australian mahogany plantations

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Forest & Wood Products Australia

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Executive Summary

African Mahogany Australia and Northern Tropical Timbers in partnership with Forest and Wood Products Australia and McGrath Forestry Services initiated a project in 2016 to understand the primary limitations to the productivity of African mahogany plantations in northern Australia. The objective was to provide guidance on the impact of silvicultural management (fertilization, thinning and pruning) on plantation productivity and processing options for the timber from the plantations in northern Australia. Initially the project had three main components:

- Assess the optimum thinning and fertilizer regimes for African mahogany across a range of sites in the Douglas Daly region. By assessing the site factors involved in determining the overall plantation productivity this knowledge will be transferable to a wider range of sites across northern Australia.
- Develop relationships between nutrient status and tree growth using data on growth and nutrient status (soil and foliage data) from existing and new fertilizer trials.
- Determine the impact of silvicultural inputs on processing performance (e.g. sawing, veneer production).

The first two components are described in the Silviculture section and the third in the Processing section of the report.

A market scoping study was added in the final year of the project as it was recognised that the knowledge gained from the silvicultural and processing studies provided the opportunity to explore the market options for Australian plantation grown African mahogany. Due to the provision of this material in a presentation format it has been included as Appendix 1.

Silviculture:

It was clear that the overall limitation to the productivity of African mahogany plantations in this region was the availability of water. The upper limit to productivity was strongly constrained by water availability and there were strong relationships between tree water status and productivity either on a short term (seasonal) or annual basis.

There were three distinct phases in the development of water stress in mahogany growing in the seasonally dry monsoon climate of the Northern Territory. During the wet season growth was rapid but ceased when maximum leaf water potential (Pre-dawn leaf water potential ψ_{PD}) declined to - 0.7 MPa. In the second phase, if the level of water stress imposed by the environmental conditions was modest, mahogany had the capacity to avoid severe drought stress by maintaining the minimum daily water potential (Midday leaf water potential Ψ_{MD}) at approximately - 2.5 MPa. However, under more severe and extended drought conditions mahogany was unable to avoid severe water stress, the end point of which was tree mortality.

Nutrient supply influenced the productivity of African mahogany in the Douglas Daly region, with combined N and P fertilizer doubling growth on low fertility sites and responses of between 30% and 50% observed on other sites. In contrast there were sites, mainly with better agricultural fertilizer history, where there was either limited or no responses to fertilizer. The response to fertilizer appears to last at least 4 growing seasons post fertilization, and the response increased over time since fertilization.

Importantly soil nitrogen (N) and soil organic matter (SOM) concentrations show considerable promise in identifying sites that will respond to fertilizer and the likely magnitude of those responses.

Plantation density influenced the level of productivity. Total volume production increased between 10% and 20% with increasing plantation density from 300 sph to 600 sph over 7 years from age 4.5 to 11.5. Increasing the density to 800 sph led to a reduction in growth and exposure of trees to mortality in dry years. On the two drier sites where the satellite thinning and fertilizer trials were installed stands at 400 sph were more productive than stands at 800 sph and on one site extensive mortality occurred in the 800 sph treatments.

On water limited sites thinning limited the water stress experienced by trees and maintained leaf water potentials above the critical threshold for tree death.

Water availability had a strong influence on the responses to fertilizer. In dry years fertilizer responses were limited and the high leaf area developed in response to fertilization under wetter conditions predisposed plantations to severe water stress and drought related mortality.

Competition from the vigorous understory that develops during the wet season had the potential to compromise the treatment effects so in addition to the normal cattle grazing that occurred in the mahogany plantations herbicides were used to control the understory/weeds in all trials. The combination of grazing and herbicides maintained the trials in a weed free condition.

Variable lift pruning increased the clear bole length of the butt logs by 1.0 m to 1.5 m. and did not reduce the growth of mahogany at a stand level. There was a small transient reduction in the individual tree diameter growth of co-dominant trees on one site. Observations from stem cross sections and veneer sheets showed that mahogany rapidly occluded pruning wounds. The presence of fungal fruiting bodies on pruning wounds on the wetter of the two pruning study sites and rot plumes in stem cross sections indicted that under some conditions pruning can degrade timber quality. It is likely that any negative impacts of pruning can be managed by pruning in the dry season so that fungal infections are minimised.

Silvicultural implications from these studies:

During the early to mid-stages of the plantations, mahogany should be maintained at or below 400 sph to optimise both stand and individual tree growth and reduce the likelihood of drought related mortality.

Growth of mahogany plantations will be optimised by the application of fertilizer at 4-5 year intervals. Further guidance on fertilizer rates is provided in Section 3.

Pruning does not reduce the stand level growth of mahogany and it is likely that any degrade in timber quality from fungal infections of pruning wounds can be managed by pruning in the dry season.

Future directions:
While the project has provided good direction on the silvicultural mamagement of plantations up to the mid rotation stage, continuing the silvicultural studies into the later part of the rotation will likely provide useful knowledge for plantaton management.

Now that process-based models are available in the APSIM framework for the Pinus and Eucalyptus industry in Australia, and that they are establishing their usefulness, it would be useful to the African mahogany industry to similarly consider process-based modelling. The data reported here could underpin that type of modelling and thereby provide a basis for yield forecasting, estimating potential carbon sequestration and virtual experiments.

Processing:

With many of the existing African mahogany plantations nearing mid-rotation, identifying suitable processing systems and target markets for material resulting from both thinning and final rotation harvesting was a priority. The wood processing laboratory operated by the Queensland Department of Agriculture and Fisheries was contracted to undertake processing studies on young African mahogany timber sourced from the Northern Territory and Queensland. In addition to the core processing studies undertaken by QDAF, the industry partners explored local sawing in the NT, producing sliced veneers and colour impregnation of young pale mahogany timber. Details of these additional studies are provided in the Appendices.

The effect of log geometry on the performance of rotary veneer production was modelled using the range of log diameter, taper and log sweep that have been measured within the current African mahogany resource, and the log geometries expected as the resource matures.

The simulations revealed that log geometry substantially affected the performance of rotary veneer manufacture. A comparison of the relative importance of log geometry characteristics on log value is subjective; however, characteristics in decreasing order of impact on log value were log length, sweep, small-end diameter under bark, taper and ovality. Log value reduced with increasing levels of taper, sweep and ovality. The analysis also revealed that the financial viability of veneering short logs (1.3 m) was challenging, suggesting 2.6 m logs lengths (or multiples thereof) need to be prioritised.

The potential recovery of veneer and sawn wood from African mahogany was assessed from four plantations in the NT and Queensland that provided a range of ages, growth rate and climate. Dry veneer recoveries between 56% and 73% of log volume where achieved with the variation mostly explained by log diameter and form (taper and sweep). Net veneer recovery ranged between 42% and 55% of log volume with the majority of veneers only achieving D-grade (Australian and New Zealand Standard AS/NZS 2269.0:2012). The recovery of veneer increased with increasing age, with more than 30% of veneers achieving C-grade or better from the oldest site (Windermere, NQ). Veneer defects which had the most impact on recovery included compression, surface roughness and grain breakout.

Sawn board recovery ranged from 35% to 49% with the variation also mostly explained by log diameter and form. The sawn-dried-dressed recovery was low with less than 20% of the log volume representing a potential saleable product in accordance with Australian Standards. Boards from all sites demonstrated high levels of board distortion. It is possible that the mechanism influencing board distortion (twist, spring and bow) in sawn boards may also influence the compression in veneers.

The impact of silviculture on veneer yield was assessed using trees from fast (low stocking, high fertilizer) and slow (high density low fertilizer) growing treatments from a dedicated silviculture trial located in the Douglas Daly region. Dry veneer recovery of 65% of log volume was achieved with butt logs from the larger fast growing trees compared with a 44% recovery from the smaller slower grown trees. The veneer grade recovery analysis showed that the majority of the recovered veneer failed to make a grade higher than D-grade, with *AS/NZS* 2269.0:2012

Recommendation

The phenomenon causing compression in the veneer and distortion in the sawn boards is not well understood. It is recommended that a focused study to understand this phenomenon is critical to developing management strategies.

Market Scoping Study

Margules Groome Pty Ltd were contracted to provide a market scoping study of domestic and international face and feature grade hardwoods to assist the current and future African mahogany growers understand the commercialisation potential of the African mahogany resource in Australia and the wider Asia Pacific region. This will allow for planning for value optimisation of the current and future African mahogany timber resource.

The details of the scope and analysis of this scoping study are provided in Appendix 1.

Recommendations:

Based on the market conditions in 2020 sawmilling, veneer/plywood processing and high-end blockboard options looks possible, subject to further research and considerations.

Additional market testing steps are required to provide:

- **(a) Proof of concept for design, marketing and manufacturing**
- **(b) Furniture design**
- **(c) Tailoring of new products to specific markets**

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Section 1: Introduction

Plantings of African mahogany (*Khaya senegalensis*) during the late 1960s and early 1970s in northern Australia demonstrated that it had wide adaptability, strong growth potential and good timber quality. Recent work on the physiological characteristics of African mahogany growing in the Douglas Daly region of NT demonstrated that the species, which evolved in a wet–dry tropical climate in West Africa (600–800 mm), appeared to be well suited to the seasonal savanna climate of northern Australia. Currently there are about 14000 ha of African mahogany plantations in the NT. Substantial plantation areas have also been established in north Queensland (Cooktown and Ingham to Bowen regions) and the Kununurra area of Western Australia.

The intended purpose of the African mahogany industry in northern Australia is to produce high-value, appearance grade timber products, which requires logs of suitable size and quality to match processing systems and wood with qualities that match market demands. The limited studies of wood properties and manufacturing suitability have demonstrated considerable promise as high value timber. However due to the limited area and relatively recent expansion of African mahogany plantations in northern Australia there is limited knowledge of how site factors and silvicultural inputs influence the productivity and wood quality of African mahogany plantations.

There has been significant investment in understanding the genetic diversity of African mahogany and defining the provenances that are suited to the northern Australian environment (Dickinson *et al.* 2009, Nikles 2006, Nikles *et al.* 2008, Reilly *et al.* 2007). However, the plantations used in the trials described in this report originate from wild seed collected from a range of geographic regions of west and central Africa. The diversity of this material is evident in the plantations. The development of superior planting material for future plantations will have a significant and positive impact on the African mahogany industry.

The capacity to market the timber into high value markets depends on ensuring both high quality and uniform wood properties are achieved. Understanding the productivity and wood quality of this emerging timber resource and the role of silviculture in optimizing both productivity and wood quality are essential for the development of the industry.

In addition to understanding the productivity of the plantations and the quality of the emerging African mahogany timber resource, ensuring that the timber will meet international sustainability certification requirements will be critical in accessing and maintaining markets for this timber.

The objective of the project was to identify the silvicultural inputs necessary to optimize the value of the African mahogany from existing and future plantations in northern Australia, this was done by:

- Determining the optimum silvicultural regimes (thinning, fertilization and pruning) for a range of sites with varying soil and climate conditions.
- Understanding the influence of nutrient status and nutrient supply on the growth of mahogany during the early to mid-rotation period.

- Determining the impact of silvicultural inputs (mid-rotation thinning fertilization and pruning) on the log and wood quality of plantation grown mahogany in northern Australia.

The first two components (Silviculture) are described in Sections 2-4 and the third (Processing) in Sections 5-7 of the report.

The project utilized well proven trial designs and experimental techniques to understand the impact of silvicultural interventions and site characteristics on the productivity and wood properties of a monoculture hardwood plantation.

This report is based on data from nine silvicultural trials established in the Douglas Daly Region of the NT. The trials were two nitrogen x phosphorus (NxP) factorial rate trials, one fertilizer rate trial, four thinning by fertilizer (TxF) trials and two pruning trials.

The locations of the trials are provided in Figure 1.1 and the brief details of the trials are provided in Table 1.1. Full details are provided in the subsequent sections of the report. Wood samples for the processing studies were sourced from both the NT and Queensland.

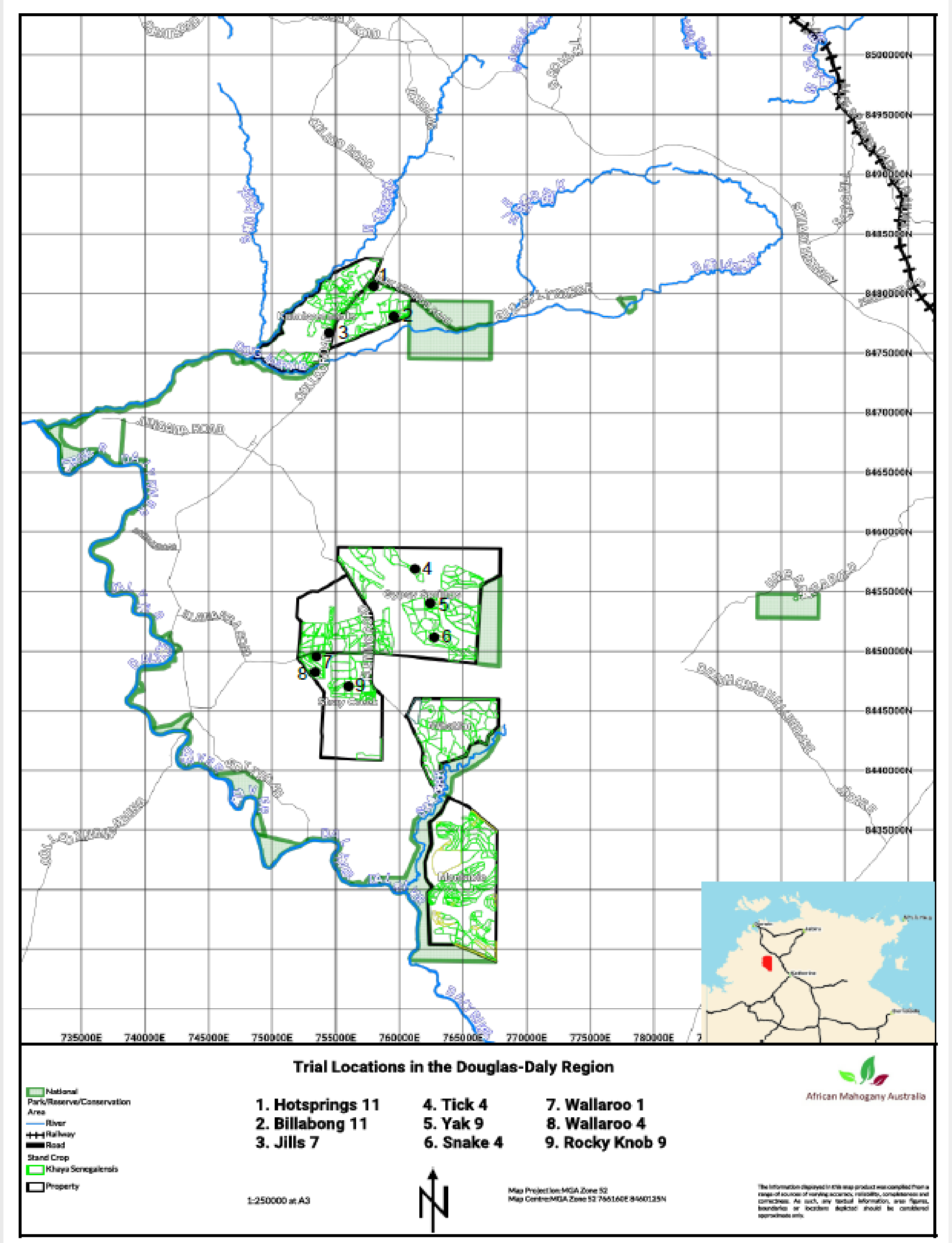

Figure 1. Location of the African mahogany silvicultural trials in the Douglas Daly Region

Table 1.1 Brief details of silvicultural trials

Trial Number	Plantation	Compartment	Trial type
1	Kumbyechants	Hot Springs	Thin x Fert
2	Kumbyechants	Billabong 11	Pruning
3	Kumbyechants	Jills	N x P rates
4	Gypsy Springs	Tick 4	Pruning
5	Gypsy Springs	Yak 9	N x P rates
6	Gypsy Springs	Snake 4	Thin x Fert
7	Stray Creek	Wallaroo 1	Thin x Fert
8	Stray Creek	Wallaroo 4	DAP rates
9	Stray Creek	Rocky Knob 9	Thin x Fert

Acronyms and Abbreviations, relevant to Sections 2, 3 and 4,

Company names	
AMA	African Mahogany Australia
DPIR	Department of Primary Industries and Resources
Huntley	Huntley Management Pty Ltd
MFS	McGrath Forestry Services Pty Ltd
NTT	Northern Tropical Timbers
QDAF	Queensland Department of Agriculture and Fisheries
DPIR	Department of Primary Industries and Resources (NT)

Measurement and technical terms	
Mahogany	African mahogany (Khaya senegalensis)
sph	Stems per hectare
DBHOB	Diameter at breast height (1.3 m) over bark
CAI	Current annual increment (measured over 1 year)
MAI	Mean annual increment (Measured over the life of the plantation
PAI	Periodic annual increment (measured over a set period e.g. 4-12 years)
LSD	Least significant difference (generally at P=0.05)
N	Nitrogen
P	Phosphorus
SOM	Soil organic matter
ψ_{PD}	Pre-dawn leaf water potential (maximum diurnal leaf water potential)
ψ_{MD}	Midday leaf water potential (minimum diurnal leaf water potential)
MPa	Mega pascal, unit of pressure/water potential
CWI	Climate wetness index = ratio of rainfall to potential evaporation (R/E)
WSI	Water stress index = Sum of ψ_{PD} * days over an annual period

Section 2: Optimising productivity and managing water stress of African mahogany *(Khaya senegalensis)* in the Douglas Daly Region NT by managing plantation density and nutrient status

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Summary

A series of trials which manipulated plantation density and fertility were installed on a range of sites that provided a gradient from low to high productivity in the African mahogany plantations in the Douglas Daly region of the Northern Territory. The variation in productivity imposed by the site and treatments and the wide range of climatic conditions experienced during the trials provided the opportunity to explore the sustainable levels of productivity in these plantations.

It was clear that the overall limitation to productivity of mahogany plantations in this region was the availability of water. The upper limit to productivity was strongly constrained by water availability and there were strong relationships between tree water status and productivity either on a short term (seasonal) or annual basis. Nutrient supply and plantation density strongly influenced the level of productivity.

There were three distinct phases in the development of water stress in mahogany growing in the seasonally dry monsoon climate of the Northern Territory. During the wet season growth was rapid but ceased when maximum leaf water potential (ψ_{PD}) declined to - 0.7 MPa. In the second phase, if the level of water stress imposed by the environmental conditions was modest, mahogany behaved in an isohydric manner with the capacity to avoid severe drought stress by maintaining the minimum daily water potential (Ψ_{MD}) at approximately -2.5 MPa. However, under more severe and extended drought conditions mahogany behaved in an anisohydric manner, the end point of which was tree death. That is, the mechanisms that contributed to the isohydric behaviour break down under more severe water stress.

There are clear silvicultural implications from these studies:

Total volume production increased between 10 and 20% with increasing plantation density from 300 stems per hectare (sph) to 600 sph over 7 years from age 4.5 to 11.5. Increasing the density to 800 sph led to a reduction in growth and exposure of trees to mortality in dry years. On water limited sites thinning maintained ψ_{PD} above the critical threshold for tree death.

Recommendation 1

During the early to mid-stages of the rotation, mahogany should be maintained at or below 400 sph to optimise both stand and individual tree growth and reduce the likelihood of drought related mortality.

Growth was optimised when fertilization eliminated nitrogen (N) and phosphorus (P) deficiencies, with growth increased between 35% and 100% by adequate levels of fertilization. It appeared that fertilizer improves growth for approximately 4 years after application hence optimising growth will require multiple fertilizer applications through the rotation.

Recommendation 2

Growth of mahogany plantations will be optimised by the application of fertilizer at 4-5 year intervals. Further guidance on fertilizer rates is provided in Section 3.

Introduction

Seasonally dry ecosystems with long dry seasons, such as the tropical savannas in northern Australia or the Mediterranean systems in southern Australia, provide significant water supply challenges for plants (Arndt *et al.* 2015). The suitable climatic range for African mahogany (*Khaya senegalensis,* hereafter mahogany*)* in Australia based on total rainfall and seasonal distribution, temperature regime and the duration of the dry season was defined by Booth and Jovanovic (2000) and subsequently revised by Arnold *et al.* (2004). The revised evaluation of the suitable climate was based on a subjective (non-quantitative) evaluation of the condition of 45 plantings of *K. senegalensis* across northern Australia. Using the climatic parameters defined by Arnold *et al.* (2004) the Douglas Daly Region in the Northern Territory (NT) was identified as a suitable climate for mahogany. Based on the success of mahogany plantings in the NT and the favourable assessment of the climate in the Douglas Daly Region ~14,000 ha of plantations were established between 2008 and 2015. While this broad climate evaluation has provided an outline of the suitable range for *K. senegalensis* it does not provide a quantitative assessment of the productivity of *K. senegalensis* growing in plantations in relation to climate and soil conditions.

An evaluation of the gas exchange and water relations of mahogany grown in plantation relative to the endemic native eucalypts of the Douglas Daly Region in the Northern Territory indicated that mahogany was well suited to the climate in this region (Arndt *et al.* 2015). Young mahogany experienced only mild drought stress with a predawn leaf water potential of -0.6 MPa in the dry season, leaf area halved from the maximum LAI of 2.4 in the wet season, and the minimum leaf water potential (midday) remained constant at -2.0 MPa across the seasons (Arndt *et al*. 2015).These authors concluded that mahogany demonstrated large phenotypic plasticity through the adjustment of leaf area and the maintenance of the minimum leaf water potential above -2.0 MPa, defined as isohydric behaviour. However this evaluation was conducted on young mahogany plantations which most likely were not fully exploiting the water resources of the site. Additionally, the relationships between water availability and the productivity of the plantations was not examined in either of these previous studies (Arnold *et al.* 2004. Arndt *et al.* 2015).

In contrast to the evaluation of the water relations of mahogany by Arndt *et al.* (2015) which indicated that mahogany was well adapted to that region, there were strong indications of localised drought stress in the Douglas Daly mahogany plantations following a below average wet season in 2014/15. In some plantations in the Douglas Daly Region extensive tip and upper crown death occurred and some whole tree mortality occurred. The majority of these symptoms occurred in unthinned stands (F. Miller, M Cleland pers. comm. 2016).

The link between biomass production and available water in seasonally dry, water limited environments in Australia has been understood since the work in defining the relationship between wheat yield and seasonal rainfall by French and Schultz (1984 a, b). Extensive studies of the impact of thinning in a wide range of species and environments have demonstrated that reducing stand density mitigates the impact of water stress in plantations and forests, e.g. Douglas-fir (Aussenac and Granier 1988), oak forests (Breda *etal*. 1995), loblolly pine (Cregg *et al.* 1990, Tang *et al.* 2003) and spruce (Laurent *et al.*2003). Studies in seasonally dry Mediterranean systems in southern Australia in hardwood eucalypts (White *et al.* 2009) and softwood plantations (Butcher and Havel 1976, Butcher 1977, McGrath and Dumbrell unpublished) plantations have demonstrated strong interactions between water availability and nutrient supply on the productivity of plantations grown in water limited environments. These studies indicate that thinning stands can reduce drought stress and promote the growth of the trees after thinning. From studies with other species, it is clear that responses to fertilizer depend on the plantations having sufficient water to respond to the increased supply of nutrients. Similar studies are lacking for mahogany in northern Australia.

Using a series of four trials we tested whether there were predictable relationships between growth and the development of water stress in *Khaya senegalensis* plantations that may be managed by thinning and the application of fertilizer. This was done by measuring the effect of thinning and the application of fertiliser on temporal patterns of growth and plantation water status on sites with varying climatic and site conditions within the Douglas Daly NT.

Background to trials

In developing the plantation estate in the Douglas Daly Region of the NT, African Mahogany Australia (AMA) has invested in expanding the knowledge base for mahogany plantations in the region and progress has been made in understanding:

- The range of sites available in the Douglas Daly Region and how that influences plantation performance.
- The techniques required to successfully establish mahogany plantations in the dry tropics.

Information on responses of mahogany to silvicultural treatments under the conditions in the NT is limited. Due to this, AMA initiated an R&D program with the objective of providing the best commercial and environmental outcomes from plantations in the Douglas Daly Region. This required a focus on optimizing the productivity and quality of timber through managing the stand density and nutrient supply to optimize growth and value from the plantations.

Wallaroo 1

An extensive trial to quantify the effects of levels of thinning, with and without fertilizer applications on plantation growth, was established in a four year old stand of mahogany in Douglas Daly Region in the NT in 2012.

Satellite TxF trials (Hot Springs, Snake 4, Rocky Knob 9)

Defining the mid rotation silviculture systems that optimize productivity in the dry tropics region of the NT was critical to optimising the value of these plantations. To achieve this, it is necessary to understand the responses to silvicultural inputs across the productivity range in the Douglas Daly Region. This series of trials extended the understanding of the responses to thinning and fertilizer by building on the comprehensive thinning by fertilizer trial established in 2012 in Stray Creek plantation (Wallaroo 1)

These additional trials were designed to:

- Assess whether thinning and fertilization increase the productivity of mahogany at both a stand and tree level across sites with a wide range of productivity.
- Determine if the level of drought stress is related to the condition of the plantation by varying the density and fertility of the plantations.
- Test whether the responses to thinning and fertilization were consistent across sites varying from low to high productivity

The aim of these trials was to provide data that will assist in defining the appropriate density for plantations on a range of sites and provide knowledge to balance productivity and the risk of drought mortality.

These trials extended the evaluation of alternative thinning and fertilisation regimes on total productivity and individual tree size across sites with a range of productivity.

Materials and Methods

Large scale thinning by fertilizer trial (Wallaroo 1)

Location

The site is located in the Stray Creek Plantation, Wallaroo Compartment 1. The trial was established in mid-2012 when the plantation was 4.5 years of age. Full details are available in the Trial Establishment Report (Unpublished; prepared by Fremlin 2012).

Table 2.1. Site description

Location	Lat/Long	Planting date	Trial established	Land Unit*	Landscape position
Stray Creek Wallaroo 1	14 ^{o}00'38.88"S /131 ^{o}20'46.14"E	Jan 2008	2012/2017	4b2 Tippera	**Mid/lower slope 0.8 % slope, west

* After Aldrick and Robinson (1972)
** While the site is a mid to lower slope site, the movement of water across the landscape is interrupted by the drains on the adjacent roads and tracks, meaning that despite its location in the landscape it is not a water gaining site.

Trial design and layout

The design had ten thinning treatments. At age 4.5 years five densities were imposed (with 8 replicates) and half of the initial treatments were thinned again at age 9.5 years to half their initial stocking (Table 2.1). There were two fertilizer levels (maintenance and adequate) with four replicate blocks that account for a slight slope and productivity gradient across the site. This provided a 10 x 2 factorial trial with 4 replicates (80 plots). The plot size was variable to provide a statistically acceptable number of trees (30) in each plot and to accommodate this requirement when half the trees were removed in the second thinning these plots initially had 60 trees. Between age 4.5 years and 9.5 years there were 8 replicates of the treatments. After age 9.5 years all treatments had 4 replicates. Treatment plots were 9 rows wide with internal measurement plots of 7 rows.

Table 2.2. Details of treatments in the Wallaroo Thinning by Fertilizer trial

Low fertilizer 400 kg Rustica/ha at Time (T)1 nil fertilizer at T2			**Plus fertilizer 800 kg Rustica/ha at T1 1000 kg DAP/ha at T2**		
Treatment number	Stocking after T1 (2012, 4.5 years)	Stocking after T2 (2017, 9.5 years)	**Treatment number**	Stocking after T1 (2012, 4.5 years)	Stocking after T2 (2017, 9.5 years)
1	800	800	11	800	800
2	800	400	12	800	400
3	600	600	13	600	600
4	600	300	14	600	300
5	500	500	15	500	500
6	500	250	16	500	250
7	400	400	17	400	400
8	400	200	18	400	200
9	300	300	19	300	300
10	300	150	20	300	150

Thinning and debris management

Thinning was done to ensure that vigorous trees with good form (straight stems with minimal lean or sweep, small branches) were retained and there was an even distribution of trees in the plots. In both thinning operations culled trees were directionally thinned so that the debris was placed in every second row which maintained access for fertilizer applications and subsequent herbicide applications in the clear row.

Fertilizer applications

The initial fertilizer was a mixed blend (Rustica®) which was broadcast. The fertilizer was applied as a basal dressing at 400 kg ha^{-1} to all plots. The basal dressing was applied as operational foliage analysis indicated the area had low and declining N and P concentrations. The basal application of 400 kg ha^{-1} Rustica applied 48 kg N ha^{-1}, 20 kg P ha^{-1}, 56 kg K ha^{-1}, 33 kg S ha^{-1}, 18 kg Ca ha^{-1} plus small amounts of Mg, Zn and B. This application was judged to provide a moderate supply of nutrients for the young plantation consequently there was no nil fertilizer (control) treatment in the first phase of the trial. The plus fertilizer treatments received an additional 400 kg ha^{-1} of Rustica at age 4.5 years, and a second fertilizer application of 1.0 tonne of DAP (180 kg N ha^{-1}, 200 kg P ha^{-1}) at the beginning of the wet season in November 2017 when the trees were 9.8 years old (Table 2.2). No additional fertilizer was applied to the nil fertilizer treatments.

Satellite thinning by fertilizer trials

Location and site details

Three thinning by fertilizer trials (TxF) were established in the Kumbyechants, Gypsy Springs, and Stray Creek plantations in the Douglas Daly Region of the NT (Table 2.3).

Table 2.3. Site description

Location	Lat/Long	Planting year	Trial established	Land Unit	Landscape position
KBC Hot Springs	13 ºº42’49”(S) 131 º23’2” (E)	Jan 2012	2016 (age 4 yrs)	3d	*Mid slope, 0.2% slope, water gaining
Gypsy Springs Snake 4	13 º59’44”(S) 131 º25’42”(E)	Jan 2012	2016 (age 4 yrs)	4a2	Mid/lower slope, 1.4% slope
Stray Creek Rocky Knob 9	14 º02’26”(S) 131 º22’13”(E)	Jan 2009	2016 (age 7 yrs)	4b2	Upper slope/ridge, flat,

* While the site is mid slope it gains considerable water from the cleared adjacent farmland. Water was observed flowing through the site in the 2016/17 and 2027/18 wet seasons and a soil pit in the site remained full of water for at least 3 months into the dry season.

Study design and layout

Sites were selected in unthinned (~800 sph) and unfertilized areas in plantations that provided low (Stray Creek, Rocky Knob 9), medium (Gypsy Springs, Snake 4), and high (Kumbyechants Hot Springs) productivity in October 2015.

The study design varied between the sites. At Rocky Knob 9 and Snake 4 the trials were factorial block design of three densities (nominally 200, 400 and 800 sph) by two fertilizer applications (+/-), replicated in 3 blocks (18 Plots total at each site). At KBC Hot Springs the trial was a factorial block design of two densities (nominally 300 and 800 sph by two fertilizer applications (+/-), replicated in 2 blocks. The reduced design at KBC Hot Springs was due to the significant variation in the initial stocking. The responses to thinning and fertilization were assessed on this high productivity site using a more limited trial design (2x2x2 reps) (Table 2.4).

Plots were 9 rows wide (32.4 m) and to provide the same number of trees in the measurement plots for the various densities the length varied from 24 m for the 800 sph treatments to 60 m for the 200 sph treatments This arrangement provided a 2 row buffer around the internal 5 row measurement plots and provided a minimum of 17 trees in the measurement plots.

A total of 44 plots were installed across the 3 sites. Tree height and diameter at breast height over bark (DBHOB) were measured and basal areas and stocking (based on the measurement plot area) were calculated and used to assess the uniformity of the site. Trees that remained after the thinning were permanently marked at breast height (1.3 m).

Prior to the fertilizer application in January 2016, soils were sampled from the inter-row area within each measurement plot with 24 cores 100 x 20 mm cores taken at 3 locations by 8 replicates

Thinning

The trial was thinned to the required densities in the dry season of 2015 (October) and the fertilizer was applied mid wet season (late January 2016). The thinning was done directionally to provide access down every second row. The thinning selection was based on both the commercial value of the trees and the spatial distribution of the trees within the plantation.

Fertilizer application

The fertilizer treatments (400 kg N ha^{-1}as urea and 100 kg P ha^{-1}as superphosphate) were broadcast by hand on 23rd and 24th January 2016.

Leaf water potential

Maximum (predawn ψ_{PD}) and minimum (midday ψ_{MD}) leaf water potentials (ψ) were measured using a pressure chamber (Model 3000, Soilmoisture Equipment Corp., Santa Barbara, CA, USA) after Scholander *et al.* (1965). Four treatments at each site (highest and lowest densities and plus and minus fertilizer) were measured at approximately 6 week intervals for three annual growth cycles covering the period from March 2017 to November 2019 for predawn (ψ_{PD}) and for the period March 2017 to November 2018 for midday (ψ_{MD}). Due to the time taken to collect and measure ψ, samples were taken from three trees near the mean diameter from two of the replicate plots for these treatments, this provided 6 samples for each measurement of ψ. Samples were cut from the lower part of the canopy (between 4 m and 7 m) using a pole clipper and the individual leaflets were immediately placed in sealed plastic bags on ice in the dark. Due to the ragged cut from the pole snipper the stems were recut with a sharp blade immediately prior to measuring ψ. Measurements were made within 15 - 30 minutes of sampling. Although longer than 15 minutes as recommended by Arndt *et al.* (2015), a series of time course studies at the beginning of the sampling in 2017 verified storing the samples for this period did not change readings.
In addition to providing an assessment of tree water status the ψ_{PD} were used to calculate the cumulative water stress integral (WSI = MPa Days) for each period and this was integrated to provide an annual estimate of WSI (Myers 1988).

$$WSI = \sum [(\psi_{PDx} + \psi_{PDX+1})*days/2]$$

Table 2.4. Summary of trial design and installation details**,**

Sites	Rocky Knob 9 and Snake 4	Hot Springs
Trial design	Factorial (3 Densities x 2 Fertilizer rates)	Factorial (2 Densities x 2 Fertilizer rates)
Replicate blocks	3	2
Total Plots	18	8
Plot arrangement	9 Row treatment plot, with a 5 row internal measurement plot surrounded by a 2 row buffer	9 Row treatment plot, with a 5 row internal measurement plot surrounded by a 2 row buffer
Plot size	Variable to provide a minimum of 17 trees per plot	Variable to provide a minimum of 17 trees per plot
Initial spacing	~800 sph	~800 sph
Treatment stocking	800, 400, 200 sph	800, 300 sph
Soil samples	21 Jan -22 Jan 2016	
Fertilizer applications	23/01/2016 400 kg N ha^{-1}as Urea 100 kg P ha^{-1}as superphosphate	24/01/2016 400 kg N ha^{-1}as Urea 100 kg P ha^{-1} as superphosphate
Initial measurements	Stray Creek Diam 23/01/16 Ht 25/01/16 Snake 4 Diam 21/01/16 Ht 06/02/16	Diam 21/01/16 Ht 05/02/16
Gross area of trial	~2.5 ha at each site	1.0 ha

Common methods

Climate

Monthly rainfall and potential pan evaporation data were obtained from SILO for the period from 1999 to 2019 (Jeffrey *et al.*, 2001) for the three plantations in which the trials were established and aggregated to provide an overview of the climate of this region. These data were used to calculate the climate wetness index (CWI) which is the ratio of rainfall to potential evaporation (R/E) for the trial sites over this period (Table 2.5). As the growth of the trees in this region is strongly related to the wet season the annual climate data are provided for the period September to August rather than on an annual calendar basis. The annual data for the measurement periods were used to assess the impact of climate on productivity (Fig 1.12)

The region has a seasonally dry monsoonal climate with constantly high temperatures and strong wet season. The mean annual rainfall in the Douglas Daly Region is ~1300 mm/year (Table 2.5). There is a significant north south rainfall gradient across the region, with the more southerly Stray Creek and Gypsy Springs plantations receiving less rainfall than the Kumbyechants (KBC) plantation. This effect is more noticeable in dry years with little variation between the sites under wet conditions, but the southern plantations received ~170 mm less rainfall in dry years (Table 2.5).

Table 2.5. Mean climate data for site locations for the 20 year period 1999/00 -2018/19

Plantation	Rainfall (mm) range	Evaporation(mm) range	CWI (R/E) range
Kumbyechants	1348 (974-2089)	2361 (2137-2725)	0.57 (0.36-1.00)
Gypsy Springs	1294 (807-2006)	2384 (2111-2737)	0.54 (0.29-0.95)
Stray Creek	1251 (801-1989)	2366 (2090-2737)	0.52 (0.29-0.95)

Coppice management

Following thinning coppice was controlled by hand spraying with a mixture of glyphosate (450 gm/L) plus metsulfuron-methyl (600 gm/kg) with an organosilicon adjuvant once coppice reached approximately 0.5 m tall. During the second thinning which was done with a mechanical harvester the stumps were sprayed with Access ® (240g/l Triclopyr 120 g/l Picloram) in diesel.

Weed control

The entire trial areas were sprayed with a mixture of glyphosate and SulfometuronMethyl 750 g/kg. At Wallaroo 1 this occurred when the trial was established and for the second phase of the trial before the fertiliser treatments were applied in November 2017. For the satellite TxF trials, the herbicide was applied after the fertilization applications in January 2016. In addition to the herbicide applications the trial areas were grazed with cattle from 2016 onwards. These combined treatments maintained the areas in a weed free condition.

Growth measurements

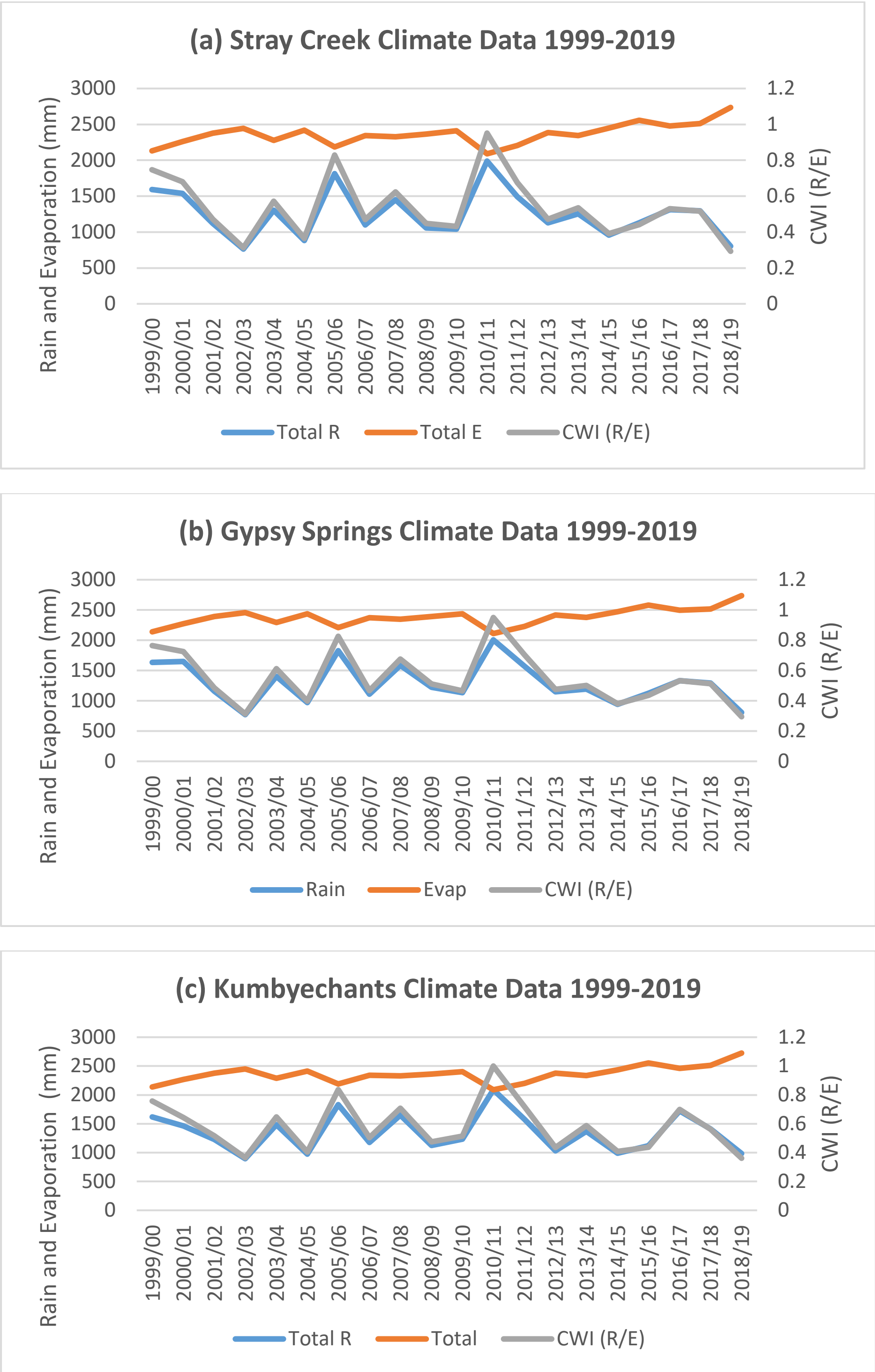
Tree height and DBHOB were measured at the commencement of the trials and annually for the calculation of current annual increments (CAI). For the large TxF trial (Wallaroo 1) the initial measurement was on 14 May 2012 (age 4.3 years) and subsequently in late May to early July from 2013 to 2020. Due to the 14 month interval between the first and second measurements the increment was adjusted to a 12 month interval for this period. These data are identified as having been adjusted in Figure 2.13. For the three satellite trials the initial measurements were taken in January 2016 and annually in the middle of the dry season (June) in 2016, 2017, 2018 and 2019. To assess seasonal growth in relation to tree water status, diameter was measured quarterly to coincide with every second measurement of leaf ψ. Diameter was measured at 3 monthly intervals as the errors were judged to be too large to be meaningful at shorter time periods. Diameter measurements were used to estimate basal area and volume. Total volume was estimated using a volume equation developed from sectional stem analysis of 49 trees ranging from 9 to 39.1 cm diameter. The equation used to estimate volume was:

$V = 0.0365 - 00.00652\ D + 0.0006\ D^2$, $R^2 = 0.992$

Results

Climate details and trends in the Douglas Daly Region

Figure 2.1 Climate indices for Stray Creek Plantation over the period 1999-2019



The climate data over the past 2 decades in the Douglas Daly Region demonstrates some clear trends. These are:

- Evaporation is relatively similar across the 20 years, with a number of high and low years.
- Rainfall is more variable than evaporation with the lower rainfall less than half of the highest rainfall.
- Dry years (~6 - 7) occur about twice as frequently as wet years (~3 - 4).
- Climate wetness index (CWI) tracks rainfall closely (due to the uniformity of evaporation), though in a couple of instances the lower evaporation in wetter years means that the CWI is a higher than expected based solely on rainfall.
- In the last 3 seasons the trend in rainfall has been different between KBC and the 2 southerly sites, with the southerly sites missing out on the above average wet season in 2016/17. This aligns with the overall analysis (Table 2.5) which indicates that the more southerly sites are noticeably drier in dry years.

The impact of thinning and fertilizer on productivity – The initial TxF trial Wallaroo

The initial thinning removed up to 20 m^3ha^{-1} from the stands resulting in between 10 and 30 m^3ha^{-1} in retained volume at age 4.5 years (Figures 2.2a and 2.2b). There was a 20% increase in volume production between 300 and 600 sph in the fertilized treatments (Table 2.6, Figure 2.2 a) and a 10% increase for the unfertilized treatments (Table 2.6, Figure 2.2a), over the same density range. There was a decline in volume production between the 600 and 800 sph treatments in both the fertilized and unfertilized treatments, which meant that over 8 years since the initial thinning that the 300 sph treatment produced the same volume as 800 sph. The modest increases in volume increment with increasing plantation density (Figures 2.2a and 2.2b) contrasted with the 45% increase in annual increment in the first year following thinning between the 300 and 800 sph fertilized treatments (Figure 2.2a). This difference had disappeared 5 years after thinning.

The response to the first and second fertilizer applications increased over time since application and this trend was consistent across all stockings (Figure 2.3). Independent analyses of variance at each measurement indicated that the differences between stocking and fertilizer treatments were significantly different at $P \leq 0.001$. There was no interaction between stocking and fertilizer as indicated by the uniform response to fertilizer over the course of 8 years (Figures 2.2a,b; 2.3a,b) and after the second fertilizer application (Figure 4a)

Table 2.6. Summary of periodic annual increments (PAI) for 2012-20 for the thinning x fertilizer trial at Stray Creek Wallaroo 1

Stray Creek Wallaroo 1	PAI ($m^3ha^{-1}yr^{-1}$)	PAI ($m^3ha^{-1}yr^{-1}$)
Stocking (sph)	**Unfertilized**	**Fertilized**
300	5.3	7.3
400	4.8	7.7
500	5.7	8.2
600	5.8	8.9
800	5.2	7.5

The similar volume production by the 300 sph and 800 sph treatments in the 8 years after the initial thinning results in significantly larger trees in the lower stocked treatments. This is likely advantageous for harvest logistics and product recoveries (see Section 5, Log Geometry). Over the period since the initial thinning and fertilization the annual increment averaged 7.9 m^3ha^-

$^{1}yr^{-1}$ for the fertilized treatments and 5.4 $m^3ha^{-1}yr^{-1}$for the unfertilized treatments or a 48% increase in growth due to fertilizer. The response to fertilizer was larger following the second fertilizer application. This may be due to the initial fertilizer treatments providing a comparison between low and high applications whereas the subsequent application was an application only to the previous high nutrient treatments and also contained more P and N.
The volume production at Wallaroo is approximately one third of the volume production that was measured at the wetter satellite TxF site trial at KBC Hot Springs (see Figures 2.6(a), 2.14, and 2.15). The absence of a strong impact of density on growth and the modest productivity on this site (Wallaroo) indicates that water availability limits growth at this site.

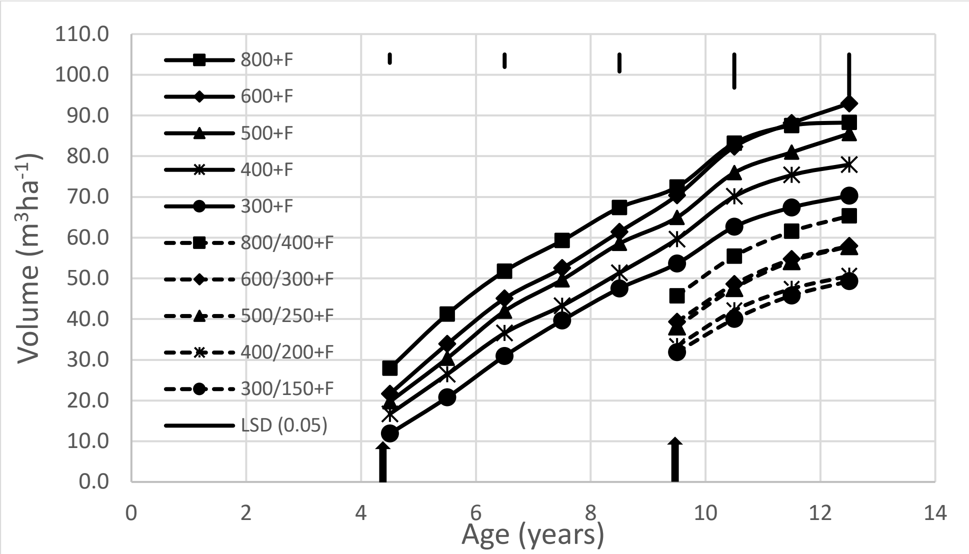


Figure 2.2(a). Impact of stocking on volume in fertilized stands at Wallaroo from age 4.5 to 9.5 years. Arrows indicate timing of thinning and fertilization at age 4.5 and 9.5 years. LSD (p=0.05) shown as vertical bars at every second measurement.

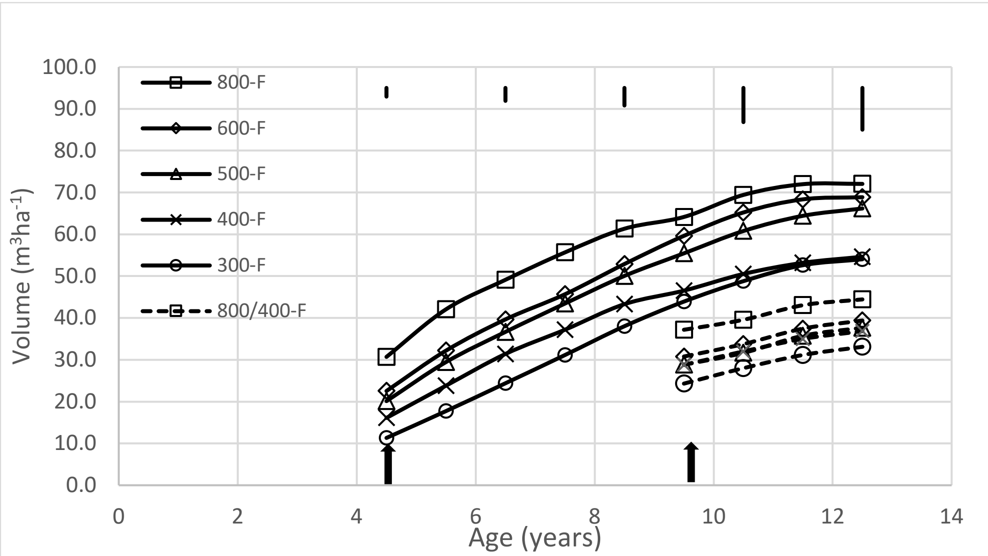


Figure 2.2b. Impact of stocking on volume in unfertilized stands at Wallaroo. Arrows indicate timing of thinning and fertilization at age 4.5 and 9.5 years. LSD (p=0.05) shown as vertical bars at every second measurement.

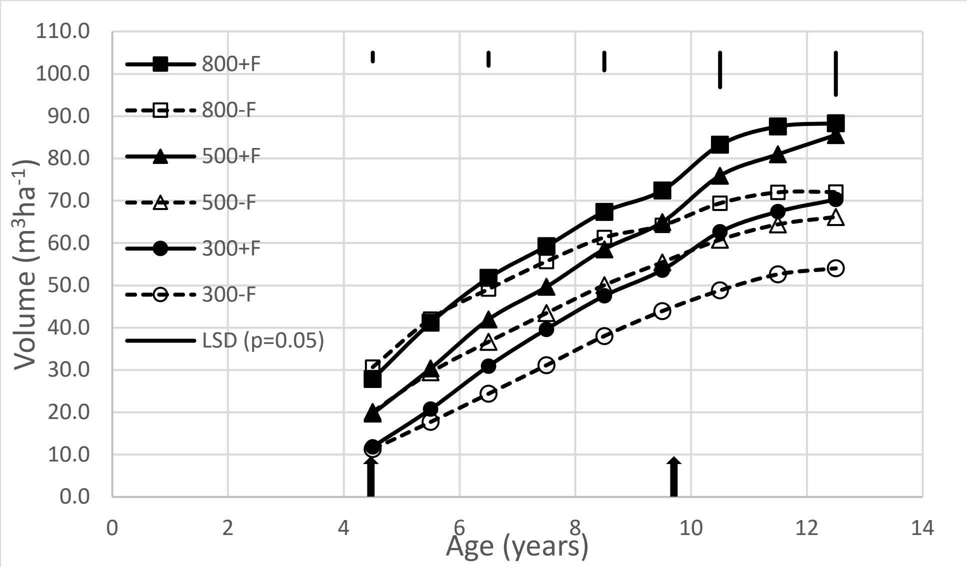


Figure 2.3a. Impact of fertilizer and stocking on volume in stands thinned at age 4.5 years to 12.5 years. Arrows indicate timing of fertilization at age 4.5 and 9.5. LSD (p=0.05) shown as vertical bars at every second measurement.

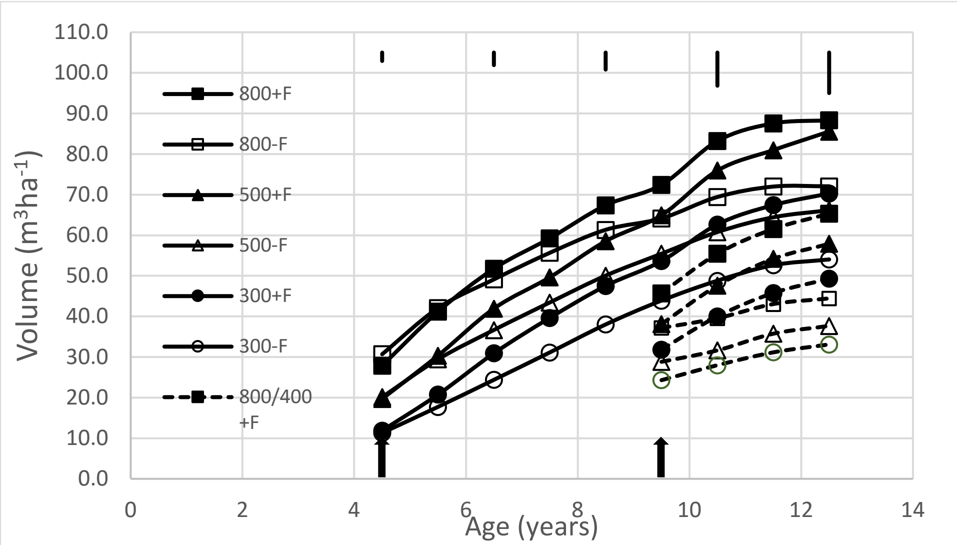


Figure 2.3b. Impact of fertilizer and stocking on volume production in stands to age 12.5 years in stands thinned at age 4.5 years and 9.5 years. Arrows indicate timing of fertilization and thinning at ages 4.5 and 9.5 years. Open symbols are unfertilized treatments, solid symbols are fertilizer treatments. Solid lines for treatments thinned once at age 4.5 years, dashed lines for treatments thinned a second time at age 9.5 years. . LSD (p=0.05) shown as vertical bars at every second measurement.

The response to fertilization following the second thinning was larger than with the initial application (Figures 2.3a and 2.3b). The fertilized treatments produced double the volume of the unfertilized treatments (17.5 m^3ha^{-1}compared to 8.8 m^3ha^{-1}Figure 2.4a). When the increment was combined for the 3 years after the second fertilizer application there was no significant influence of stocking on volume production (Figure 2.4a).

Despite that absence of an overall interaction between stocking and fertilizer (Figure 2.4a), the volume increment varied between the first, second and third years after the second thinning and fertilization at age 9.5 years (Figure 2.4b). In the first year after fertilization, when rainfall was near the long term mean at 1295 mm, volume increment increased from 8 and 12 $m^3ha^{-1}yr^{-1}$ as stand density increased from 150 to 600 sph (Figure 2.4a) In contrast the increment in the second year, which was drier (802 mm) the increment was relatively similar across the density range at approximately 6 $m^3ha^{-1}yr^{-1}$, though with a slight tendency to decline with increasing density (Figure 2.4b). In the third year post fertilization when rainfall was also low (850mm) the volume increment was again lower and declined with increasing stocking, with virtually no growth occurring at the highest density (800 sph). In the first two years the volume increments for the unfertilized treatments were similar across the density range at about 4 $m^3ha^{-1}yr^{-1}$.(Figure 2.4b). In the third year very little growth occurred in the unfertilized treatments with 2 $m^3ha^{-1}yr^{-1}$ growth occurring at densities between 150 and 500 sph and virtually no growth occurring at 600 and 800 sph (Figure 2.4b).

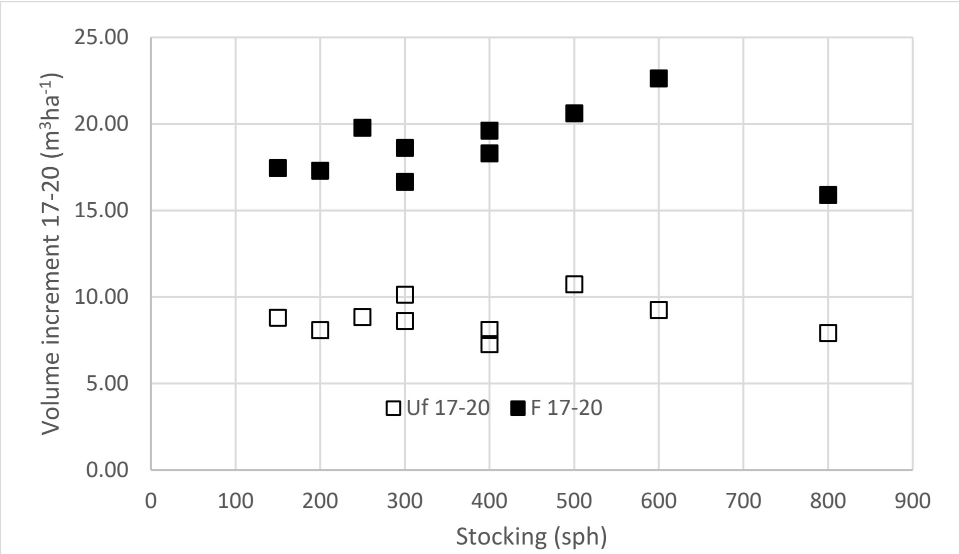


Figure 2.4a. Impact of fertilizer and stocking on the volume increment in the three years post thinning in stands second thinned at age 9.5 years (2017-20).

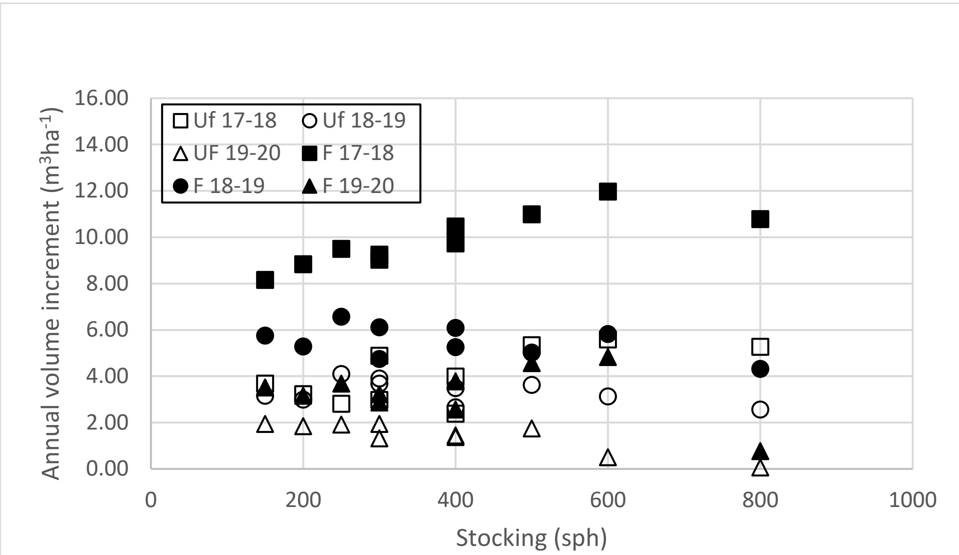


Figure 2.4b Impact of fertilizer and stocking on annual volume increment in the three years post thinning in stands thinned at age 9.5 years (2017-18, 2018-19, 2019-20).

Diameter increment was strongly influenced by both stocking and fertilizer application (Figures 2.5a and 2.5b). Fertilizer strongly increased diameter increment and diameter increment increased as stocking decreased. The same variation observed for volume in the 3 years following the second fertilizer treatment were apparent for diameter. Diameter growth in the fertilized treatments were greater in the first year and was successively lower in the second and third years. There was little difference between diameter growth of the unfertilized treatments in the first and second years (Figure 2.5b). In the third year the diameter increment was considerably lower that in the first two years. The differences in diameter growth were smaller as the stocking increased and in drier years (Figure 2.5b). This indicates that the response to fertilizer depends on having sufficient water to respond to the additional supply of nutrients. This is explored further later (see Figures 2.12 and 2.13).

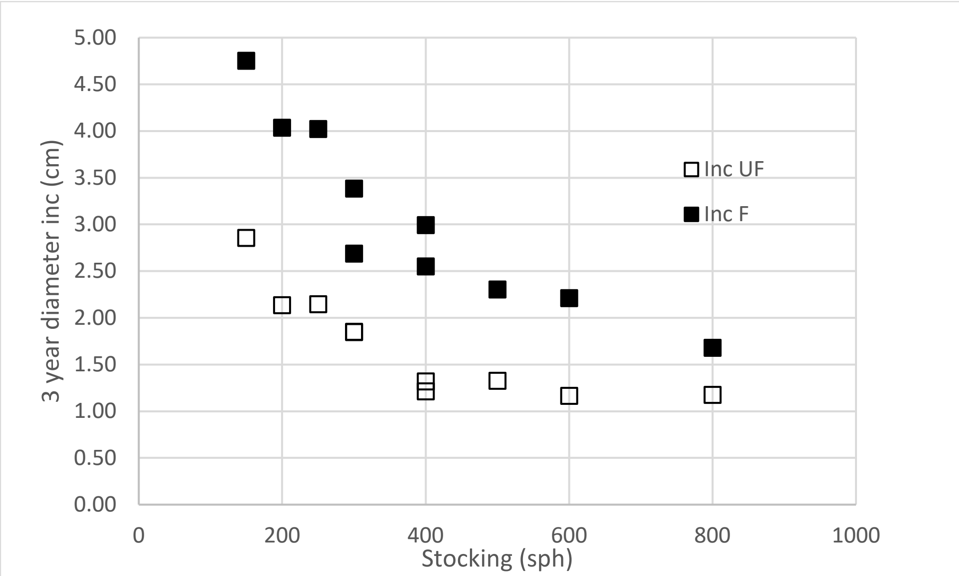


Figure 2.5a. Impact of fertilizer and stocking on the diameter increment in the three years post thinning in stands thinned at age 9.5 years (2017-20). Open squares unfertilized, solid squares fertilized.

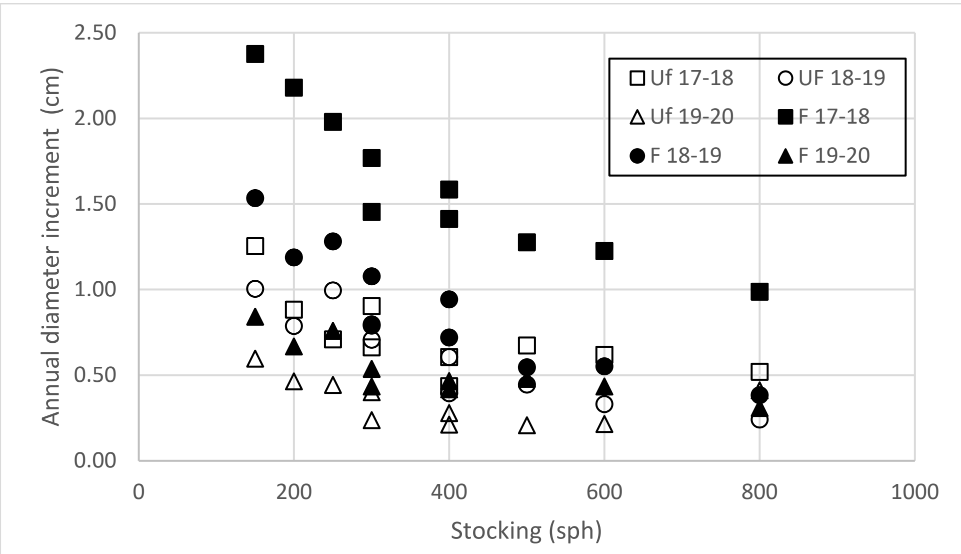


Figure 2.5b. Impact of fertilizer and stocking on annual diameter increment in the three years post thinning in stands thinned at age 9.5 years (2017-18, 2018-19, 2019-20). Open symbols unfertilized, solid symbols fertilized.

Summary of trends

The lack of a response in volume production to increasing density (from 150-800 sph, Figure 2.4b) indicated that growth at this site was strongly limited by water supply.

Growth was also limited by nutrient supply with the overall increase in growth from fertilizer application in the order of 48% (Figure 2.3). This is likely to be an underestimate of the full fertilizer response as in the initial phase of the trial there was no nil fertilizer treatment, with the 'minus' fertilizer treatment receiving half the fertilizer application of the high fertilizer. This limited the apparent fertilizer response. Volume growth was doubled in the two years following the second application of fertilizer.

The absence of a strong response to stocking in terms of volume productions indicates that there is little or no growth penalty from maintaining plantation density in the order of 200-300 stems per ha.

The larger stem volumes in the lower stocked treatment and the lower levels of water stress in the less dense treatments on similar sites (see following section Figures 2.7, 2.9) provide significant advantages from low density stands.

Impact of site, thinning and fertilization on the productivity and drought stress of mahogany - The Three satellite T x F trials

Tree growth

There were large differences in the volume production between the sites (Table 2.7, Figures 2.6 to 2.8) which appears strongly related to the availability of water (Figures 2.9 and 2.10). At the KBC Hot Springs site, where the lowest level of water stress was measured, the PAI in the 3.5 years since the thinning and fertilizer treatments were applied the best performing treatment (800+F) has averaged 22.5 $m^3ha^{-1}yr^{-1}$. In contrast for the most productive treatments the PAI's for the Snake 4 and the Rocky Knob sites, which experienced significant water stress, were respectively 9.7 and 8.2 $m^3ha^{-1}yr^{-1}$ (Table 2.7).

Table 2.7. Summary of periodic annual increments (PAI) for 2016-19 for the thinning x fertilizer trials at Hot Springs, Snake 4 and Rocky Knob 9.

Stocking (sph)	PAI ($m^3ha^{-1}yr^{-1}$)	PAI ($m^3ha^{-1}yr^{-1}$)
Hot Springs	**Unfertilized**	**Fertilized**
300	14.08 (0.35)	18.92 (0.20)
800	16.84 (1.85)	22.49 (3.65)
Snake 4		
200	5.27 (0.48)	8.31 (1.64)
400	7.06 (0.69)	9.69 (1.42)
800	5.58 (1.68)	8.41 (3.62)
Rocky Knob 9		
200	3.33 (0.52	6.21 (0.44)
400	3.62 (0.47)	8.24 (0.51)
800	3.77 (0.27)	5.66 (1.51)

There was a significant difference in the progression of growth through the seasons with the high productivity Hot Springs site growing continuously throughout the year (Figure 2.6a) until July 2019, while the lower productivity sites at Snake 4 and Rocky Knob 9 showed distinctly seasonal growth patterns in each year with lengthy periods in the dry seasons where growth ceased and in some cases the trees appeared to shrink (Figures 2.6b and 2.6c).

These patterns were even more pronounced during the dry season in 2019 (Figure 2.6) which followed a wet season with very low rainfall of ~800 mm across the Douglas Daly region and a late commencement of the 2019/20 wet season. There was no significant increase in growth from April 2019 to late January 2020 in any of the treatments at the Snake 4 and Rocky Knob sites (Figure 2.6 b and 2.6c). There was significant mortality in the higher density fertilized treatment at Snake 4 late in 2019- early 2020 (Figure 2.6 c). At the wetter Hot Springs site the cessation in growth occurred later in the lower density (300 sph) treatments (Figure 2.6 a).

There were significant responses to fertilizer at all three sites (Table 2.7 and Figure 2.6). These responses emerged in the second growing season after application and were sustained for the subsequent 3 growing cycles (Figure 2.6). The exception to the continued positive impact of fertilizer occurred in the 800 fertilized treatment at Snake 4 where significant mortality occurred at the end of the 2019 dry season. The impact of this was unevenly distributed within the trial with some mortality evident in all replicates, however one replicate (Rep 3) experienced 90% mortality.

Individual tree volume increased strongly with both decreasing density and increasing fertilizer application at all sites (Figure 2.7 a, 2.7b and 2.7c)

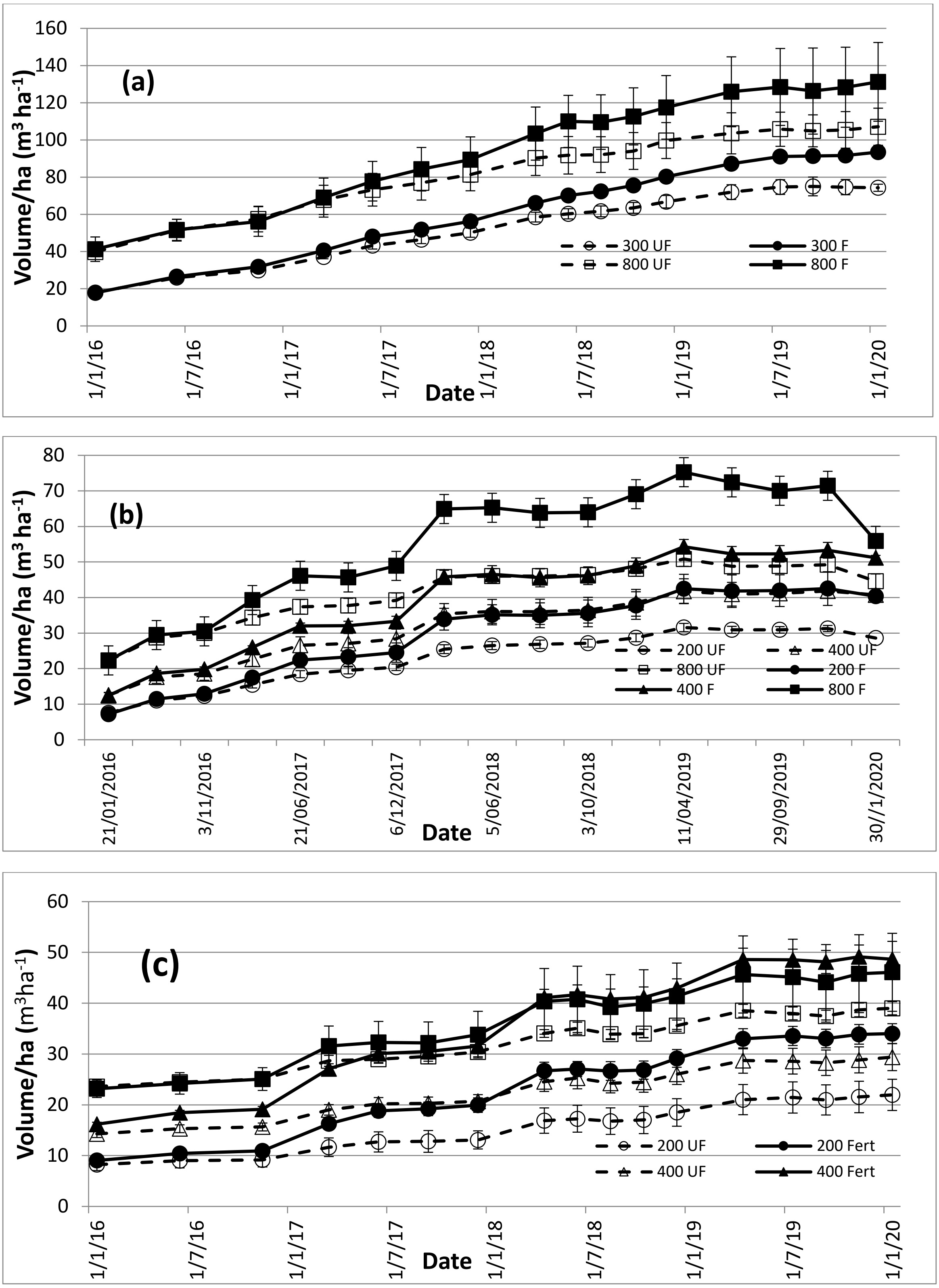


Figure 2.6: Impact of stocking and fertilizer application on total volume production at three separate sites (a) Hot Springs, (b) Snake 4, (c), Rocky Knob 9. Note the difference in scale between the volume growth for the different sites. Note the change is scale on the Y axes at the different sites.

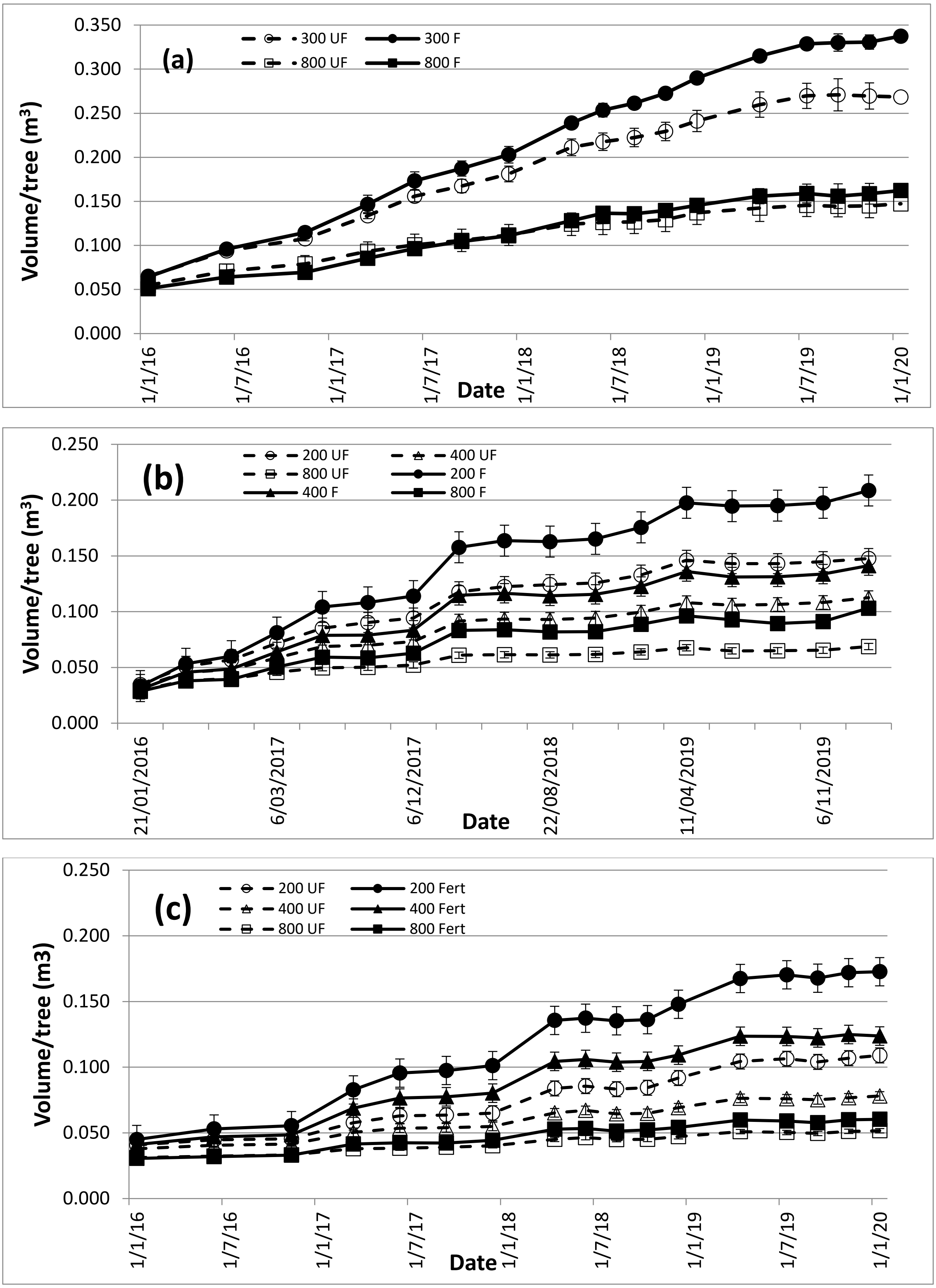


Figure 2.7: Impact of stocking and fertilizer application on mean tree volume production (m^3/tree) at three separate sites (a) Hot Springs, (b) Snake 4, (c), Rocky Knob 9. Note the change is scale on the Y axes at the different sites.

Similar to volume growth, there was a strong influence of site on height growth over the period of the trial with height decreasing in the order Hot Springs, Snake 4 and Rocky Knob. While there was a consistently lower height in the denser plots (Figure 2.8), this effect was small relative to the trends in volume growth

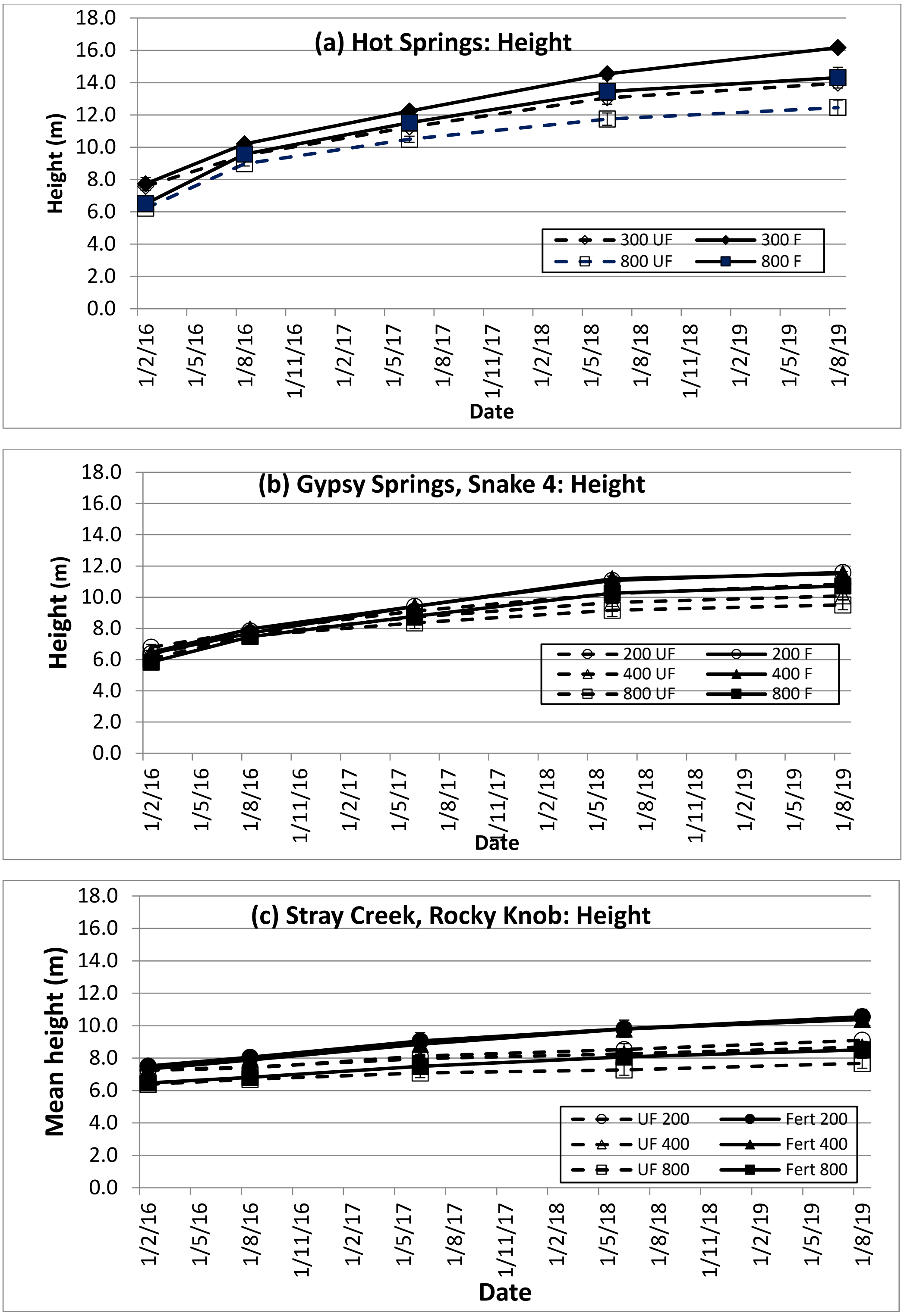


Figure 2.8. Impact of stocking and fertilizer application on mean tree height (m) at three separate sites (a) Hot Springs, (b) Snake 4, (c), Rocky Knob 9.

Site, season, and treatment influences on tree water stress levels

The pre-dawn leaf water potentials (ψ_{PD}), which provide a measure of the minimum daily level of water stress experienced by the trees showed distinct differences between the sites and across the seasons (Figures 2.9 a, 2.9b and 2.9c). Until the third year of monitoring there was only a small decline in ψ_{PD} during the dry season at Hot Springs, and there were virtually no differences between the thinning and fertilizer treatments in the first two years post thinning (Figure 2.9a). By late September in the third year (2019) ψ_{PD} declined to ~-1.8 MPa in the higher density fertilized treatment (800 sph +F, and to between -0.8—1.1MPa in the other treatments (Figure 2.9 a).

There were strong seasonal and treatments differences in ψ_{PD} at the drier Snake 4 and Stray Creek Rocky Knob sites (Figures 2.9 b and 2.9c). At both these sites there was a strong decline in ψ_{PD} during the dry season in all three years. The lower rainfall in the 2018/19 wet season (Figure 2.1) is reflected in the lower ψ_{PD} at all sites, particularly in more southerly sites and denser treatments. There was a strong impact of the high density/high fertilizer treatments on ψ_{PD} which experienced lower ψ_{PD} (Figure 2.9). This effect was most marked at the Snake 4 site where ψ_{PD} declined to ~-3.7 MPa in 2019 (Figure 2.9b). These trends became stronger both as the plantations have become older and in response to the drier conditions experienced following the dry 2018/19 wet season. It was not possible to partition the influence of the drier seasons and plantation age with the available data.

Midday leaf water potentials (ψ_{MD}) were measured over 2 years from 2017 -2018, which covered two complete drying and wetting cycles (Figure 2.9). The magnitude of the seasonal differences and differences between treatments were less than observed for the pre-dawn water potentials. The maximum ψ_{MD} during the wet season was approximately -2.0 MPa which declined to stabilise at -2.5 - 3.0 MPa during the dry season at Hot Springs (Figure 2.9a) and Rocky Knob 9 (Figure 2.9 b). The exception was the high density fertilized treatment at Snake 4 (800 sph +Fert) where the Ψ_{MD} declined to below -3.5 MPa from (Figure 2.9 b)..

The diurnal difference between the maximum (ψ_{PD}) and minimum (Ψ_{MD}) remained relatively constant at the Hot Springs site across both the seasons where Ψ_{MD} was measured (Figure 2.9a). This difference declined to between 0.8 and 1.0 MPa at the Rocky Knob 9 site during the 2017 and 2018 dry seasons (Figure 2.9 c). In both the 200 sph treatments and the 800 sph unfertilized treatments at the Snake 4 site the diurnal difference in ψ declined in a similar manner to that at the Rocky Knob site with the difference in the dry season declining to 0.8 and 1.0 MPa. In contrast during the period August to November 2018 there was virtually no difference between the ψ_{PD} and the Ψ_{MD} in the 800 sph fertilized treatment (Figure 2.9 b).

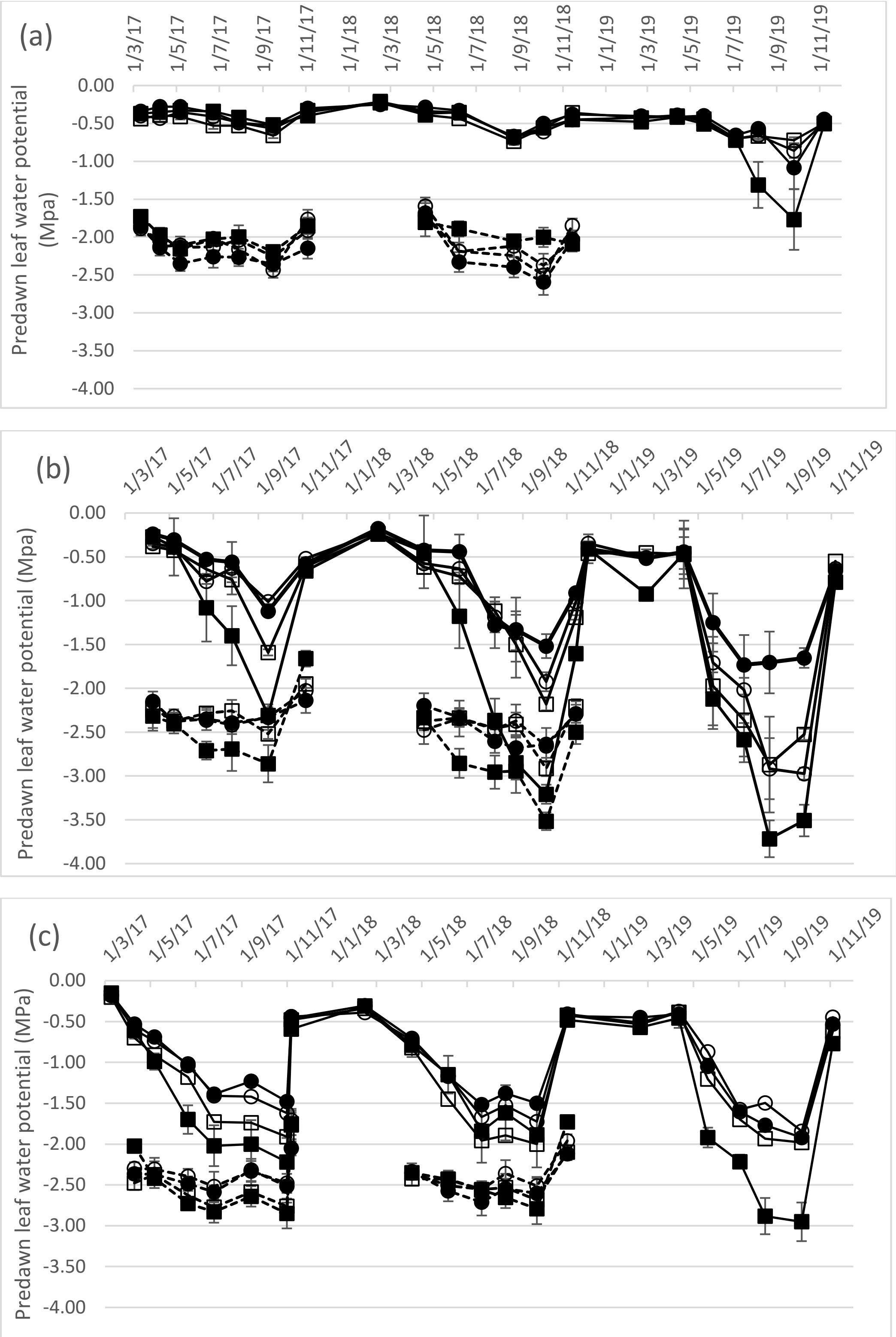


Figure 2.9. Impact of stocking and fertilizer application on seasonal trends in pre-dawn and midday leaf water potentials at three separate sites (a) Hot Springs, (b) Rocky Knob 9, (c), Snake 4. Solid lines indicate pre-dawn data(2017-19), dashed lines indicate midday data(2017-18). ■ 800 sph fertilized, □ 800 sph unfertilized ● 200 sph fertilized ○ 200 sph. Note the lower density treatment at Hot Springs was 300 sph rather than 200 sph.

Integrating the impact of silvicultural manipulation and climate on tree water stress and growth of Mahogany

Relationships between growth and water stress

The level of water stress varied substantially between the three sites, the imposed thinning and fertilizer treatments and across the three seasons that the trials were monitored. The variation in leaf water potential (water stress) and growth provided the opportunity to assess the relationship between volume production and water stress and the impact of plantation density and nutrient status on those relationships.

There was a strong response to increasing water stress with stem growth virtually ceasing at a ψ_{PD} of ~ -0.7 MPa (Figure 2.10). This is considerably higher than the ψ_{PD} at which growth ceases in other species (e.g. growth ceases when *P. radiata* reaches a ψ_{PD} of -1.5 MPa). This suggests that the stem growth of mahogany is very sensitive to water stress. Following the first rain in the wet season there was an apparent rapid increase in diameter. This expansion was likely due to the rehydration stems due that have shrunk under severe water stress during the dry season. The data contained in the ellipse are from the period immediately following the first rains.

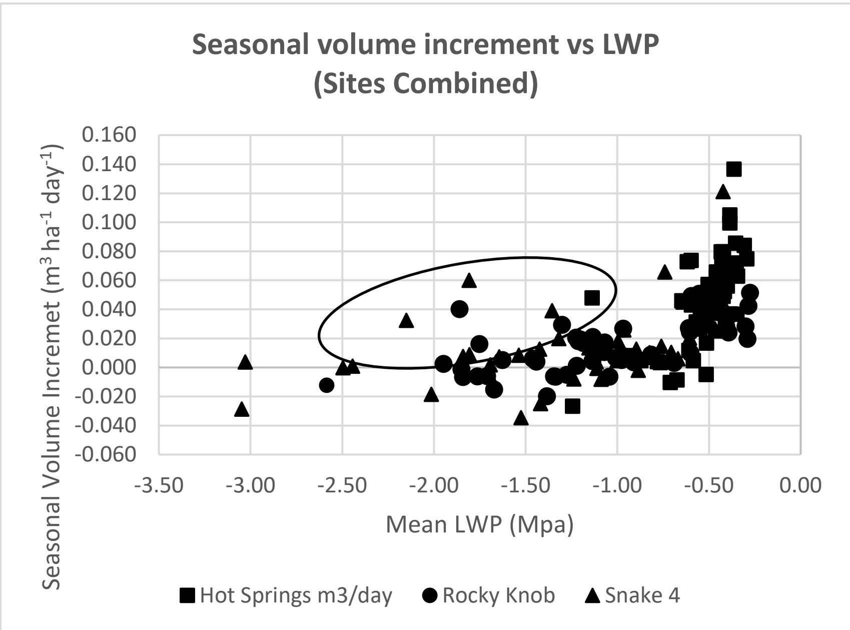


Figure 2.10. Relationship between seasonal growth (expressed as m^3 ha^{-1} day^{-1}) and mean leaf water potential for the relevant period.

The longer term relationship between annual volume production (CAI) and plant water stress integrated over a full growing season (WSI, MPa days) also demonstrated a strong relationship between growth and water stress (Figure 2.11a). It appears that beyond a cumulative level of annual water stress of ~-350-400 MPa days that growth was limited to ~5 m^3 ha^{-1} yr^{-1}under the climatic conditions in the Douglas Daly Region. In 2017 the high density fertilized treatment (800 sph +Fert) from the Snake 4 site did not conform to this model (data highlighted as a red square Figure 2.11a). A possible explanation for this is that this rapidly growing treatment exhausted the available soil water growing rapidly during the wet season and early in the dry season and was then ‘exposed’ to significant water stress.

The lower water potentials (stronger water stress) that developed at both the Snake 4 and Rocky Knob 9 sites during the 2019 dry season (Figures 2.9 b and 2.9c) provided a test of whether WSI provided a useful index of water stress for mahogany under the conditions in northern Australia, and it appears that it does.

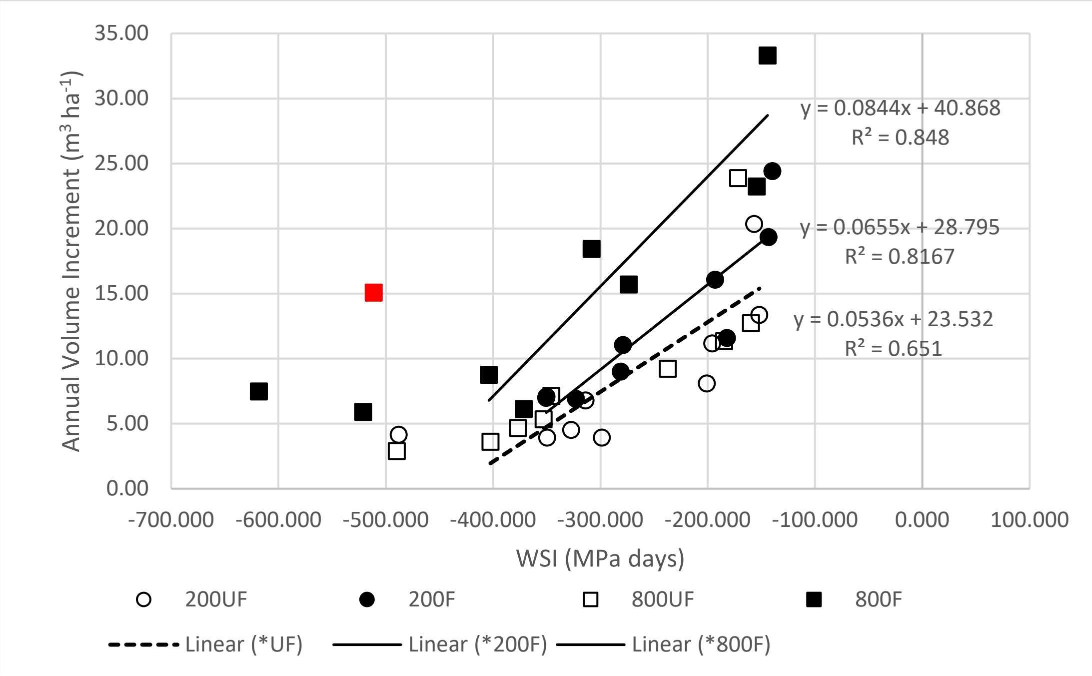


Figure 2.11a. Relationship between annual volume increment and annual water stress integral. (WSI = MPa x Days) showing the influence of increased stocking and fertilization on the relationship between volume production and water stress

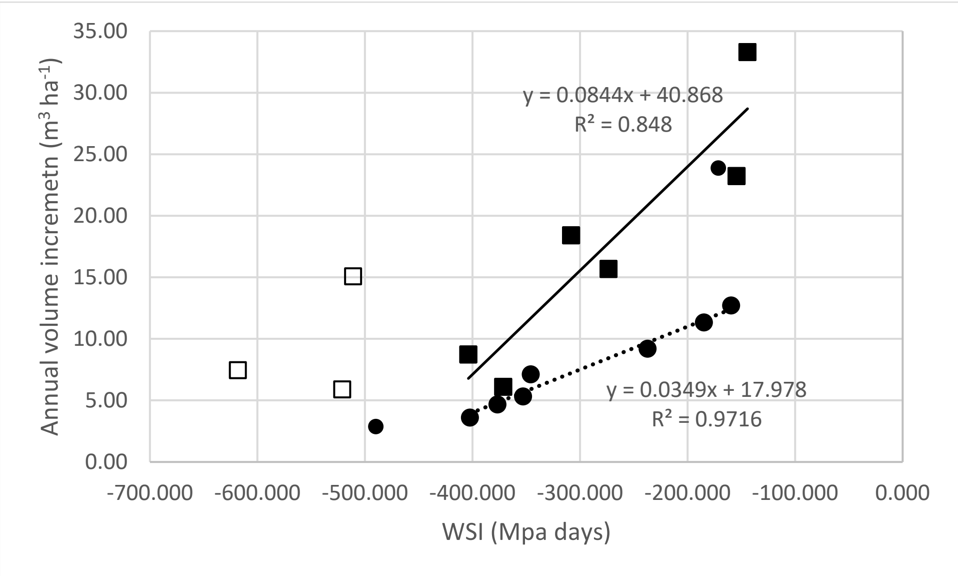


Figure 2.11b. Relationship between annual volume increment and annual water stress integral (WSI = MPa x Days) showing the different levels of growth and water stress in the 800 sph fertilized (■) and 800 sph unfertilized (●) treatments at 3 sites over 3 years. The data for the fertilized treatments shown as open squares were not included in the regression for the fertilized treatments.

Relationships between growth and climate

The wet season climate data (September to August) was combined with the growth data across all four sites (Wallaroo and the three-satellite thinning x fertilizer trials) to explore the relationship between climate and tree growth. There are sufficient data by combining the Wallaroo and Rocky Knob 9 data to establish an upper limit to growth based on climate driven water supply (climate wetness index, CWI). There was a large range in volume growth between the stocking and fertilizer treatments within each year due to the range of density and fertilizer treatments (Figure 2.12). The upper limit to productivity is defined as the maximum growth achieved in each year at each site. This was always in the high (adequate) fertilizer applications. However, the mortality that occurred in the denser (800 sph) treatments in the initial density trial at Wallaroo 1 meant that the 600 sph rather than the 800 sph treatment provided a better estimate of optimum growth. Similarly, the largest annual increments occurred in the 400 +Fert treatment at Rocky Knob 9 (Figure 2.6c), so those data were used to define the upper limit to growth. Due to the location of these trials in the landscape little or no run-on would have influenced the water available on these sites.

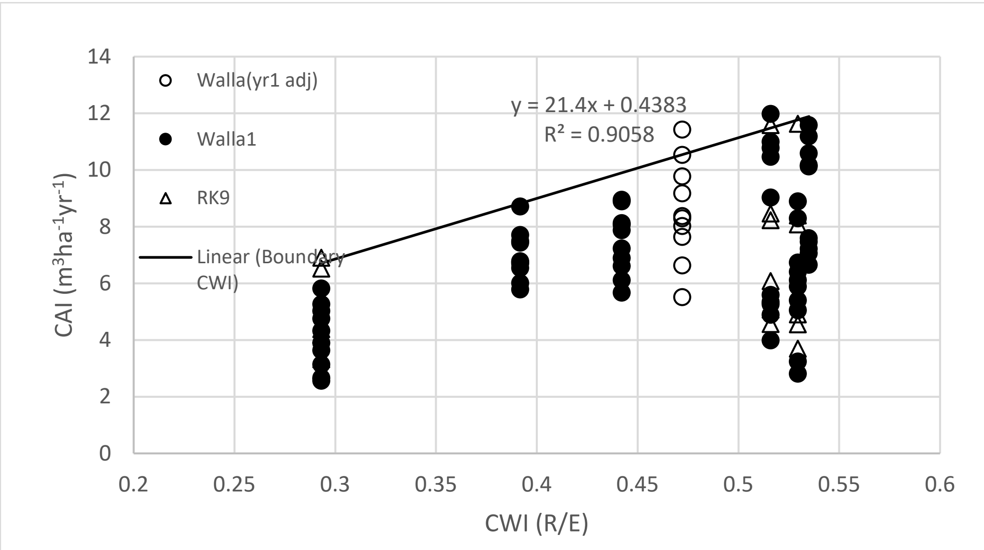


Figure 2.12. Current annual volume increments for the individual treatments for the Wallaroo and Rocky Knob 9 TxF trials (in Stray Creek plantation) vs Climate Wetness Index (R/E).

When the data for all the T x F trials are included, there was not a consistent relationship between growth and rainfall (Figure 2.13a) or CWI (Figure 2.13b). This is despite a relatively consistent relationship between growth and the level of water stress measured in the plantations either in the short term as the relationship between ψ_{PD} and growth (Figure 2.10) or integrated over a growing season as CAI vs WSI (Figure 2.11). For the Hot Springs site which produced 2 to 2.5 times more volume that the other sites (Figure 2.6) and maintained ψ_{PD} at high levels throughout the trial period (Figure 2.9a), this is likely due to the additional water that was observed to move onto this site from the adjacent cleared farmland.

The explanation of why the growth at the Snake 4 and Yak 9 sites appeared greater than in the rain fed sites at Wallaroo1 and Rocky Knob 9 is more difficult to explain (see Notes on Figures 2.13a and 2.13b and Section 3 for full details of the Yak 9 trial). These data are included as the trends observed in both trials were similar). In wet years, the growth at these sites was higher than anticipated based on the growth at the Wallaroo 1 and Rocky Knob 9 sites. In drier years, the growth was consistent with the non-water gaining sites (Figures 2.13a, 2.13b). A possible explanation for this is that in wetter years these sites receive water as runoff from the extended slopes above the trial sites. While all the slopes in this subdued landscape are low, it is worth noting that the slopes at both Snake 4 and Yak 9 are 1.4% (Table 2.3) which in larger than for the other sites which were between 0.2 and 0.8% (Tables 2.1, 2.3). As no measurements of overland flow were undertaken this is a speculative hypothesis. There was significant mortality in the highest density treatments at Snake 4 and across the trial at Yak 9 at the end of 2019 (see Section 3) which followed the low rainfall in the 2018/19 wet season and the dry commencement to the 2019/20 wet season. While there was evidence of drought stress in other trials as shown by significant leaf drop and low water potentials there was no evidence of mortality in these other trials. This suggest that the higher growth at the Snake 4 and Yak 9 sites in wetter years was not sustainable in dry years.

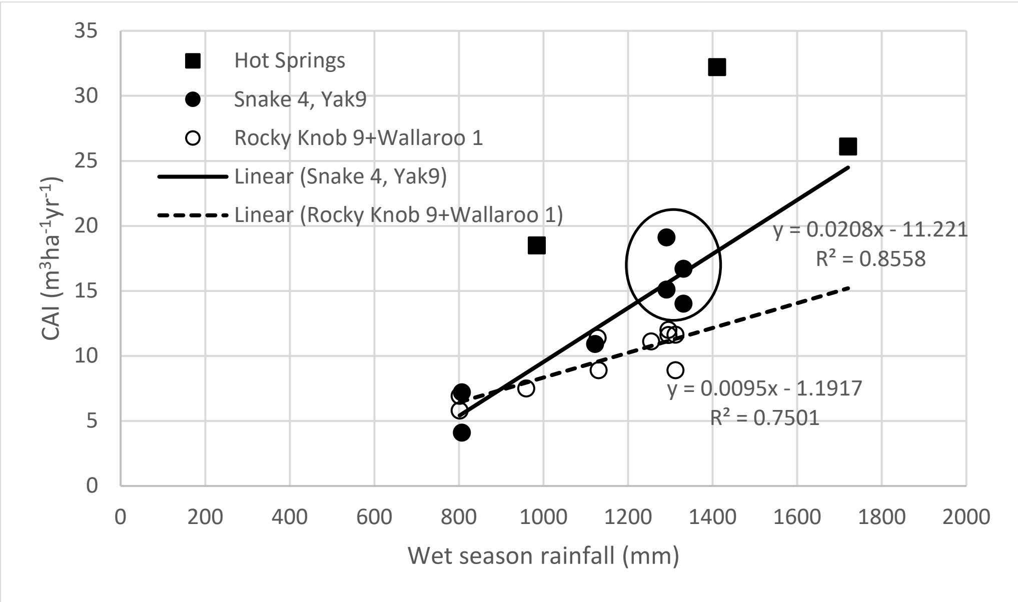


Figure 2.13a. Current annual volume increments (CAI, $m^3\ ha^{-1}\ y^{-1}$) vs Growing season rainfall (mm) for the optimum treatments at all four TxF trials (Wallaroo 1 and Rocky Knob 9 combined, Snake 4 and Yak 9 combined and Hot Springs). Notes: 1. Additional data from the Yak 9 N x P fertilizer trial were included with the Gypsy Springs data, (see Section 3 for full details). 2. The solid data points contained in the ellipse was derived from plots that sustained severe mortality in drier years.

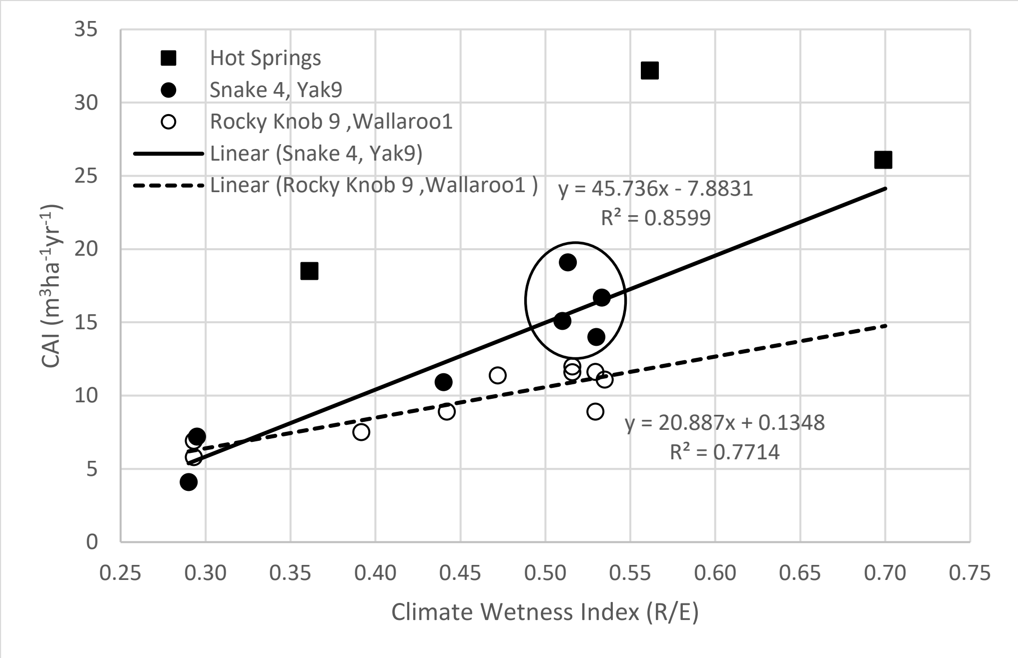


Figure 2.13b. Current annual volume increments (CAI, $m^3\ ha^{-1}\ y^{-1}$) vs Climate Wetness Index (R/E) for the optimum treatment at all four TxF trials (Wallaroo 1and Rocky Knob 9 combined, Snake 4, and Yak 9 combined and Hot Springs trials).
Notes: 1. Additional data from the Yak 9 N x P fertilizer trial were included in the Gypsy Springs data, (see Section 3 for full details).
2. The solid data points contained in the ellipse was derived from plots that sustained severe mortality in drier years.

The positive interaction between water availability (measured as CWI) and fertilization on annual volume increment (CAI $m^3\ ha^{-1}\ y^{-1}$) was demonstrated by the higher slope of the linear relationships between annual volume increment (CAI) vs CWI for the fertilized treatments in the trials at Snake4 and Yak 9 (Figure 2.14) and Rocky Knob and Wallaroo1 (Figure 2.15). The greater slopes of the relationships for the fertilized treatments at both sites indicates that the response to fertilizer increases as water availability increases. The fewer points in the minus fertilizer relationship for the Rocky Knob and Wallaroo1 sites is due to the absence of a true control treatment (unfertilized) in the first phase of the Wallaroo 1 trial. The response in the last two years of this trial are included as the second fertilization resulted in a doubling of growth and it is assumed that there is little or no residual effect of the initial N application. This compared with an increase or ~45% between the half rate and full rate fertilization in the initial phase of the trial.

The difference in the slopes of the relationships between CAI and CWI at Stray Creek (Wallaroo1 and Rocky Knob) and Gypsy Springs (Snake 4 and Yak 9) could be due to the Stray Creek sites being drier than those at Gypsy Springs. As outlined above this could be due to greater water movement onto both the Gypsy Springs sites in wetter years as both have long slopes above the trials and have greater gradients across the landscape that at the Stray Creek sites.

Alternatively, the growth at the Stray creek sites may have been limited by the availability of other nutrients. The much lower annual increments in the unfertilized treatments at the Stray Creek trials relative to the Gypsy Springs trials suggests that part of the limited response to increasing water availability or supply at Stray Creek is likely due to a lower availability of nutrients. This is supported by the doubling of growth in both these trials (see Section 3).

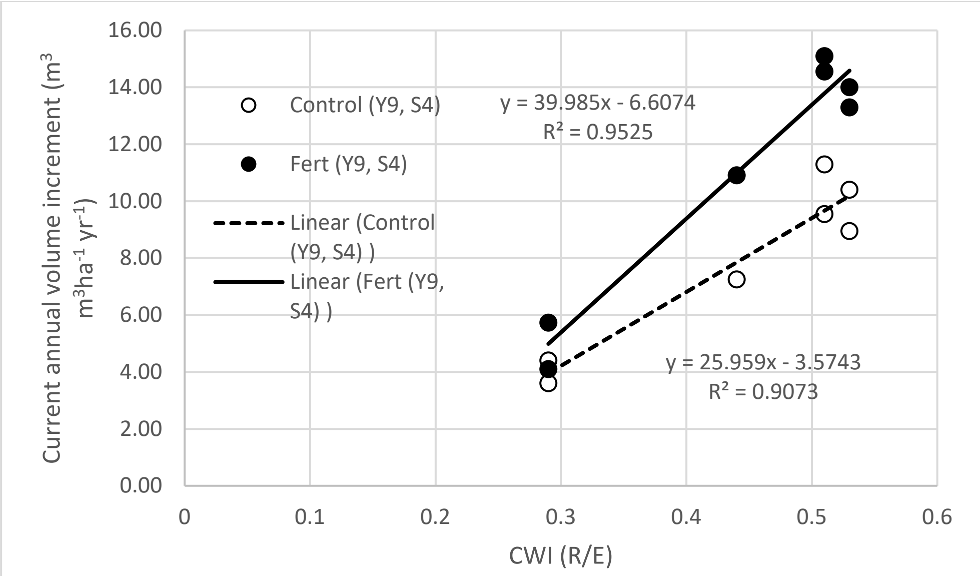


Figure 2.14 Current annual volume increments (CAI) vs CWI (R/E). for the fertilized (optimum) treatment and the unfertilized (control) treatments at the Gypsy Springs Snake 4 and Yak 9 trials.

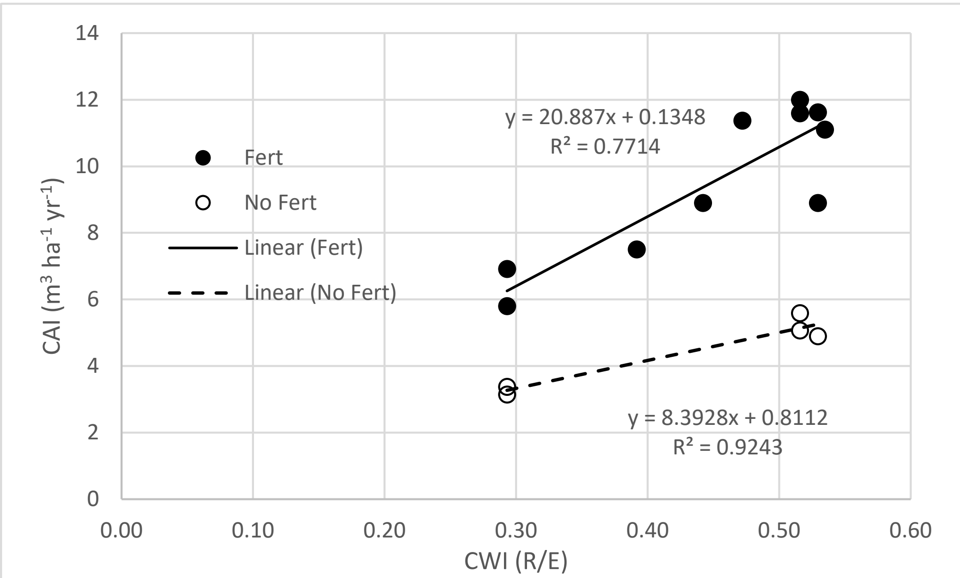


Figure 2.15 Current annual volume increments (CAI, m^3 ha^{-1} yr^{-1}) vs CWI (R/E). for the fertilized (optimum) treatment and the unfertilized (control) treatments at the Stray Creek Wallaroo 1 and Rocky Knob 9 trials.

Discussion

How mahogany responds to water stress

Seasonal trends in water stress and growth

The level of water stress, measured as predawn (maximum) leaf water potential (ψ_{PD}), experienced by mahogany in the Douglas Daly Region was strongly influenced by rainfall, the site, the density and nutrient status of the plantations (Figure 2.9). Midday (minimum) leaf water potential (Ψ_{MD}) was much less sensitive to the seasonal, site and treatment effects. For much of the monitoring period Ψ_{MD} remained between -2.0 and -2.5 MPa (Figure 2.9). These values are similar to those recorded by Arndt *et al.* (2015). The variation in ψ and tree growth provided the opportunity to understand the manner in which the growth of mahogany responds to water availability.

There was a strong relationship between ψ_{PD} and seasonal growth. As ψ_{PD} declined from ~-0.3—0.4 MPa, in the wet season, to -0.7 MPa, growth effectively ceased. This cessation of growth occurred at a higher ψ_{PD} than observed in other species. For example, in *P. radiata* growth ceased at -1.5 MPa (McGrath and Dumbrell unpublished). Over the course of the dry season ψ_{PD} continued to decline beyond the point where growth ceased on the drier Rocky Knob 9 and Snake 4 sites (Figures 2.9 and 2.10).

The level of water stress increased due largely to the decline in annual rainfall over the period 2016 to 2019. At the wettest site (Hot Springs) ψ_{PD} remained above - 0.7 MPa throughout the first 2 years and fell below this during the third dry season (2019). The decline was modest, relative to the other sites, but was still sufficient to halt growth for a period in the 2019 dry season. On the drier Rocky Knob 9 and Snake 4 sites the ψ_{PD} declined below the threshold of -0.7 MPa for growth early in the dry season in all years. The decline in ψ_{PD} was greater in the higher density fertilized plots at all three sites, indicating that the faster growth that occurred in these treatments was associated with higher levels of water stress.

An earlier study in this region which compared the water relations of 6-year-old mahogany with the natural eucalypt woodland found only modest levels of water stress in mahogany. The lowest ψ_{PD} reached in the dry season was -0.6 MPa and the Ψ_{MD} remained above -2.0 MPa (Arndt *et al.* 2015). The rainfall for the year in which the former study was conducted was above average (~1500 mm). and the preceding year had the highest rainfall recorded in the Douglas Daly Region in the past 20 years (~2100 mm). This was higher than the rainfall at the sites during this study (range 800 – 1300 mm). Thus the former study was conducted during a significantly wetter period.

Water stress and tree mortality

Tip death, partial crown death and whole tree death were observed in isolated patches of mahogany plantations in the Douglas Daly following the dry 2014/15 monsoon in where the rainfall varied from ~ 950 - 1000 mm (F. Miller, M Cleland 2020 pers. comm). This resulted in some tree death in the highest density (800 +Fert) treatments in the Wallaroo 1 trial. In the satellite trials, tree death was only recorded in the higher densities at the Snake 4 trial (also 800 +Fert) and were associated with ψ_{PD} below -3.5 MPa in 2019. In the study of Arndt *et al.* (2015) leaf hydraulic conductivity declined by 88% (P88) at -3.0 MPa. The decline in hydraulic conductivity has been associated with cavitation of the xylem which further restricts the flow of water to the tree canopy. This decline in hydraulic conductivity (P88) has been defined in some studies as the lethal threshold for cavitation (Brodribb *et al.* 2020). The trees in the 800+Fert treatment in the Snake 4 trial experienced ψ_{PD} below -3.5 MPa for nearly 2 months in the 2019 dry season. No mortality was observed in treatments where the ψ_{PD} remained at or above -3.0 MPa at either the Snake 4 or at Rocky Knob 9 sites. This indicates that the lethal threshold for terminal xylem cavitation in mahogany may be lower than -3.0 MPa (Arndt *et al* 2015) and that very significant water stress is required to kill mahogany.

While leaf shedding has been identified as a key mechanism in reducing water demand under drought conditions (Brodribb *et al.* 2020) and leaf shedding was observed during the dry season by Arndt *et al.* (2015) we observed seasonal leaf shedding irrespective of the level of water stress with significant leaf shedding occurring from mid to late dry season even on the wetter site where ψ_{PD} was maintained above -0.7 MPa in the first two years of the trial. When ψ_{PD} declined to -3.0 MPa the extent of leaf shedding increased. Almost complete defoliation occurred in the treatments with ψ_{PD} below - 3.5 MPa.

Based on the low level of water stress found in the earlier study (Arndt *et al.* 2015) where the daily maximum ψ (ψ_{PD}) remained above -0.6 MPa and the minimum ψ (Ψ_{MD}) recorded during the dry season was maintained about -2.0 MPa, mahogany was categorised as an isohydric species. Isohydric species maintain minimum leaf water potentials primarily by minimising water loss through tight stomatal control (Tardleu and Simonneau 1998). The maintenance of modest levels of water stress and leaf shedding to reduce water use during the dry season was judged to provide mahogany with significant resilience to drought stress (Arndt *et al.* 2015). In the current study we observed that at relatively low levels of water stress (ψ_{PD} was above -1.5 MPa) the minimum (Ψ_{MD}) water potentials were maintained at ~-2.5 MPa, which was lower than the minimum value of -2.0 MPa reported by (Arndt *et al.* 2015). However, as the annual drought progressed both maximum (ψ_{PD}) and minimum (Ψ_{MD}) water potentials declined to a greater extent than previously reported. The greater water stress and the associated cessation of growth for extended periods in the Douglas Daly plantations clearly demonstrated that mahogany exhibited anisohydric characteristics where the minimum water potential decreased in response to increased evaporative demand and decreased availability of soil water (Larcher 2003).

There appeared to be three phases in the development of water stress in mahogany growing in the seasonally dry monsoon climate of Northern Territory. During the wet season growth was rapid but ceased when leaf water potential (ψ_{PD}) declined to - 0.7 MPa. In the second phase, if the level of water stress imposed by the environmental conditions was modest, mahogany behaved in an isohydric manner with the capacity to avoid severe drought stress by maintaining the minimum daily water potential (Ψ_{MD}) at approximately -2.5 MPa. However, under more severe and extended drought conditions mahogany behaved in an anisohydric manner, the end point of which was tree mortality. That is, the mechanisms that contributed to the isohydric behaviour break down under more severe water stress.

Within the progression from low to severe water stress there were two different critical levels for mahogany. The first was that growth ceased at a relatively modest level of water stress when ψ_{PD} declined to -0.7 MPa. The relatively sharp decline in growth relative to water potential and the modest level at which growth ceases means that growth of mahogany on most sites in the Douglas Daly Region is confined to the wet season and the early part of the dry season. The second critical point was the water potential at which trees die from drought stress and appears to be at a ψ_{PD} of -3.5 MPa. Whether this is a critical limit or whether it is influenced by the duration of this level of water stress was not able to be determined in the current study. However significant mortality was observed following 2 months at ψ_{PD} of -3.5 MPa.

Impact of site and silvicultural treatments on growth and water (drought) stress.

The impact of plantation density on growth and water stress.

At all sites water and nutrient supply were major constraints on tree growth. When nutrients are adequately supplied then water supply limited growth, but to different extents at different sites. The current annual increment (CAI $m^3 ha^{-1} yr^{-1}$) at the Hot Springs site was 2 to 2.5 times the growth at all other sites (Rocky Knob 9, Snake 4, Wallaroo 1). The growth at the Hot Springs site did not appear to be limited by water supply for the first 2 years of the trial (age 4 (2016) to age 6 (2018)) as growth was continuous until June 2018 when growth ceased in the densest treatments. The cessation of growth at the highest density on this site occurred for a longer period in the following drier year (2019). However, growth continued in the lower density treatment (300 sph) at the Hot Springs site until the middle of the dry season in 2019 which was the driest of the seasons during the measurement period. On all other sites water availability limited growth in all years, with extended periods during the dry season where growth ceased. The cessation in growth was related to the water status of the plantations and occurred when the ψ_{PD} (daily maximum leaf water potential) dropped below - 0.7 MPa (Figure 2.10).

While seasonal growth patterns were not assessed at Wallaroo1 the small increases in volume production across the range of densities suggest there was limited scope to increase growth as growth was limited by water availability. Most of the increase in volume production with increasing plantation density occurred between the two lowest densities (300 and 400 sph). Therefore maintaining the plantations at a high density reduced the size of individual trees which will reduce the value of the harvested material due to significantly lower timber recoveries with decreasing log diameter (Section 5).

Thinning reduced the level and duration of water stress experienced by the plantations on the two drier sites (Snake 4, Rocky Knob 9) in each year. On the wettest site (Hot Springs) the level of water stress was not influenced by plantation density until the 2018/19 season when rainfall was well below average. On this wetter site growth was maximised in the highest density fertilized treatments (800 sph+ Fert). On the other sites maximum growth occurred at 400 sph (Rocky Knob 9 and Snake 4) and 600 sph at Wallaroo 1. Reducing stocking maintained the ψ_{PD} at higher levels when water was limited, and this provides a sound silvicultural strategy for managing the level of water stress in plantations. As noted earlier, ψ_{PD} remained above critical levels for mortality in all except the densest treatments on the driest site in the driest season.

Nutrition

Although water supply provides the overall limitation to volume production, fertilization increased the growth at all sites by between 35% (Hot Springs) and >100% (Wallaroo 1, Rocky Knob 9). The scale of responses depended on both the initial nutrient status of the sites (see Section 3) and the availability of water. In wetter seasons the responses to fertilizer were higher than in dry seasons (Figures 2.4, 2.5, 2.14, 2.15). The relationships between both volume growth and climate wetness index (CWI) (Figure 2.14) and volume growth and the cumulative annual water stress (WSI MPa days) (Figure 2.15) both demonstrate that the response to improved nutrient supply is higher in wetter seasons. Whether this increase in growth response to nutrients when water availability increases is due to increased water use efficiency or higher water use was not determined in these silvicultural trials. Water use measured through sap flow measurements or soil water balance measurements would shed some light on this issue. Despite this lack of information, the efficiency of rainfall use was higher in fertilized plantations as growth is increased with fertilization. In dry seasons when water availability significantly limits growth the response to fertilizer was minimal. The absence of a response to fertilization under dry conditions suggests that the increased growth under wetter conditions is due to increased water use rather than increased water use efficiency.

Climate and sites influences

The relationship between the measured level of water stress, either as quarterly growth and mean ψ_{PD} for this period (Figure 2.10), or integrated over the full annual growth cycle (Figure 2.11), showed a strong and consistent relationship across the sites. These relationships demonstrated the strong influence of water supply on the growth of mahogany. In contrast the relationship between CWI and growth was not consistent across the sites (Figures 2.13 a 2.13b). At the most productive site (Hot Springs) tree growth was continuous until the 2019 dry season which followed a wet season where rainfall was 40% less than long term mean. This continuous growth was associated with the maintenance of ψ_{PD} above -0.7 MPa where growth ceased. The Hot Springs site is adjacent to and down slope from an extensive cleared farm and water flows from this farm across the site. This means that climate indices do not provide an accurate indication of the water available at this site. In contrast the two sites in the Stray Creek plantation where there appeared to be limited movement of water onto the trial areas (Rocky Knob and Wallaroo) show a strong upper limit to CAI which is related to rainfall and Climate Wetness Index (CWI).

At the Snake 4 site the CAI matched the non-water gaining sites in dry years but the CAI at this site (and the Yak 9 N x P trial located in a similar location in this plantation) had a higher CAI in wet years. This suggests that in wet years water moved onto these sites which were both mid to lower in the landscape and had extensive slopes above the trial areas. The higher density (800 sph Fert) treatments at the Snake 4 site experienced significant drought related mortality in the 2019 dry season. This suggests that these sites were unable to sustain the higher growth rates in the higher density fertilized treatments in dry years. No mortality occurred in treatments with lower density. The sustainable CAI across all sites except the water gaining site at Hot Springs was between 8.5 and 9.5 $m^3\ ha^{-1}\ yr^{-1}$. We suggest that in the wetter years that water moved across the landscape and influenced the growth at these sites. However this creates an unstable situation where leaf area and hence water use is higher than sustainable on such sites in dry years. Maintaining plantation density and the level of fertility below levels that create high water demand provide the tools to manage the level of water demand and hence the level of water stress experienced by the plantations.

When the productivity of the non-water gaining sites was related to CWI the slope of the relationship was very similar to the slope of a relationship developed for blue gum plantations in southern Western Australia where mean annual increment (MAI) was related to CWI over the length of the plantation (White *et al.* 2009 Figure 2.16). Due to the shorter duration of this mahogany study annual volume increments (CAI) was related to annual climate wetness index (CWI). The considerable variation in rainfall over the study period provided the opportunity to relate CAI to annual CWI, despite the much shorter period available for this study. This relationship defined the upper limit of volume production for mahogany in this region.

A feature of the blue gum data is that these plantations were first rotation sites on deep lateritic soils with a significant store of water in the profiles (Mendham *et al.* 2011). The high ‘zero’ intercept (5.9 $m^3\ ha^{-1}\ yr^{-1}$) in that data is likely due to growth supported by the stored water in those profiles. If the blue gum data is adjusted for that, then the observed relationship between CAI and CWI for mahogany was similar to the MAI vs CWI relationship for blue gums. This suggested that the responsiveness of mahogany to increased water supply was similar to eucalypts grown in very different environments.

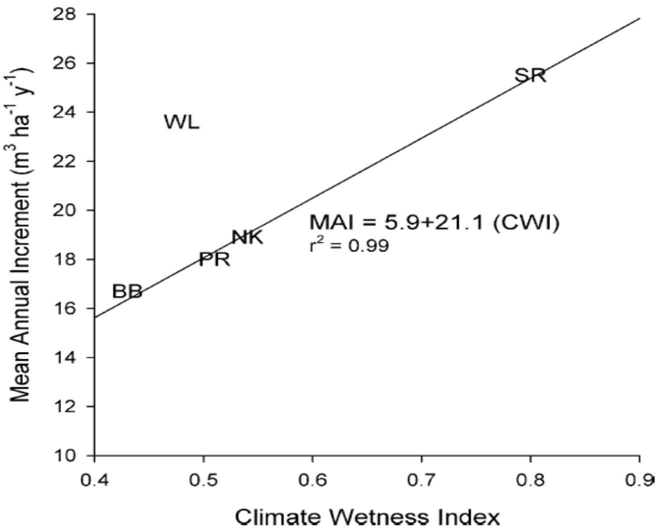


Figure 2.16 Mean annual increment calculated at the end of the rotation (9 years) as a function of average annual climate index from the time of planting to the time of measurement. The linear relationship did not include the Welastead (WL) data (Copied from White *et al.* 2009).

Implications for plantation management

The primary limitation to the growth of mahogany plantations in the seasonally dry monsoonal climate of the Northern Territory is water supply. The rainfall in this region is very variable with the highest rainfall more than double the lowest rainfall. Rainfall is skewed towards dry years in this region with dry years twice as common as wet years. In dry years, the plantations can be exposed to levels of water stress sufficient to kill trees.

On water limited sites thinning maintained ψ_{PD} above the critical threshold for tree death.

Total volume production increased between 10 and 20% with increasing plantation density from 300 sph to 600 sph over 7 years from age 4.5 to 11.5. Increasing the density to 800 sph led to a reduction in growth and exposure of trees to mortality in dry years.

Individual tree volume increased with decreasing stocking which would increase the value of harvested logs and compensates for the decrease in the number of trees (refer Section 5, DAF log geometry study).

Recommendation 1

During the early to mid-stages of the rotation, mahogany should be maintained at or below 400 sph to optimise both stand and individual tree growth and reduce the likelihood of drought related mortality.

Growth was optimised when fertilization eliminated nitrogen (N) and phosphorus (P) deficiencies. Growth was increased 35% and 100% by adequate levels of fertilization.

It appears that fertilizer improves growth for approximately 4 years after application. In addition, significant growth responses at Wallaroo 1 when re-fertilized after 5 years in both re-thinned treatments and treatments where the density remained constant demonstrated that strong responses to multiple fertilizer applications can be achieved. Optimising growth will require multiple fertilizer applications through the plantation.

Recommendation 2

Growth of mahogany plantations will be optimised by the application of fertilizer at 4-5 year intervals. Further guidance on fertilizer rates is provided in Section 3.

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Section 3 The impact of fertilization and water availability on growth

J McGrath, C. Oliver, F Miller

Summary

The response of African mahogany plantations in the Douglas Daly region of the Northern Territory to nitrogen and phosphorus fertilization was assessed across a range of sites with varying nutrient status and water availability. Data from factorial nitrogen by phosphorus fertilizer trials and fertilizer by thinning trials provided a wide range of environmental and silvicultural management conditions for this assessment.

Nutrient supply influenced the productivity of African mahogany in the Douglas Daly region, with combined N and P fertilizer doubling growth on low fertility sites and responses of between 30% and 50% observed on other sites. In contrast there were sites, mainly with better agricultural fertilizer history e.g. Hot Springs and Jill's compartments in Kumbyechants plantation, where even with good water supply there were limited or no responses to fertilizer. The response to fertilizer appears to last at least 4 growing seasons post fertilization, and the response increased over time since fertilization.

Soil nitrogen (N) and soil organic matter (SOM) concentrations show considerable promise in identifying sites that will respond to fertilizer and the likely magnitude of the responses.

Water availability had a strong influence on the responses to fertilizer. In dry years fertilizer responses were limited and the high leaf area developed in response to fertilization under wetter conditions predisposed plantations to severe water stress and drought related mortality.

Sampling foliage in mid-dry season is unlikely to be useful for assessing the nutrient status of African mahogany plantations. While nutrient concentrations during the wet season appear responsive to nutrient supply the measures undertaken were unable to identify relationships between foliage nutrient concentrations and growth. Additional work will be required to determine if foliage nutrient sampling can provide useful indicators of the nutrient status of African mahogany plantations.

Introduction

African mahogany *(Khaya senegalensis*) has been identified as a prospective species for the seasonally dry tropical regions of northern Australia (Booth and Javanovic, 2000, Arnold *et al.* 2004). While there has been significant investment in understanding the genetic diversity of African mahogany and defining the provenances that are suited to the northern Australian environment (Dickinson *et al.* 2009, Nikles 2006, Nikles *et al.* 2008, Reilly *et al.* 2007), there have been few studies of the silvicultural management strategies required to optimise the growth of mahogany in plantations. There are no published data on the nutrient requirements of African mahogany under the growing conditions in northern Australia. In contrast, the nutrient requirements of hardwood (eucalypt) plantations in temperate regions of Australia have been extensively studied since the expansion of these in Australia in the 1990's. A recent review of this work concluded that hardwood plantations growing on infertile soils generally respond strongly to nitrogen and phosphorous applications (McGrath and Mendham 2018). The establishment of most southern Australian hardwood plantations on farmland, often with extensive history of fertilizer use, has meant that responses to fertilizer are limited to sites with limited fertilizer applications and hence low nutrient availability (Szota *et al* 2014, McGrath and Mendham 2018).

Despite the general relationship where increasing foliage nitrogen concentrations leads to increased plant growth (for example Ingestad 1977, Agren 1985, 1988, Agren and Ingestad 1987, Greenwood *et al.* 1991) and strong relationships between photosynthetic capacity and leaf nitrogen concentrations in both wild plants (Field 1983, Field and Mooney 1986) and crop plants (Evans 1989) there does not appear to be a strong relationship between leaf nitrogen and eucalypt growth under plantation conditions (Szota *et al* 2014, McGrath and Mendham 2018).

Considerable work has been done on the nutrient requirements of softwood plantations in the subtropical south east Queensland region. On the leached podsolic soils of this region phosphorus is essential for the development of softwood plantations (Simpson and Grant 1991, Zu *et al.* 1995a). Once the primary phosphorus deficiency was addressed smaller responses to nitrogen were found (Simpson and Grant 1991). Soil type and water availability influence the response to phosphorus leading to site specific fertilizer recommendations for these plantations (Simpson and Osborne 1993, Xu et al. 1995b and Xu et al. 1995c). Only limited studies on the silvicultural requirements of tropical hardwoods in northern Australia have been undertaken and no work on the nutrient requirements of mahogany plantations in this region have been reported.

When this project was initiated there was a strong focus on understanding the responses to fertilizer by mahogany plantations in the Douglas Daly region. Over the course of the project it has become clear from a number of trials, that evaluated the responses to and interactions between thinning and fertilization across a range of sites, that the primary limitation to plantation productivity in the Douglas Daly region of the NT is water availability (see Sections 1 and 2). These trials also demonstrated that nutrient supply can have an important role in optimising productivity on many sites and soils in this region. However those trials did not investigate the role of individual nutrients or rates of application on the response or attempt to determine if foliage or soil nutrient concentrations can be used to discriminate between responsive and unresponsive sites.

Results from three trials designed to assess the responses to nitrogen and phosphorous are presented, along with additional analyses that integrate the responses found across all seven trials where nutrient supply was manipulated in the Douglas Daly region.

This study sought to determine the relative importance of N and P and the nutrient applications required to optimise the growth of thinned *K. senegalensis* early in the rotation on a range of first-rotation sites in the Douglas Daly region. These studies also examined the longevity of the fertiliser effects of N and P and by examining the responses to nutrients in both these specific fertilizer trials and the responses in the thinning and fertilizer trials. By integrating the fertilizer responses across the seven sites where the responses to fertilizer were assessed, the role of soil nutrients as indicators of the nutrient status and hence the responsiveness to fertilizer has been tested.

Materials and methods

Site characteristics and trial details

Table 3.1 Site characteristics for the three trial sites

	Trial sites		
Characteristic	**Yak 9 N x P**	**Jills N x P**	**Wallaroo 4 DAP rates**
Land Unit and soil type*	5e/4a2 Deep sandy red massive earth (Blain)	Generally 3d (Loamy red earth mainly Tippera and Tindal) some patches with surface brow loam grading to red at <0.5 m.	4b2 Deep sandy red massive earth (Blain)
Aspect	Gentle slope west	Flat. Low lying	Gently sloping, relatively low lying
Previous Vegetation	Tropical pasture grasses and legumes.	Tropical pasture grasses and legumes.	Tropical pasture grasses and legumes.
Elevation	693 m.a.s.l		~130 m.a.s.l
Latitude/longitude	14.58' 10.13"S 131.25' 46.14'E	13 º43'51"/131 º21'12"	14 º1' 28.3"S/131 º20'40.2"E
20 year mean wet season rainfall Sept- Aug. (99/00-18/19)	: ≈1294 mm/year	1348 mm/year	≈1251 mm/year

* After Aldrick and Robinson (1972)

Table 3.2. Trial details for the three trials

	Trial sites		
Characteristic	**Yak 9 NxP**	**Jills NxP**	**Wallaroo 4 DAP rates**
Planted	January 2012	January 2012	January 2013
Trial establishment	11/03/2015	06/04/2017	14/02/2018
Trial design	Factorial 4 N x 4 P (16 treatments)	Factorial 3 N x 3P (9 treatments)	4 rates of DAP, plus Ca at highest DAP (5 treats)
P rates (kg/ha)	0, 50, 100, 150 kg/ha	0, 50, 100 kg/ha	0, 25,50,100 kg/ha
N rates (kg/ha)	0, 200, 400, 600 kg/ha	0, 200, 400 kg/ha	0, 22.5, 45, 90 kg/ha
Ca rates	Nil	Nil	125 kg/ha
Replicate blocks	3 (Spatially arranged)	3 (Spatially arranged)	3 (Spatially arranged)
Total Plots	48	27	15

External/treatment plot areas	0.107 ha (9 rows, 32.4 x 33 m, 2 row buffer	0.162ha (10 rows 36 x 45 m), 2 row buffer	0.12ha (8 rows 28.2 x 42 m), 1 row buffer
Internal/measurement plot areas	0.039 ha (5 rows, 18 x 21.6 m)	0.067 ha (6 rows, 21.6 x 31 m)	0.076 ha (6 rows, 21.6 x 35 m)
Initial spacing	3.6m x 2.2 m	3.6m x 2.2 m	3.6m x 2.5 m
Nominal initial stocking at trial establishment	500 sph	300 sph	300 sph (Actual 265 sph)
Gross area of trial	~5.2 ha	~4.9 ha	~1.9 ha
Initial measurements	17-18/02/2015	28/11/2016	12 & 15/02/2018
Soil sampling	18/02/2015	15/12/2016	15/12/2017
Fertilizer application	10-11/03/2015	06/04/2017	14/02/2018
Coppice control	Stump application of Access©, plus follow up foliar spray	Stump application of Fightback©, plus follow up foliar spray	Stump application of Fightback©, plus follow up foliar spray
Weed control	Post treatment application of Glysophate and Sulfometuron-Methyl, plus annual spraying during the wet season. Cattle grazing from 2016. Details in the text	Post treatment application of Glysophate and Sulfometuron, plus annual spraying during the wet season. Cattle grazing from 2015. Details in the text	Nil, plots were virtually weed free and no herbicide was applied. Cattle grazing from 2015.
Measurements	At establishment, then annual mid dry season	At establishment and quarterly diameter measurements to track seasonal growth patterns	At establishment and annual on that anniversary
Leaf sampling	Annual mid dry season for 3 years	Quarterly to assess seasonal patterns	Nil

Plot dimensions: Due to the variation in stocking the dimensions of the treatment and measurement plots varied between the three trials to provide a mean of 20 measurement trees in each treatment with a buffer between the measurement plots. In the two N x P trials, which were intended to be measured for an extended period a 2 row buffer was used. For the third trial comparing lower rates of nutrient applications and intended for a shorter duration a 1 row buffer was used.

Soil sampling: A surface soil sample consisting of 24 cores (~20 mm x 100 mm) taken at 3 places (3 x 8 = 24) in the inter row area in the measurement plots were taken from all plots in all trials prior to fertilization. Samples were kept cool following sampling in the field and dried and sieved in Darwin prior to forwarding for analysis by CSBP laboratories in Perth WA.

Stand conditions: The Yak 9 site was standing at the establishment stocking of ~800 sph when the trial was established. The fertilizers were applied to the trial before the area was thinned to 500 sph to facilitate the spreading of the fertilizer. The trial area was marked for thinning prior the fertilization operation. The trial was thinned immediately (in the week after fertilization) post the fertilizer application. The Jill's and Wallaroo 4 sites had been thinned in the previous dry season prior to the trial establishment and were standing at approximately 300 sph. These sites had been directionally felled which allowed clear access in every second row.

Tree measurement: Trees within the measurement plots were permanently marked at breast height (1.3 m) and diameters were measured with a tape. Annual height measurements at both the N x P trials and at 2-year intervals for the additional low rate trial were measured with a Vertex hypsometer. Prior to the establishment of the treatments tree height and diameters were measured and basal areas and stocking calculated. Total volume was estimated using a volume equation developed from sectional stem analysis of 49 trees ranging from 9 to 39.1 cm diameter. The equation used to estimate whole tree volume was: $V = 0.0365 - 00.00652\ D + 0.0006\ D^2$, $R^2 = 0.992$
The variation in the performance of the plantation when the trials were established was used to arrange the blocks within the trials at the Jill's and Wallaroo 4 sites. There was a relatively uniform distribution of the variation in growth across the Yak 9 trial site and the replication was based on the three blocks being arranged laterally along the gentle slope across the trial area.

Coppice management: Following thinning at all sites coppice was controlled by spraying the stumps immediately post felling with Access (240 g/L Triclopyr, 120 g/L Picloram) 1/60l diesel (Yak 9) or Fightback (300 g/L Triclopyr and 100 g/L Picloram) at 0.5l/100l water (Jills and Wallaroo 4). Follow up treatment of the coppice was applied as required as a spot application of Fightback 0.5L/100 L with Sprinta (Spraying oil adjuvant) at 0.1L/100L.

Weed control: The inter row areas of the trials were sprayed with a mixture of glysophate @ 1.6 kg/ha, Sulfometuron-Methyl@50 g/ha applied with 0.5 l/ha spray oil and 0.5 kg/ha ammonium sulphate at the commencement of the trials and as required annually during subsequent wet seasons to ensure that weed competition did not confound the responses to fertilization. In addition to the herbicide applications the trial areas were grazed with cattle from 2016 onwards. The combined impact of herbicide application and grazing maintained the trial areas in a weed free condition.

Fertilizer application.

Materials: For the two N x P trials nitrogen was applied as urea (46% N) and phosphorus as triple superphosphate (20% P). The rate trial used di ammonium phosphate (DAP, 18% N and 20% P) and calcium was applied as gypsum (19% Ca).

Spreading: Fertilizers were broadcast by hand. The unthinned condition of the Yak 9 site allowed access to each row for broadcasting. The directional felling of the thinned trees at the Jill's and Wallaroo 4 sites allowed access in every second row and the fertilizer was broadcast across all rows, including those with thinning debris. The applications for each plot was based on applying the appropriated number of calibrated buckets of fertilizer per plot. These calibrations were checked against the remaining fertilizer amounts left in the bulk bags after the fertilizer had been applied to all trials and was within 5% of the required rates over each trial. Multiple aliquots of each fertilizer were applied to the plots which facilitated even spreading of the fertilizer over the whole plot area.

Timing: It was intended to apply the fertilizers in the middle of the wet season (late January/early February) however heavy monsoon rainfall and wet soil conditions prevented that occurring for both the N x P trials with the fertilizers being applied on 10/11 March 2015 at Yak 9 and 6 April 2017 at Jills. The subsequent responses to fertilizer in both growth and elevated foliage nutrient concentrations indicates that the applications were effective. While the application at Jills was particularly late the wet soil conditions at that site, which had prevented access until late in the season, and 40 mm of rain 2 days after the fertilizer was applied facilitated access to the applied nutrients. Application of the fertilizer at Wallaroo 4 was conducted on the 14/02/2018, with good rain (~50 mm) falling on the site immediately after fertilizer application.

Climate

Monthly rainfall and potential evaporation data were obtained from SILO for the period from 1999 to 2019 (Jeffrey et al., 2001) for the three plantations in which the trials were established and aggregated to provide an overview of the climate of this region. These data were used to calculate the climate wetness index (CWI) the ratio of rainfall to potential evaporation (R/E) for the trial sites over this period (Figure 3.1, Gypsy Springs; Figure 3.9, Kumbyechants, Figure 3.14, Stray Creek). As the growth of the trees in this region is strongly related to the wet season the annual climate data are provided for the period September to August rather than on an annual calendar basis.

Results and Discussion

1 Nitrogen by phosphorus interaction trial – Gypsy Springs Yak 9

Objectives of the trial

The trial aimed to separate the influence of nitrogen and phosphorus applications on the growth of recently thinned mahogany. The trial was established in February 2015 in a 3y.o. stand thinned to ~500 sph.

The wet season rainfall in the first two years of the trial was below the long term mean of 1294 mm (Table 3.2) at 941 and 1122 mm respectively, in the subsequent two years rainfall was close to the long term mean (1331, 1290 mm) while the rainfall in the fifth growing season was the lowest during the measurement period at 807 mm (Figure 3.1). The climate wetness index (Rainfall ÷ Evaporation; R/E) reflected the trend in rainfall and varied from 0.53 in the third year (2016/17) to 0.29 in 2018/19.

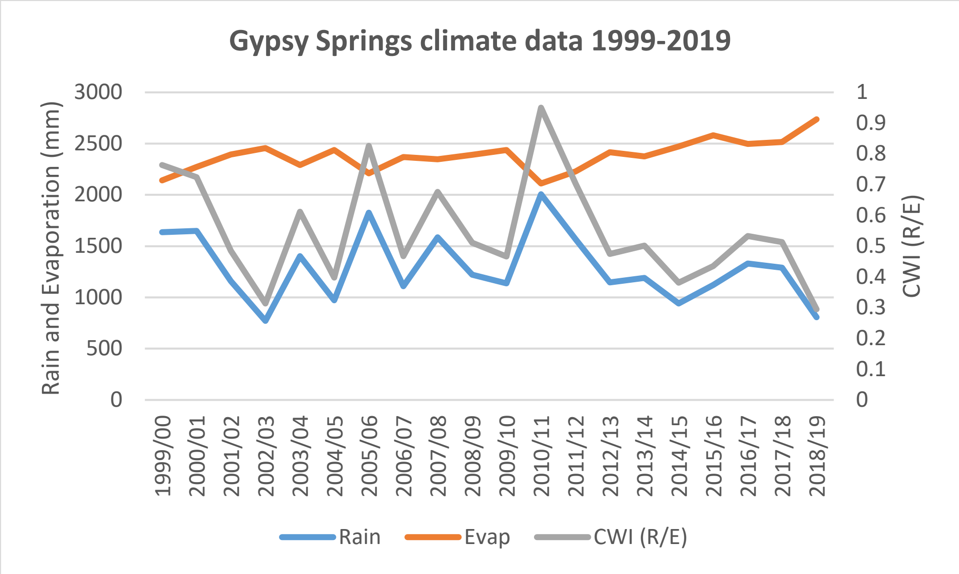


Figure 3.1. Wet season (September to August) climate indices, rainfall (R), evaporation (E) and Climate Wetness Index (CWI = R/E) at Gypsy Springs Plantation for the period 1999/2000 to 2018/19.

The response to fertilizer was lower in the first two growing seasons after fertilization (Figures 3.2 and 3.3) than in the subsequent two seasons which were considerably wetter. Growth was very limited in the fifth year post fertilization (Figures 3.2 and 3.3). This response pattern is different to that observed in other species and situations where the responses to fertilizer are larger in the years soon after fertilization, although often there is a lag in response in the first year for example in softwoods (McGrath *et al* 2001, a, b) and in hardwoods (Smethurst *et al*. 2004, White *et al*. 2009,). The overall response to N and P, measured as standing volume is shown at 0.5, 1.5, 2.5, 3.5 and 4.5 years after fertilization (Figure 3.2 and 3.3). The overall increment at 3.5 years after fertilization indicated that the largest responses of approximately 35-40% were obtained with either a high rate of phosphorus (150 kg/ha) or combined applications of 200 kg/ha N and 50 kg/ha P. It is likely, due to the initial dry period at the beginning of the trial the response to fertilizer increased for the first 3.5 years after application. In the dry season between 3.5 and 4.5 years post fertilization growth was low relative to that in the previous seasons and there was only a limited response to fertilizer measured in this period (Figures 3.2 and 3.3).

Diameter growth was increased by about 1 to 1.5 cm in the 3.5 years since fertilization which was consistent with the fertilizer response shown by trees at a similar stocking in Wallaroo 1 (see Section 2) of 1.7-1.8 cm over 5 years. Noting however that the response to fertilization at Wallaroo is likely underestimated due to the absence of an unfertilized control treatment as the initial phase of that trial had moderate and high fertilizer applications. The increased response over time (Figures 3.1, 3.2) suggest that the response to fertilizer in young mahogany followed a Type 2 response as defined by Snowdon and Waring (1984) where fertilizer applications result in long-term increases in site productivity. A similar sustained response to fertilizer was also observed in the Wallaroo 1 T x F trial (See section 2). The maintenance of the response to nitrogen for at least 4 years indicates that African mahogany must efficiently recycle nutrients before the canopy undergoes the annual leaf shedding phase.

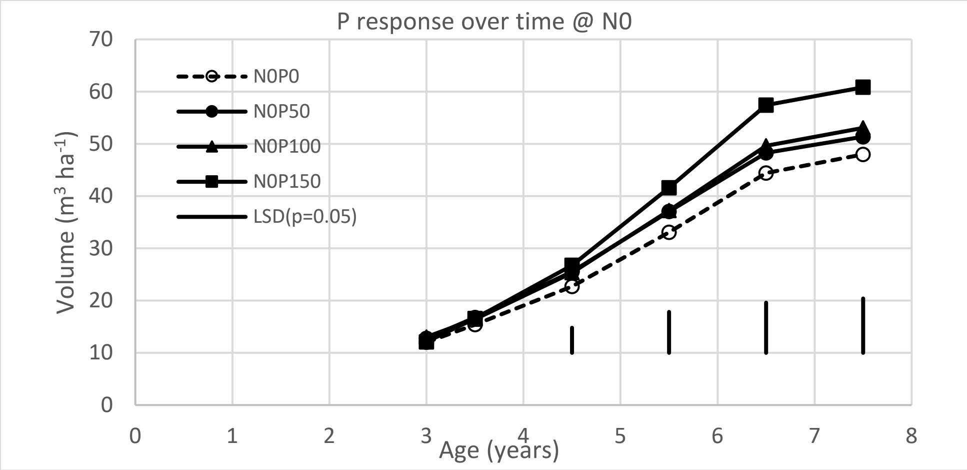


Figure 3.2 Progression of total volume production (m^3 ha^{-1}) related to the application of increasing rates of phosphorus in the absence of applied nitrogen from fertilization at age 3 to age 7.5 years. (February 2015 to May 2019)

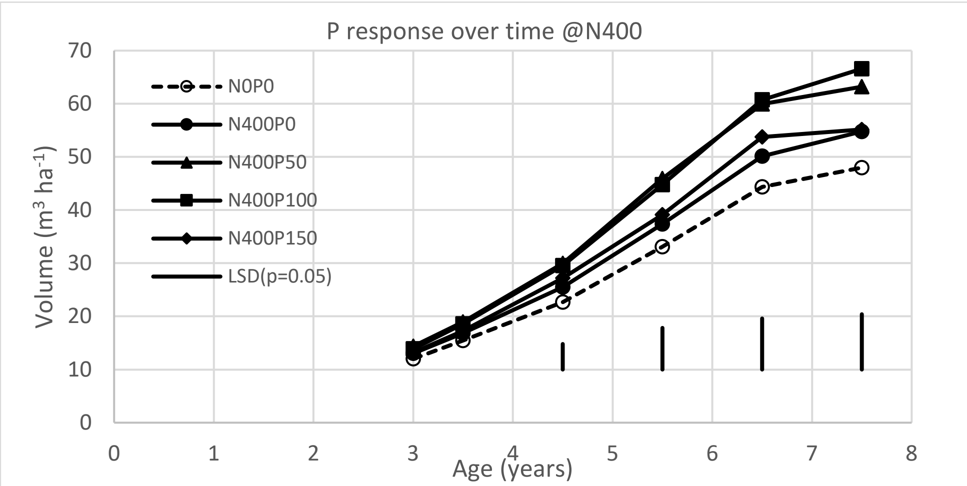


Figure 3.3 Progression of total volume production (m^3 ha^{-1}) related to the application of increasing rates of phosphorus in the presence of nitrogen applied at 400 kg/ha N from fertilization at age 3 to age 7.5 years (February 2015 to May 2019). The control treatment (N0P0 is also included in this figure).

The relationship between CWI (R/E) and annual volume increment for fertilized and unfertilized treatments (Figure 3.4) shows a strong positive interaction between water availability and the response to fertilizer. For this analysis the 'fertilized treatment' is the mean of the 6 treatments that make up the plateau of the response curves in the Yak 9 N x P trial, (i.e. P50 with N200, 400, 600, and P100 with N200, 400 600, see Figures 3.5 and 3.6). This clearly demonstrates that water supply is the key limitation to the growth on this site and the response to fertilizer depends on having sufficient Rainfall ÷ Evaporation available soil water to utilize the additional nutrients. In the driest season where rainfall was ~800 mm during the wet season which provided a CWI of 0.29 there was no significant difference between the volume increments of fertilized and unfertilized trees. In contrast, as rainfall increases there is a progressive increase in the growth of both unfertilized and fertilized trees, however this increase is greater for the fertilized treatments. In years with wet season rainfall of ~1300 mm (the long term mean for this areas) the annual volume increment of fertilized treatments was ~14 m^3 ha^{-1} yr^{-1}, compared to that when the wet season rainfall was ~800 mm when then growth was less than a third of that at ~4 m^3 ha^{-1} yr^{-1} (Figure 3.4). The overall response to fertilizer at the Yak 9 site was ~33% averaged over the 4.5 years from age 3 to age 7.5 years (Figure 3.6).

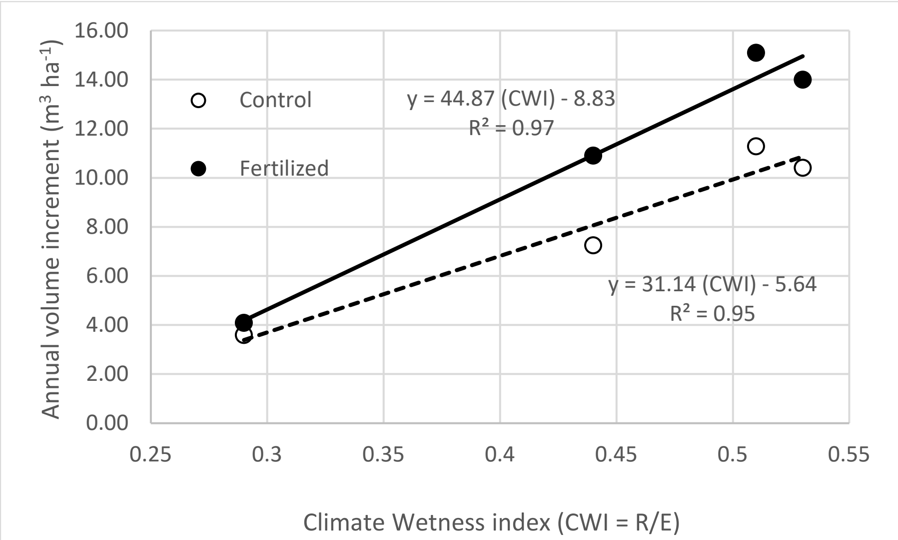


Figure 3.4. The Impact of water availability (measured as CWI) and fertilization on annual volume increment. Note the fertilized treatment is the mean of the adequate fertilizer applications determined from the response curves shown in Figures 3.2 and 3.3 and are for the six treatments (P50 with N200, 400, 600 and P100 with N200, 400 600).

Using triple super and urea the optimum fertilizer applications appeared to be either 150 kg of phosphorus without nitrogen or 50 kg/ha of phosphorus and 200 kg/ha of nitrogen (Figures 3.5 and 3.6). Volume production was not increased by additional applications of either N or P. These optimum fertilizer applications are likely relevant to rain fed and hence water limited sites in the Douglas Daly with similar fertility to that at the Yak 9 site. Optimising productivity on wetter sites or sites with lower nutrient status may require higher applications of nutrients.

It should be noted that the denitrification and leaching losses of nitrogen in this tropical region are likely to be high particularly when using volatile nitrogen sources such as urea (e.g. Dourado-Neto *et al.* 2009, Rowlings *et al.* 2016,). Thus, less volatile nitrogen sources would likely require lower rates of applied N.

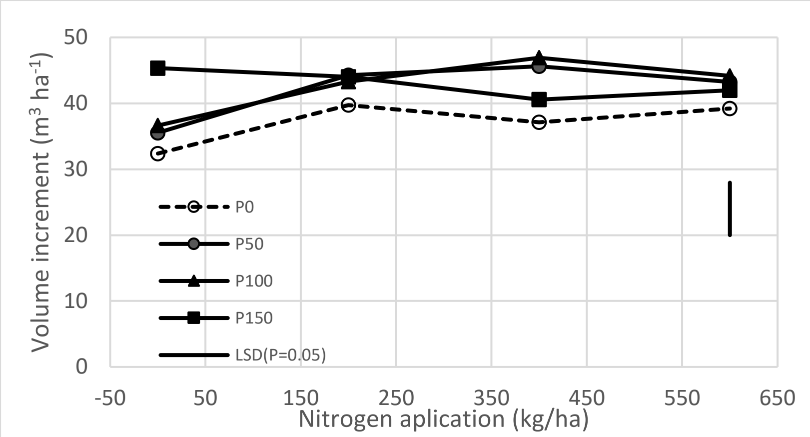


Figure 3.5. The influence of nitrogen and phosphorus applications on the volume increment from age 3 to age 6.5 years in African mahogany in compartment Yak 9c, Gypsy Springs plantation, Douglas Daly NT. LSD p=0.05 shown as a vertical bar

The apparent depression in growth at high levels of N and P (150 kg/ha and 400, 600 kg/ha N) in the 5th growing season post fertilization (Figure 3.6) is likely due to the increased water stress that the high fertilizer applications induced in periods when rainfall was low. In the first two years after the trial was established there was considerable mortality in the adjacent plantation, which was not thinned until age 5 years, 2 years after the trial area was thinned. The lower impact of the dry conditions within the trial area was likely due to the earlier thinning of the trial area and better competition (weed) control in the trial.

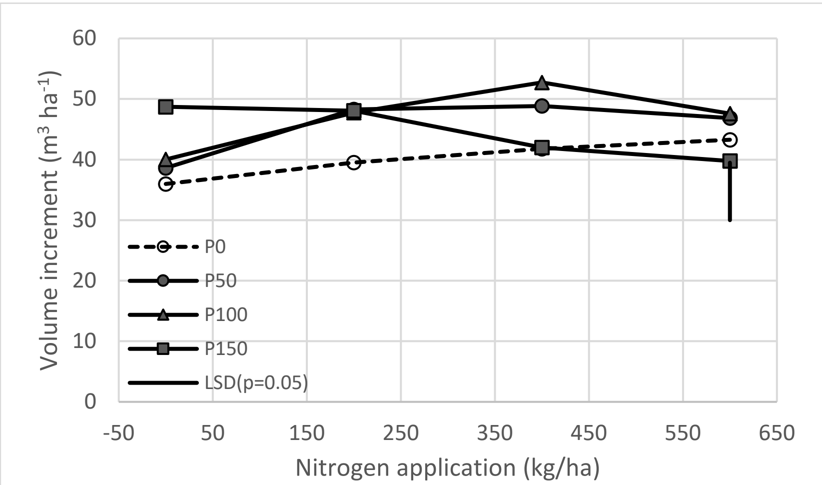


Figure 3.6. The influence of nitrogen and phosphorus applications on the volume increment from age 3 to age 7.5 years in African mahogany in compartment Yak 9c, Gypsy Springs plantation, Douglas Daly NT

When the trial was measured at age 7.5 years (mid dry season 2019) significant mortality and tip death was observed, with 13% of trees across the trial showing either dieback from the tip or complete canopy death, with ~3% assessed as dead. At that point there appeared to be greater mortality and morbidity in the higher fertilizer treatments, though this is not clear cut with all treatments showing evidence of morbidity. The greater morbidity and mortality in the higher fertilizer treatments is consistent with the poorer growth in the 2018/19 growing season and the depression in overall increment that occurred in the higher fertilizer treatments in this year (Figure 3.6). The data from the T x F trials (Section 1) indicates that water stress is the most likely cause of this morbidity and mortality.

Due to the level of morbidity in the trial it was decided to discontinue the measurements and thin the trial to a density that the recent data from the thinning trial had demonstrated was more likely sustainable during dry periods. Despite thinning the stand in December 2019 the mortality continued and by February 2020 up to 80 % of the stand had been affected (C Oliver Pers comm). The continued mortality despite the recent thinning is likely due to the poor early wet season rains in the 2019/20 season which did not result in significant recharge of the soil profile. While thinning would have reduced the water demand at a site level, unless there was recharge of the soil profile then the individual trees would remained water stressed.

Nutrient concentrations in mahogany foliage were measured in the middle of the dry season from age 3.5 to age 5.5 years which was 6, 18 and 30 months after fertilization. Phosphorus concentrations increased in successive years and by age 5.5 years, 2.5 years post fertilization, P concentrations were higher in the fertilized treatments than in the control treatments and were significantly higher than in the six months after fertilization. The progressive increase in P concentration from 6 to 30 months after fertilization suggests that access to the fertilizer P increased over this period.

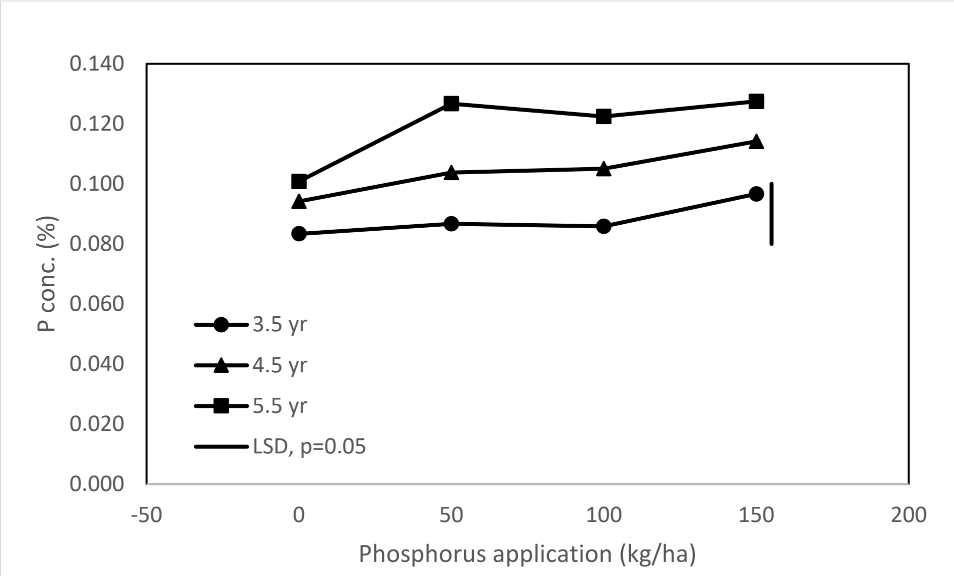


Figure 3.7. The influence of phosphorus application on leaf phosphorus concentration in the first 3 years after fertilization when sampled in the mid dry season (June 2015-2017, age 3.5 to 6.5 years)

In contrast to the increasing P concentrations over time there was no significant increase in N concentrations in relation to increased N application or over time since fertilization (Figure 3.8). This could indicate that N applied as urea was not available to the trees. The condition of the tree canopy however, was changed with fertilization, with noticeably heavier, denser and greener canopies in high nitrogen treatments. Additionally, there was a significant response to moderate applications of N (200 kg/ha) (Figures 3.2 to 3.6). These data suggest that sampling in the dry season may not provide a useful measure of tree nutrient status, at least for nitrogen. Further data from the second N x P trial also indicates that this may be the case.

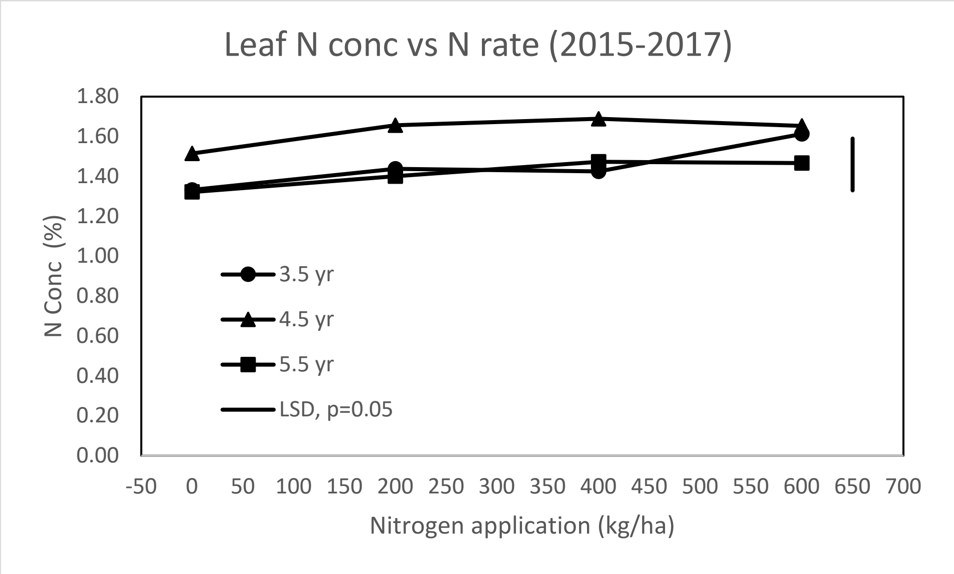


Figure 3.8. The influence of nitrogen application on leaf nitrogen concentration in the first 3 years after fertilization when sampled in the mid dry season (June 2015-2017, age 3.5 to 6.5 years)

2 Nitrogen by phosphorus interaction trial – KBC Jill's

Objectives of the trial

Similar to the trial established in 2015 this trial was designed to evaluate the optimum application rates of phosphorus and nitrogen and define any interaction between these nutrients on the overall productivity and individual tree size in young *Khaya senegalensis.*

Specifically, this additional trial was installed to provide information on:

- The response surfaces for nitrogen and phosphorus from a wetter site with a heavier textured soil and assist in identifying whether other nutrients (K, S, Ca, trace elements) are likely to influence plantation performance and hence whether initiating trials to cover these nutrients is required.
- Refining the relationships between both soil and foliage nutrients concentrations and tree performance, which will improve the capacity to identify deficiencies and optimise nutrient supply for plantations.

The trial was intended to be initiated in November/December 2016 however heavy rain prevented access to the site until the end of the wet season, with the fertilizer being applied on 6th April 2017 at the end of the wet season with significant rain falling in the few days after fertilization.

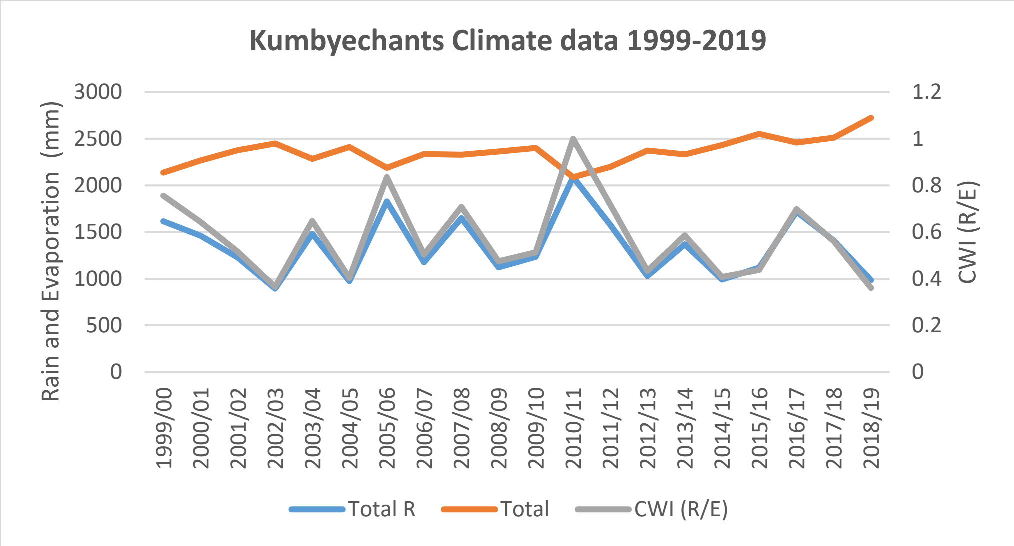
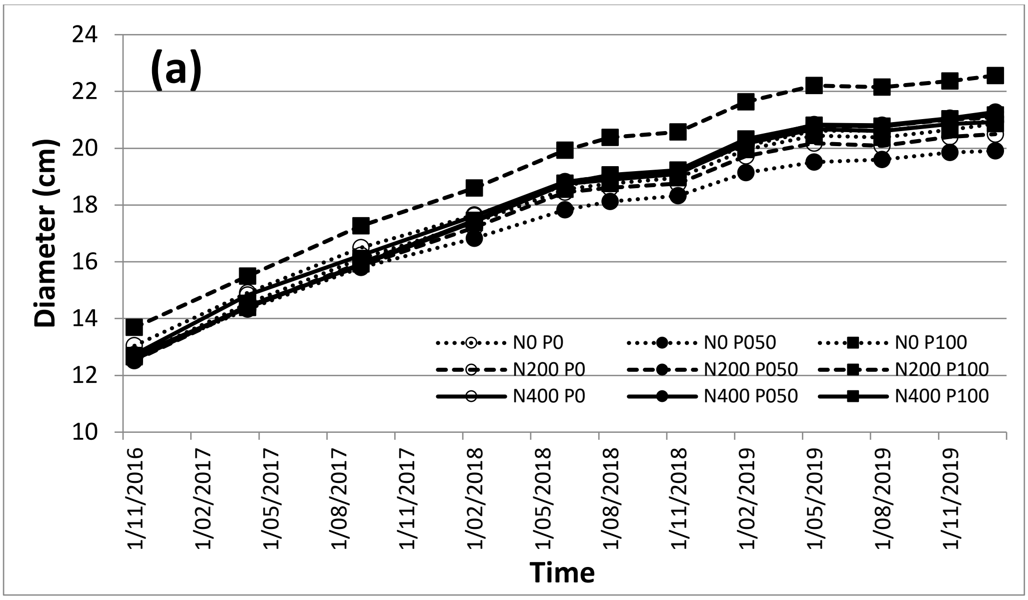
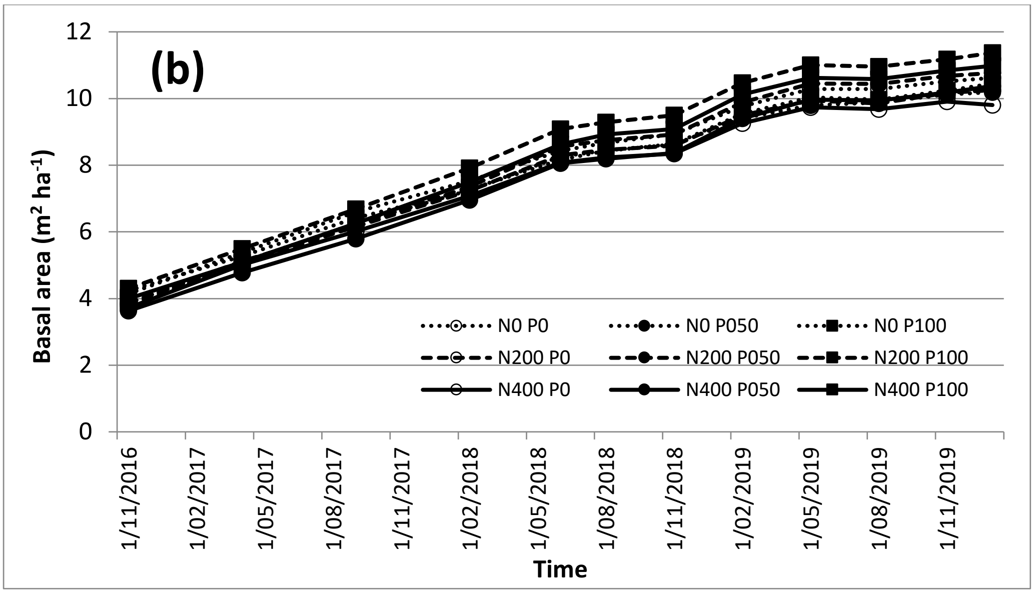


Figure 3.9. Wet season (September to August) climate indices, rainfall (R), evaporation (E) and Climate Wetness Index (CWI = R/E) at Kumbyechants Plantation for the period 1999/2000 to 2018/19.

In contrast to the initial N x P trial at Yak 9 this trial was established when the wet season rainfall was above the long term mean of 1348 mm (Table 3.2) with wet season rainfall of 1720 and 1410 mm respectively in the first two years after fertilization, the rainfall in the third growing season post fertilization was the lowest during the measurement period at 984 mm (Figure 3.9). The higher rainfall at this site meant that the climate wetness index (R/E) varied from 0.70 in the third year (2016/17) to 0.36 in 2018/19, which was considerably higher than for the Yak 9 site.

Quarterly measurement since the fertilizer application demonstrate that there has been no response in diameter (Figure 3.10a), basal area (Figure 3.10b) or volume (Figure 3.10c) to the applied fertilizer. Analyses of variance annually since the fertilizer application verified that there was no significant response to fertilizer application in the three years since fertilization.





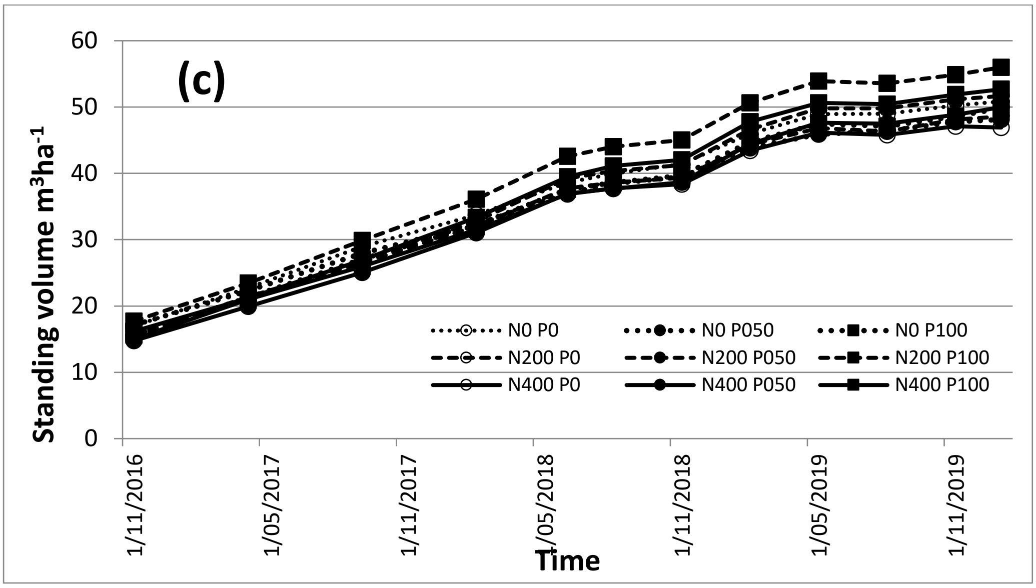


Figure 3.10. Progression of (a) diameter (cms), (b) basal area (m^2 ha^{-1}) and (c) total volume production (m^3 ha^{-1}) related to combined phosphorus application (0, 50 100 kg/ha) and nitrogen application (0, 200, 400 kg/ha at age 5 to age 8 years (April 2017 to February 2020).

The absence of a response to fertilizer is likely due to an adequate supply of nutrients at this site (see subsequent integrated analysis). The other possibility is that growth at the site is limited by water availability. To assess this we measured the leaf water potentials at this site at the beginning of October 2017 and the trees were only experiencing a very modest level of water stress, indicating that it was unlikely that water availability was a major limitation on this site. The continuous linear growth trend in the first 18 months following fertilization (Figures 3.10 a, b, c) also indicate that water supply did not limit growth during this period. In the 2nd and 3rd seasons when conditions were progressively drier the growth slowed during the dry season for successively longer periods, indicating that water supply limited growth during the dry season in these years. From the T x F trials (Section1) where seasonal growth trends were assessed, it appeared that the responses to fertilizer occur during the wet season and as there was no response during this period we conclude that this site was not responsive to N and P applications**.**

As there was no response to fertilizer at this site the mean annual increment for all the treatments is presented as the site mean in relation to CWI (Figure 3.11). For this trial the annual increments were measured from November 2016 to November 2019, which provided three full growing seasons over which growth was measured. As the dates of measurements varied due to logistic and weather conditions, the annual estimates were made by calculating the increments to an anniversary date at the end of November each year. While this is different to the period used to calculate the annual increments for other trials in this program the measurement prior to the commencement of the wet season allowed a full annual estimate of growth for three separate years. The virtual cessation of growth toward the end of 2018 and from mid-2019 (Figures 3.10 a, b c) also indicate that measuring growth in November allowed the growth over the full growing season to be captured.

There was a very strong relationship between annual volume growth (CAI) and CWI, indicating again that water availability provides a very strong control over growth in this region (Figure 3.11). The slope of the relationship between CWI and volume growth was lower than from the Yak 9 site. This will be discussed further in the General Discussion for this section.

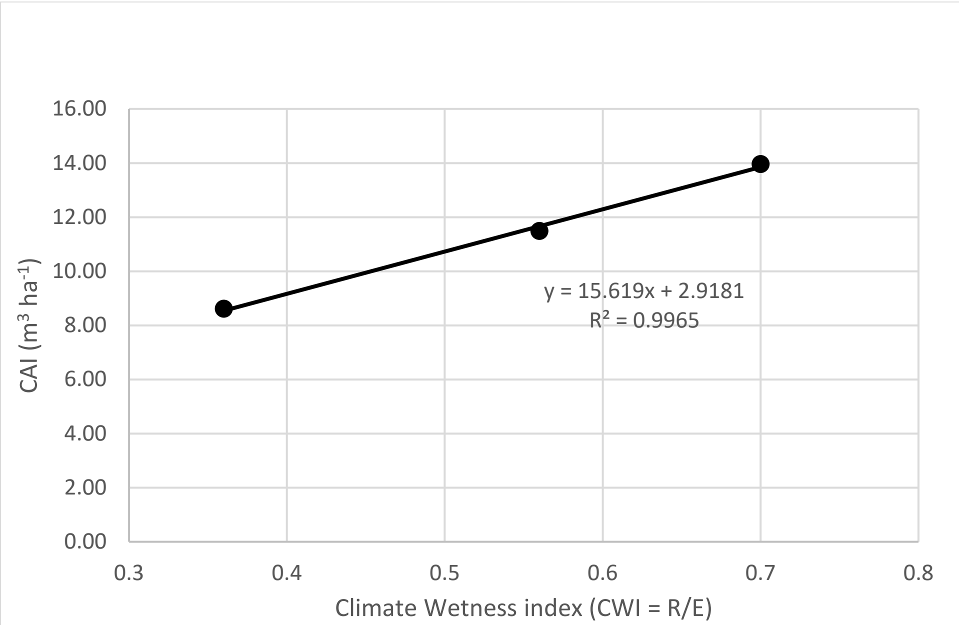


Figure 3.11. The Impact of water availability (measured as CWI) on annual volume increment.

Foliar nutrient concentrations

Based on experience with other species in different environments foliage sampling in the mid-dry season was used operationally to assess the nutrient status of mahogany (J Turner Pers. comm.). Due to the absence of a response in foliage nitrogen concentrations sampled in mid-dry season in the first N x P trial (Yak 9) a program of seasonal sampling was conducted to investigate the impact of altered nutrient supply and season on foliage nutrient concentrations.

There was a strong seasonal pattern of leaf N (Figure 3.12) and P (Figure 3.13) concentrations with the highest concentrations observed early in the wet season with concentrations declining until the end of the dry season. Following fertilization late in the 2016/17 wet season (06/04/17) the N concentration in foliage increased above that in the unfertilized control by May 2017 (Figure 3.12). In contrast there was no increase in foliage P concentrations above the control until the following wet season commenced (Figure 3.13). The difference in the pattern of response may be due to the different availability of N and P in the soil. Nitrogen is likely rapidly available due to the high solubility of N in the soil, while P is less mobile in the soil and hence less likely to be rapidly available to the trees following application late in the wet season. Clearly fertilizer applications altered the nutrient availability to the trees and this was reflected in increased nitrogen (Figures 3.12) and phosphorus (Figure 3.13) concentrations in leaves. This effect was greater for N than for P. Concentrations of both N and P increased rapidly early in the wet season and declined throughout the wet season and the following dry season (Figures 3.12 and 3.13).

The seasonal trends in leaf N (Figure 3.12) and leaf phosphorus concentrations (Figure 3.13) show that the lowest variation in nutrient concentrations between the fertilizer treatments occurred in the mid-dry season period. This indicates that it is unlikely that sampling at this time will reflect differences in nutrient supply or tree nutrient status. If sampling was restricted to the mid-dry season then the conclusion would be that there had been limited or no impact of the fertilization on tree nutrient status, this is particularly so for nitrogen.

There appeared to be a difference in the longevity of the impact of N and P fertilization with the impact of N fertilization apparent soon after the application of fertilizer (Figure 3.12). The impact of N application appeared to be short lived with a much lower seasonal increase in N concentration in the third season post application and only modest differences between treatments (Figure 3.12). In contrast the impact of P fertilizer was not apparent until the beginning of the wet season after application (Figure 3.12), however the increase in P concentration appeared to extend strongly into the second wet season post application (Figure 3.13).

The lack of responses to either N or P make it impossible to establish relationships between leaf nutrient concentrations and growth and thus determines whether foliar nutrient concentrations are useful in assessing the nutrient status of mahogany.

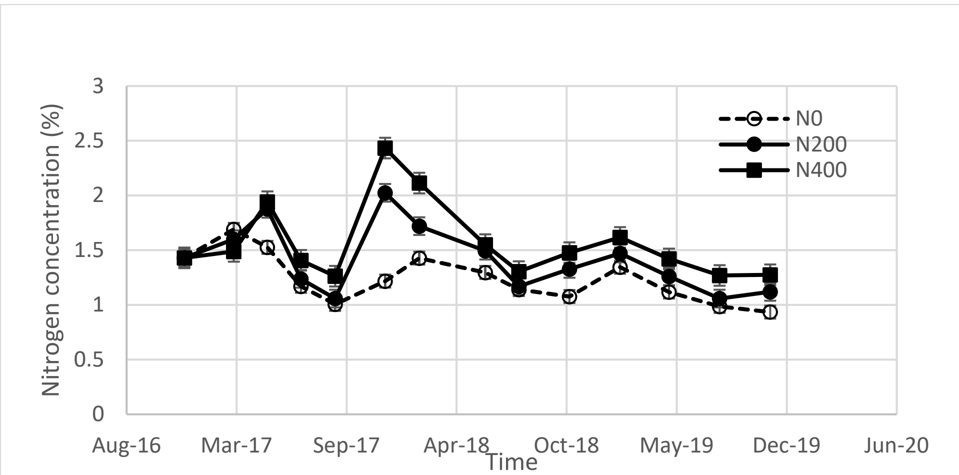


Figure 3.12. The influence of nitrogen application on leaf nitrogen concentrations from November 2016 (age 4.8 years) to November 2019 (age 7.8 years)

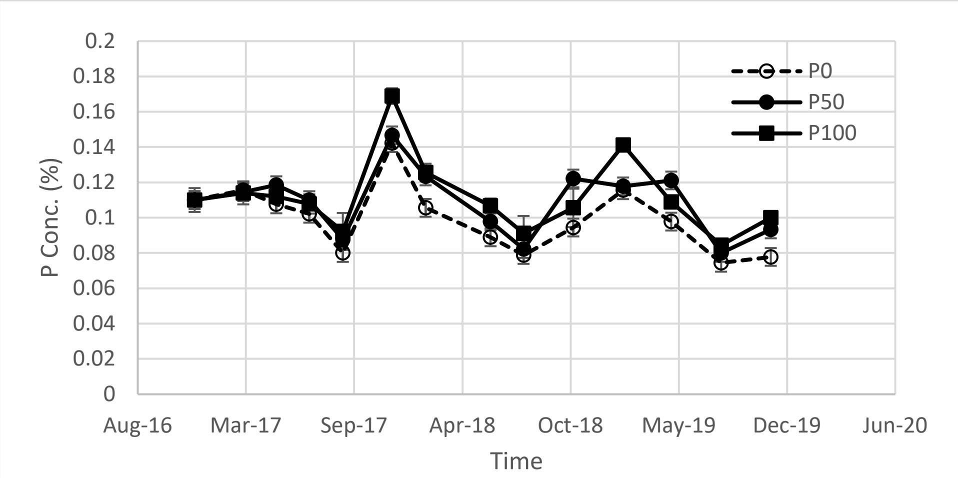


Figure 3.13. The influence of phosphorus application on leaf phosphorus concentrations from November 2016 (age 4.8 years) to November 2019 (age 7.8 years)

3. Diammonium phosphate (DAP) rate trial Wallaroo 4 Stray Creek plantation

Objectives of the trial

A small trial designed to assess the response to increasing rates of Diammonium phosphate (DAP) application that were judged to be operationally feasible was established in February 2018 in a 5 year old plantation in Stray Creek Plantation compartment Wallaroo 4. In addition to the rates of DAP a treatment that tested the application of calcium at 125 kg/ha Ca was added to the highest rate of DAP.

Due to the installation of this trial in 2018 only two years data are available, the first growing season received 1295 mm over the wet season which was close to the average rainfall of 1251 mm. In the second year only 820 mm of rain was received (Figure 3.14).

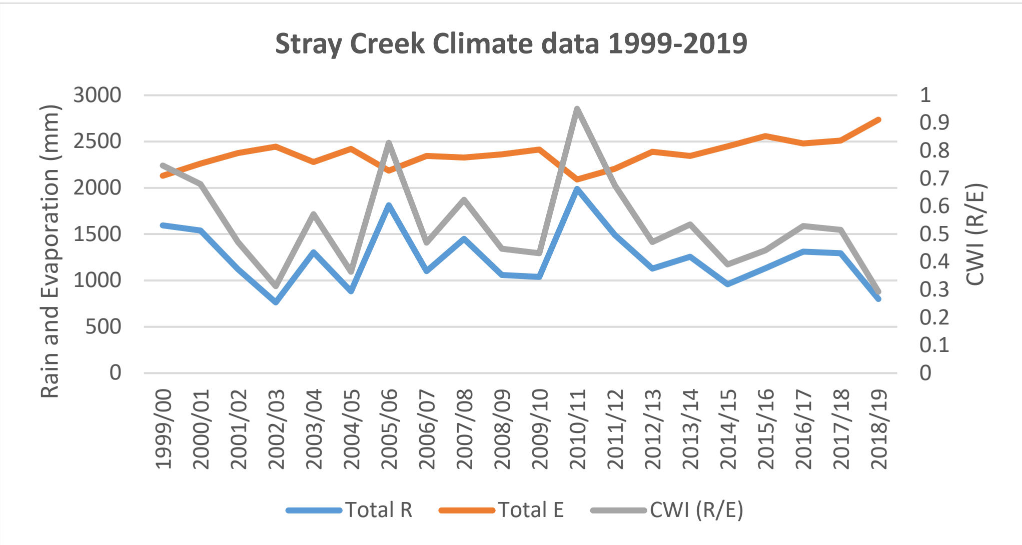


Figure 3.14. Wet season (September to August) climate indices, rainfall (R), evaporation (E) and Climate Wetness Index (CWI = R/E) at Stray Creek Plantation for the period 1999/2000 to 2018/19.

There was strong linear response to increasing applications of DAP in the first year after application (Figure 3.15 and 3.16). However, there was a much lower increment in the second season after the fertilizer application (Figure 3.15 and 3.16). In the second year there was no detectable response to fertilizer application (Figure 3.16) and the annual increment was very low at 2 $m^3\ ha^{-1}\ yr^{-1}$. Applying calcium did not significantly increase volume growth in either the first or second year.

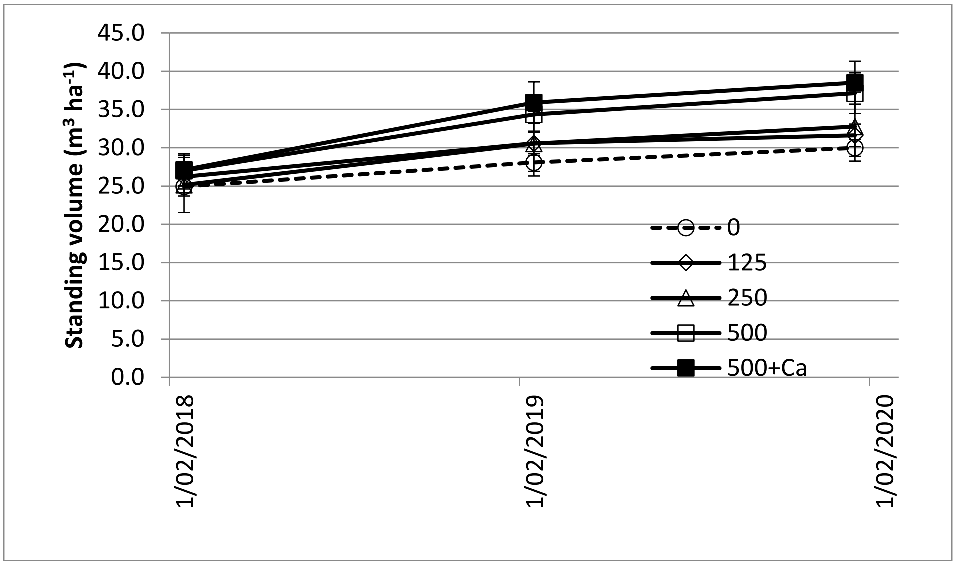


Figure 3.15 Impact of the application of diammonium phosphate (0, 125, 250, 500 kg/ha) and calcium as gypsum at 250 kg/ha on total volume production ($m^3\ ha^{-1}$) in the two years after fertilization at age 5 (February 2018 to February 2020).

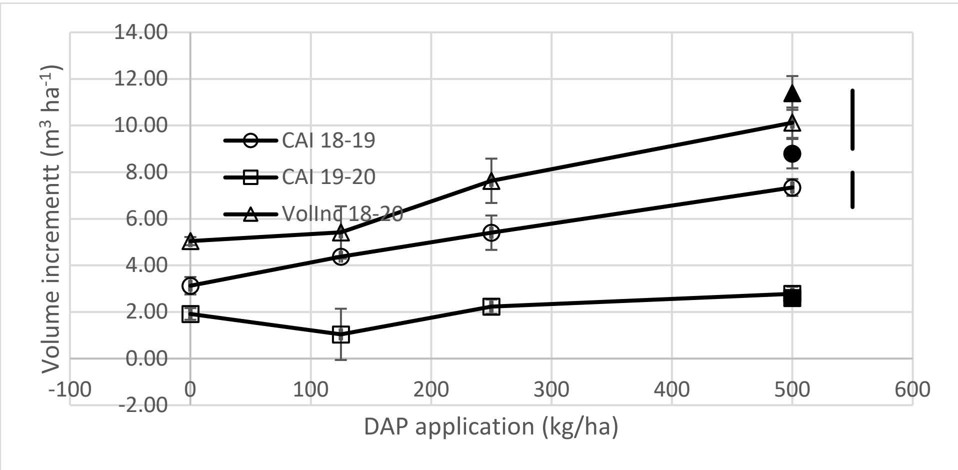


Figure 3.16 Impact of the application of diammonium phosphate (0, 125, 250, 500 kg/ha) and calcium as gypsum at 250 kg/ha on total volume production ($m^3\ ha^{-1}$) on the annual and two year increments in the two years after fertilization at age 5 (February 2018 to February 2020). LSD p=0.05 show as vertical bars for the 2018/9 increment and the 2 year 2018/20 increments. There was no significant difference between the treatments in the second year after fertilization.

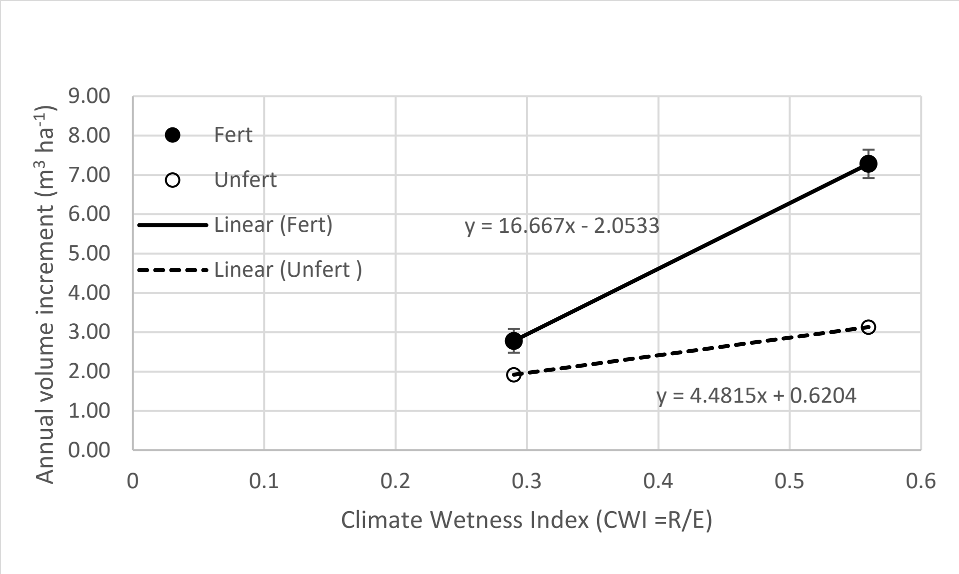


Figure 3.17. The Impact of water availability (measured as CWI) and fertilization on annual volume increment (m^3 ha^{-1}). The fertilized treatment is the 500 kg/ha application without additional calcium.

The volume growth in this trial over the first two years after fertilizer application which has strongly contrasting water supply, demonstrated a very strong positive interaction between water availability and the response to fertilizer. In the dry second year there was a very limited response to applied fertilizer while in contrast the volume increment more than doubled when rainfall was near the long-term average for this site and water supply was less of a constraint (Figure 3.17).

4. Integrating the responses across multiple sites

Fertilizer responses in relation to soil nutrient status

An assessment of the response to fertilizer in relation to the initial fertility of the trial sites (Table 3.3) shows that sites with low concentrations of N and P respond strongly (e.g. Stray Creek Rocky Knob 9) while there has been a smaller response to a high fertilizer application at KBC Hot Springs which has higher concentrations of N and P in the soil and similarly there is only a small response to fertilizer in the N x P trial in Jill’s compartment Kumbyechants. Between these ranges the response to fertilizer is between 30-50%. Comparing the responses over comparable periods and eliminating other influences such as water availability and other limiting nutrients will likely assist in assessing whether soil nutrient concentrations are a useful tool for assessing plantation nutrient status for African mahogany. The initial indications are that soil nutrient concentrations provide a useful guide to those sites that will respond to fertilizer.

Table 3.3. Responses* to fertilizer in relation to soil nutrients from the current Douglas Daly trials at 2018

Site	Organic Carbon (%)	Total N (%)	C/N ratio	Colwell P (ppm)	Colwell K(ppm)	% fertilizer response *
KBC Hot Springs (T x F) **(estab. 2016)**	1.92	0.17	11.3	17.1	311	28
KBC Jills (N x P) **(estab. 2017)**	1.18	0.1	11.8	5.4	179	**0**
Wallaroo 4 **(estab. 2012)**	0.46	0.06	8.3	7.0	25	**113**
Gypsy Springs Snake 4 (T x F) **(estab. 2016)**	0.54	0.05	10.7	2.3	80	52
Gypsy Springs Yak 9 (N x P) **(estab. 2015)**	0.6	0.06	10.0	6.4	117	38
Stray Creek Rocky Knob (T x F) **(estab. 2016)**	0.48	0.03	16.3	3.7	20	111
Stray Creek Wallaroo 1 **(estab. 2012)**	0.35	0.02	17.5	3.0	-	**117****

* The responses were measured over the first 3 years post fertilization to provide a standard period for the response to be measured. The exception in the Wallaroo 4 trial where the trial was established in 2018 meaning that there are only 2 years of data available.

**The response included for the Stray Creek Wallaroo 1 site is for the second phase of the trial as the response in the first phase from 3-9 years likely underestimated the response as there was no fertilizer control on this trial only a 'low' fertilizer application, the recent measurements following refertilization in 2017 provide a better estimate of the response, and growth was more than doubled at this site.

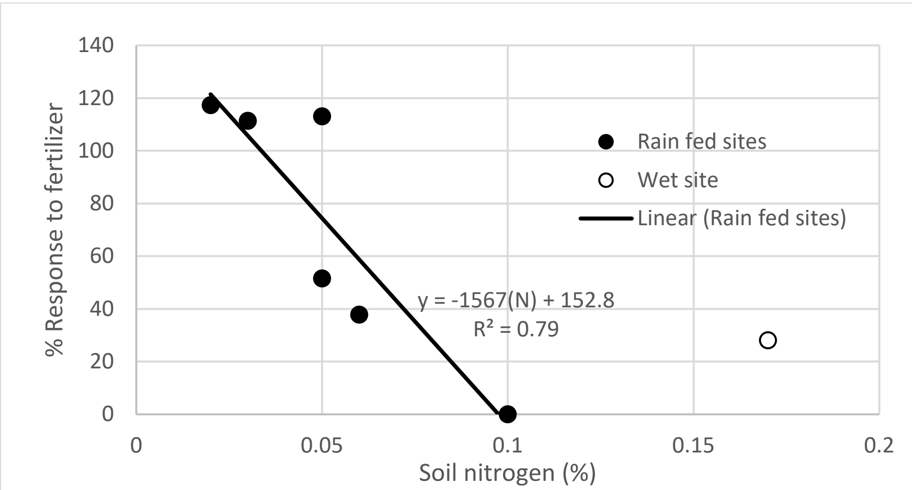


Figure 3.18. Fertilizer response related to soil nitrogen concentration for sites which were rain fed.

Note: The period of measurement was 3 years post fertilization for all trials with the exception of the Wallaroo 4 trial which was measured for only 2 years as the trial was established in 2018. The data for the water gaining site in the Hot Springs compartment of Kumbyechants plantation (open circle on RHS) was not included in the regression analysis as the response was likely influenced by the additional water on that site from the adjacent farmland.

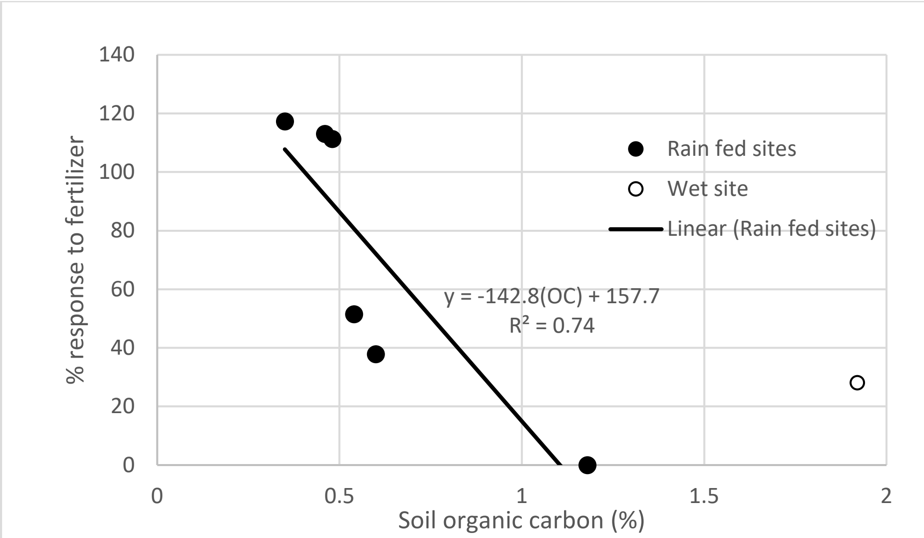


Figure 3.19. Fertilizer response related to soil organic carbon concentration for sites which were rain fed.

Note: The period of measurement was 3 years post fertilization for all trials with the exception of the Wallaroo 4 trial which was measured for only 2 years as the trial was established in 2018. The data for the water gaining site in the Hot Springs compartment of Kun Bye Chants plantation (open circle on RHS) was not included in the regression analysis as the response was likely influenced by the additional water on that site from the adjacent farmland.

The relationships between soil nitrogen and soil organic carbon and the response to fertilizer both show a strong increase in response as both soil organic carbon and nitrogen decline.

The data are from three fertilizer trials (the NxP response trials at Yak 9 and Jills plus the DAP rates trial at Wallaroo 4) and four TxF trials (Wallaroo 1 and the three smaller trials). The regressions indicate that for the 'responsive part of the relationship' where SOC is <1.1% and soil N <0.1%, that ~79 % (N) and 74 % (OC) of the variation in response is explained by the relationships. The data are from thinned plots (200/300 sph for the TxF trials, including Wallaroo 1) and for Yak9, Jills and Wallaroo 4 all of which were thinned at or immediately prior to fertilization.

These relationships integrate the responses for rain limited sites across a range of growing seasons and appear to provide strong guidance as to the sites that will respond to fertilizer. As the majority of mahogany estate in the Douglas Daly is on water limited sites the responses to fertilizer are likely to be similar to the responses demonstrated in these relationships.

A possible reason that Hot Springs appears responsive above the cut-off (critical) concentration may be because of the additional water available at that site meaning that it still responds despite the higher soil OC and N concentrations. It seems from the seasonal growth plots which show a distinct dry season slowing in growth (with the exception of Hot Springs) that growth at all sites except Hot Springs is limited by water first and then N.

A similar relationship for blue gums in WA has a critical soil N concentration of about 0.2% N (twice what these data indicate). However, those data come from sites which have a much greater climate wetness index, largely driven by much lower evaporation in these southern plantations.

Fertilizer responses in relation to water availability

By combining the data from the two trials in the Gypsy Springs plantation, which are on near identical soil types and similar topographic locations a similar trend is observed and with plus fertilizer treatments with the response to increased water availability the same as for Yak 9 alone (Figure 3.4). The response to increasing CWI for the unfertilized (control) treatments at these sites has a lower slope (i.e. is less responsive) when the data are combined and it is considerably more variable (Figure 3.20a). When the data for the unfertilized control treatments are separated for each site then it appears that the sites respond differently to increasing water supply in the absence of fertilizer (Figure 3.20(b)). This lower response to increased water availability at Snake 4 implies that the fertility of the Snake 4 site is lower than that at Yak 9. While the availability of nitrogen appears similar at both sites (Table 3.3) the phosphorus availability as indicated by the Colwell P value is much lower at Snake 4 (2.3 ppm) compared to Yak 9 (6.4 ppm) (Table 3.3). It is possible that the difference between the response to increased water availability at Snake 4 relative to Yak 9 is due to the greater nutrient deficiencies at Snake 4.

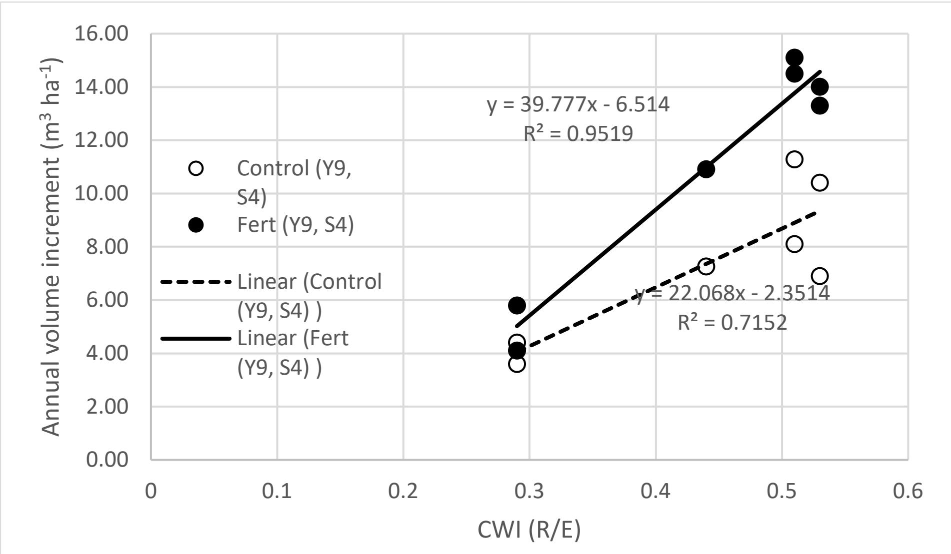


Figure 3.20a. Impact of water availability (measured as CWI) and fertilization on annual volume increment (m^3 ha^{-1})(Yak 9 and Snake4 trials)

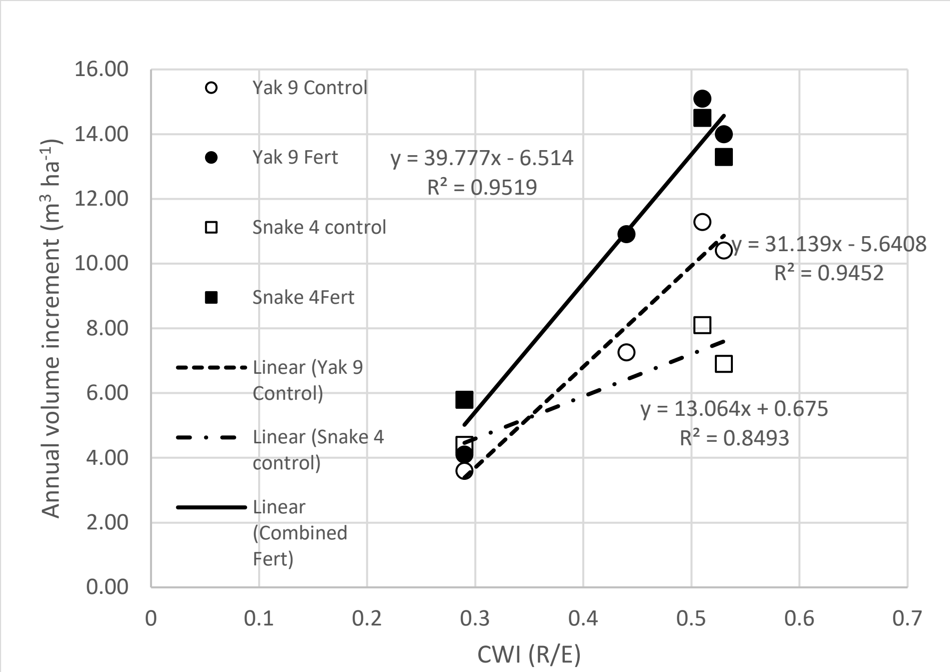


Figure 3.20b. Impact of water availability (measured as CWI) and fertilization on annual volume increment (m^3 ha^{-1}) for Yak 9 and Snake4 trials, showing the unfertilized control data for the 2 sites separately.

The limitation on growth imposed by water availability restricts the responses to fertilizer in drier years and drier sites and responses to fertilizer need to be evaluated within the constraints imposed by water availability. Even on dry sites it is possible to achieve responses to N and P as water availability does not limit growth during the wet season or in all years (Section 1). Promoting strong canopy growth during the wet season can lead to more rapid use of the available water, resulting in extended periods of water stress in the trees. As previously outlined the progression of growth in the longer-term thinning x fertilizer trial (T x F) at Wallaroo clearly demonstrated that stand level volume production in thinned stands matches that in unthinned stands and that in dry periods high stocking can result in mortality. Individual tree growth is significantly enhanced by thinning in combination with fertilization and this effect appears most marked in wetter periods, noting that the data collected during this project has been derived from a period with average to below average rainfall. Thinning to either low or moderate residual densities reduced the water demand sufficiently to eliminate mortality in dry years.

Conclusions:

- Nutrient supply influences the productivity of African mahogany in the Douglas Daly region. Fertilizer application has doubled growth on low fertility sites and responses of between 30 and 50% were observed on other sites.
- The response to fertilizer is strongly dependent on the availability of water. In dry years the responses to fertilizer are limited and high leaf area developed in response to fertilization can predispose plantations to severe water stress and drought related mortality.

- In contrast there are sites, mainly with better agricultural fertilizer history e.g. KBC, Hot Springs and Jill's sites, where even with good water supply there were limited or no responses to fertilizer.
- The response to fertilizer appeard to last at least 4 growing seasons post fertilization.
- Variation in soil nitrogen (N) and soil organic matter (SOM) concentrations show considerable promise in identifying sites that will respond to fertilizer.
- Sampling foliage in mid-dry season is unlikely to be useful for assessing the nutrient status of African mahogany plantations. While nutrient concentrations during the wet season appear responsive to nutrient supply the measures undertaken were unable to identify relationships between foliage nutrient concentrations and growth. Additional work will be required to determine if foliage nutrient sampling can provide useful indicators of the nutrient status of African mahogany plantations.

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Acknowledgements

See Section 2

Section 4. Impact of selective lift pruning on stand and tree level growth of African mahogany

Summary

Following the first non-commercial thinning two pruning trials were established in stands aged 4 years and 5 years with different residual stocking. Three years post thinning and pruning there were no measurable changes in stand level growth and only a small transitory impact on the diameter growth of the codominant tree cohort at one of the sites.

Observations from stem cross sections, veneer sheets and from the rate of pruning wound occlusion demonstrated that mahogany rapidly occluded pruning wounds. There is evidence that under some conditions fungal infections occur on pruning wounds. Based on limited data it appears that this was more prevalent under wetter conditions. A potential solution to this could be to undertake pruning early in the dry season, particularly on wetter sites.

Introduction

The African Mahogany plantations in the Douglas Daly Region were established to provide material for the high-quality furniture market. Providing clear stems that can be used for solid wood or veneer production is critical to the success of the project. AMA's objective initial objective was to produce trees with a minimum of 38cm DBHOB and a 6 m clear bole.

While some genetic selection has been undertaken the plantations have been established with a mixed seed lot and the growth and form of the trees is variable. There are considerable differences in both branching habit and stem straightness within the existing plantations. Assessing the impact of pruning using the current genetic base was important to optimize the value of the current stands.

Operational pruning has been be applied after the first thinning. Initially it was intended to retain ~500 sph at first thinning, however with the recent re-evaluation of the silvicultural objectives for the plantations in the Douglas Daly Region following the series of dry seasons the target stocking at first thinning has been reduced to 300 sph. Under the revised silvicultural system it is likely that all the retained stems will be pruned.

The trial was established in areas that represent both the earlier 500 sph and the more recent 300 sph stands to provide information on the impact of pruning in both these stand types.

The trials were designed to assess the impact of pruning on the growth and wood quality of selective lift pruning young mahogany in the Douglas Daly Region. The initial phase of the trial which will occurred during the FWPA project assessed the impact of pruning on stand level growth and individual tree growth and the impact of pruning on bole length.

Research method

Two trials using a fully randomised design which compared two pruning treatments (Pruned and Unpruned), with four replicates were established in December 2016 at separate sites in the Kumbyechants and Gypsy Springs plantations.

Table 4.1. Site description

Location	Lat/Long	Planting year	Trial established	Land Unit
KBC Billabong 11	13 °45’20”/131 °23’41”	2011	Dec 2016	5d
Gypsy Springs Tick 4	13 °56’56”/131 °25’17”	2012	Dec 2016	4b1

The sites were selected to provide contrasting silvicultural regimes under which pruning was evaluated. The KBC Billabong 11 compartment had been thinned in late 2015 to a nominal density 500 sph (actual density 556 sph). The Gypsy Springs Tick 4 trial area was thinned to 300 sph immediately prior to the pruning operation in December 2016

Plots were established with a 1 row buffer around the internal measurement plots. As all other silvicultural operations were uniformly applied (fertilizer, competition control) the single row buffer provided sufficient distance to separate the measurement plots from adjacent treatments. The plot dimensions varied between the two sites to accommodate the different stocking with the plots at Tick 4 larger that at Billabong 11 due to the lower stocking. A minimum of 30 trees per plot was targeted as only some trees were pruned and to assess these impacts it was judged that a total sample of at least 30 trees was required to provide sufficient numbers for a realistic assessment of the impact of pruning.
Plots were pegged on all corners of the treatment plots and the internal measurement plots. Pegs were placed on the tree row rather than between the rows so that future access was facilitated. Trees that remained after the thinning were marked with white paint at breast height (DBHOB at 1.3 m). Tree height and diameters were measured and basal areas and stocking (based on the measurement plot area) were calculated and used to assess the uniformity of the site.

Pruning treatments
The trials were pruned on 01/12/2016 (Billabong 11) and 02/12/2016 (Tick 4).

Mahogany has a strong crown break habit so the bole length is often determined early in the life of the tree. The variable genetic base of the stands also added to the complexity of establishing a pruning evaluation as there is considerable variation in the form of the trees. The strategy used was to assess each tree in the pruned stands and determine if pruning would improve the outcome for the bole length of the tree. Trees with crown break were not pruned, Tall Skinny trees were only pruned if pruning was judged to improve the outcome for the bole. This approach is essentially a variable lift pruning based on the likely impact of pruning in increasing the bole length of the logs.

Tree assessment and pruning strategy
The impact of pruning was measured by assessing the proportion of the crown removed by pruning and by measuring the diameter of all branches removed to provide an index of the severity of pruning.

Growth:
Diameter, Height, Bole height pre- pruning and Bole height post- pruning were measured
Tree Form: Three basic forms of tree are evident Short bole (Short fat =SF) with crown break established below 3 m. Tall thin trees (Tall Skinny = TS) where the trees have few branches below the canopy (which keeps rising) and a ‘hybrid’ (H) which falls between these extremes.
Straightness: A 4 point straightness scale was be used to assess stem straightness

Dominance class: Assessed as Suppressed(S), Sub-dominant (SD), Co- dominant (CD), Dominant (D)

Pruning impacts

To assess the impact of pruning on each tree the Percentage of crown removed, Number of branches removed and the Diameter of removed branches were assessed and measured.

Table 4.2. Design details

Number of treatments	2 (Pruned and Unpruned)
Replicate blocks	4
Number of sites	2 (Contrasting silviculture and sites KBC wetter than Gypsy Springs)
Total plots per site	8
Nominal initial stocking at establishment	300 sph (Tick 4), 500 sph (Billabong 11)
Gross area of trial	~4.9 ha

Results and Discussion :

The stand and tree level responses three years after pruning were assessed. Observations on the impact of knots on product quality are contained in the report on the Silviculture impacts of veneer grade recovery undertaken by QDAF (Sections 6 and 7)

The data from the third measurement confirms the observations after the first two years that selective variable lift pruning did not reduce the growth of the trees at a stand level with no significant difference in either the height, diameter or basal area increments (Table 4.2).

Based on three years growth data post pruning it is clear that selective pruning has no measurable impact on the growth of the plantations at a stand level (Table 4.2).

Pruning increased the mean bole length of the trees by between 1.2 to 1.4 m at the Tick 4 and Billabong 11 sites which increases the overall clear butt log length by approximately 220 m per ha at Tick 4 and 380 m at Billabong 11 (Table 4.3).

While the proportion of trees pruned was higher at the Tick 4 site the lower stocking at that site meant that number of trees ha^{-1} was significantly less than at the Billabong 11 site (181 vs 278 trees ha^{-1}) (Table 3). The pruning costs would have been proportionally lower at the Tick 4 site and given that the recommendations from the thinning and fertilizer studies is to reduce stocking early in the rotation reducing stocking prior to any pruning operation will likely reduce costs significantly.

Table 4.2 Impact of pruning on stand level growth 3 years after pruning

a. Height data 2016-19: Billabong 11 KBC

Treatment		Ht 2016	Ht 2017	Ht 2018	Ht 2019	Inc 16-19
Unpruned	**Mean**	**7.90**	**8.59**	**9.26**	**9.74**	**1.84**
	SD	0.27	0.26	0.39	0.33	0.11
Pruned	**Mean**	**8.10**	**8.89**	**9.64**	**10.03**	**1.93**
	SD	0.29	0.47	0.46	0.60	0.35

b. Height Increment 2016-17: Tick 1 Gypsy Springs

Treatment		Ht 2016	Ht 2017	Ht 2018	Ht 2019	Inc 16-19
Unpruned	**Mean**	**6.87**	**7.85**	**8.92**	**9.44**	**2.58**
	SD	0.37	0.40	0.48	0.52	0.18
Pruned	**Mean**	**6.95**	**7.90**	**8.97**	**9.51**	**2.57**
	SD	0.17	0.23	0.33	0.33	0.17

c. Diameter increment 2016-17: Billabong 11 KBC

Treatment		Diam 2016	Diam 2017	Diam 2018	Diam 2019	Inc 16-19
Unpruned	**Mean**	**12.19**	**14.34**	**15.75**	**16.78**	**4.59**
	SD	0.27	0.38	0.46	0.43	0.23
Pruned	**Mean**	**12.44**	**14.45**	**15.84**	**16.78**	**4.34**
	SD	0.31	0.44	0.43	0.47	0.24

d. Basal Area increment 2016-17 Billabong 11 KBC

Treatment		BA m^2/ha 2016	BA m^2/ha 2017	BA m^2/ha 2018	BA m^2/ha 2019	Inc 16-19
Unpruned	**Mean**	**4.37**	**5.97**	**7.22**	**8.19**	**3.82**
	SD	0.21	0.37	0.49	**0.49**	0.33
Pruned	**Mean**	**4.41**	**5.90**	**7.08**	**7.94**	**3.53**
	SD	0.35	0.50	0.55	**0.64**	0.34

e. Diameter Increment 2016-17: Tick 4 Gypsy Springs

		D16	Diam 17	Diam 2018	Diam 2019	Inc 16-19
	Mean	**10.05**	**12.75**	**15.83**	**17.10**	**7.06**
	SD	0.47	0.40	0.53	**0.49**	**0.13**
	Mean	**10.16**	**12.59**	**15.64**	**16.98**	**6.83**
	SD	0.23	0.15	0.32	**0.37**	**0.25**

f. Basal Area increment 2016-17: Tick 4 Gypsy Springs

Treatment		BA m^2/ha 2016	BA m^2/ha 2017	BA m^2/ha 2018	BA m^2/ha 2019	Inc 16-19
Unpruned	**Mean**	**1.62**	**2.62**	**4.07**	**4.75**	**3.13**
	SD	0.12	0.19	0.25	**0.27**	**0.16**
Pruned	**Mean**	**1.74**	**2.78**	**4.13**	**4.87**	**3.13**
	SD	0.09	0.12	0.33	**0.42**	**0.33**

Impact of pruning on tree level growth

To compare the impact of crown removal and dominance class on tree growth both the pruned and unpruned stands were assessed in the same manner with trees in the unpruned plots assessed for the extent of crown removal if they were to be pruned. The whole population of trees was pooled across the four replicate plots so that there were sufficient trees in each dominance by crown removal class.

Segregating the growth based on the initial dominance class and the extent of crown removal showed very limited impacts at a tree level on the distribution of diameter growth within the stand with the diameter increments for pruned and unpruned cohorts showing very similar increments across the three years following pruning (Table 4.4). The possible exception to this is that the codominant cohort that had more than 25% of the canopy volume removed appeared to have a lower diameter increment (0.4 -0.7 cm lower) than the unpruned cohort. The annual increment data (not shown) show that this reduced growth occurred in the first year post pruning.

Table 4.3. Stand characteristics and the impact of pruning on bole length

Trial		Stocking (stems ha^{-1})	Pruned trees (stems ha^{-1})	% of trees pruned	Stand bole length (m) prior to pruning	Bole length of pruned* trees (m)			
						Pre pruning	Post pruning	Increase in bole length per tree (m)	Increase in bole length per ha ** (m)
Billabong 11 (KBC)	**Mean**	**554**	**278**	**50**	**2.97**	**2.73**	**4.10**	**1.37**	**380**
	SD	21	55	10	0.12	0.14	0.12	0.05	
Tick 4 (Gypsy Springs)	**Mean**	**300**	**181**	**60**	**2.99**	**2.69**	**3.93**	**1.24**	**224**
	SD	14	24	7	0.2	0.12	0.19	0.14	

* The trees in the unpruned plots were assessed in the same manner as the pruned plots so that it was possible to compare the same cohort of trees from the pruned and unpruned stands.

** The increase in total bole length per ha was estimated from the stocking of pruned trees and the mean increase in bole length on a plot basis

Table 4.4 Impact of dominance class and the extent of crown removal on tree level diameter growth following selective lift pruning.

Billabong		**Unpruned**					**Pruned**				
Dom Class	**% Crown removal**	**n**	**Diam 2016**	**Diam 2019**	**Diam Inc 2016-19**	**SE (Inc)**	**n**	**Diam 2016**	**Diam 2019**	**Diam Inc 2016-19**	**SE (Inc)**
Sub Dom	0-20	6	9.9	13.6	**3.7**	0.2	14	10.1	13.8	**3.7**	0.2
	25+	4	10.0	14.3	**4.3**	0.6	6	10.2	14.2	**4.0**	0.2
Co-dom	0	59	12.3	16.8	**4.5**	0.1	48	12.4	16.8	**4.4**	0.1
	5-20	19	11.2	15.5	**4.3**	0.1	11	12.1	16.4	**4.3**	0.2
	25-40	21	12.1	17	**4.9**	0.2	17	12.4	16.9	**4.5**	0.6
	50+	17	11.8	16.6	**4.8**	0.2	28	12.3	16.4	**4.1**	0.2
Dominants	0-20	12	14.7	19.6	**4.8**	0.3	13	16.0	21.2	**5.4**	0.3
	25+	7	14.8	19.5	**4.7**	0.3	5	15.0	19.7	**4.7**	0.5
Tick 4		**Unpruned**					**Pruned**				
Sub Dom	0-20	12	8.5	15.2	**6.7**	0.4	10	7.9	13.5	**5.6**	0.4
	25+	7	8.5	15.2	**6.7**	0.6	6	7.9	14.2	**6.3**	0.7
Co-dom	0	30	9.9	16.7	**6.8**	0.2	40	10.3	17.2	**6.9**	0.2
	5-20	7	9.8	16.9	**7.1**	0.5	8	9.6	16	**6.4**	0.6
	25-40	20	10.1	17.0	**6.9**	0.3	14	10.4	17.4	**7.0**	0.4
	50+	30	9.9	17.0	**7.1**	0.2	32	10.0	17.0	**7.0**	0.2
Dominants	0-20	7	13.1	21.4	**8.3**	0.4	9	13.2	20.8	**7.6**	0.4
	25+	7	12.5	20.5	**8.0**	0.1	4	12.7	20.2	**7.5**	0.8

Occlusion of pruning wounds

The observations from both veneer sheets (Figure 4.1) and cross sections of logs (Figure 4.2) indicate that mahogany effectively occludes pruning wounds and the rapid closure of wounds Figure 4.3 suggests that the occlusion process is rapid. However, the presence of fungal fruiting bodies on the surface of the pruning wound in almost all trees on the wetter site and the apparent rot plume in the cross section of the stem through a pruned branch whorl (Figure 4.2) which also came from the wetter Kumbyechants plantation indicates that under some circumstances pruning can degrade timber. No fruiting bodies were observed in the trial located at the drier Gypsy Springs site. This site had a more open stand (~300 vs 550 sph) which may also have reduced the humidity within the stands.

The pruning operation in these trials occurred in December 2016 at the beginning of what was a strong wet season in this region. We suggest that any issues related to fungal infection and subsequent rot plumes within the stems, could be minimised by undertaking pruning operations early in the dry season so that the trees either have time to occlude the pruning wounds prior to the wet season or the wounds have the opportunity to dry out prior to the commencement of the wet season.

Figure 4.1 Veneer sheet from the Grade Recovery study demonstrating effective occlusion of pruned mahogany knot.

Figure 4.2 Occlusion of pruned knots from operational pruning in Kumbyechants Plantation

Figure 4.3 Fungal fruiting bodies in the pruning wounds from the Billabong 11 pruning trial in May 2017 approximately 6 months post pruning.

Conclusions

- Three years after pruning it is clear that selective variable lift pruning has no significant influence on stand level height, diameter or basal area growth. This confirms the observations after the first 2 seasons and this was consistent in stands of differing density.
- There appears to be a small reduction in diameter growth in co-dominant trees which are heavily pruned. However, this impact is small and appears confined to the first season after pruning. The absence of any stand level growth impact indicates that this reduced growth is allocated to other trees within the stand.
- Observations from log sections, veneer sheets and observations of wound occlusion in the trials demonstrates that mahogany rapidly and effectively occludes pruning wounds.
- There was evidence that under some conditions fungal infections occur on pruning wounds. Based on limited data it appears that this was more prevalent under wetter conditions. A potential solution to this could be to undertake pruning early in the dry season, particularly on wetter sites.

Acknowledgements

See the acknowledgements for Section 2.

Section 5: Impact of log geometry on gross margins from rotary veneer production

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Acronyms and Abbreviations

CD	Peeler core diameter
CV	Peeler core volume in cubic metres
GM/h	Gross margin per hour of operation
GM/m^3	Gross margin per cubic metre of marketable veneer
GR	Veneer recovery by grade
LC	Log cost per cubic metre of marketable veneer
LEDUB	Large-end diameter under bark
LSEDUB	Largest small-end diameter under bark
MDLC	Mill-delivered log cost
MDLV	Mill delivered log volume
MVRPLV	Marketable veneer recovery from peelable log volume
MVV	Marketable veneer volume produced per hour of peeling time
NR	Net recovery of marketable veneer from mill-delivered log volume
OV	Log ovality in percent, measured on the small-end of log
P	Price
PLV	Peelable log volume in cubic metres
PS	Lathe operating speed
PT	Peeling time in seconds
R	Marketable veneer value per hour of operation
RLD	Rounded log diameter
SEDUB	Small-end diameter under bark
SSEDUB	Smallest small-end diameter under bark
TVT	Total veneering time
VT	Veneer thickness

Summary

Research by the Queensland Department of Agriculture and Fisheries (DAF) has demonstrated the technical feasibility of using emerging spindleless rotary veneering technologies to process hardwood plantation and native forest logs of sizes and qualities previously considered unmerchantable. This study has investigated the effect of log geometry on the financial performance of rotary veneer production.

To support forest management decisions, along with providing guidance to processing strategies and target product groups, the maximum that can be paid for mill-delivered logs ($MDLC_{max}$) with alternative log geometries (small-end diameter under bark (SEDUB), length, taper, sweep, and ovality), while achieving particular target gross margins per hour of operation, has been determined. Findings reveal that log geometry substantially affects the financial performance of rotary veneer manufacture. A comparison of the relative importance of log geometry characteristics on the maximum that can be paid for mill-delivered logs is necessarily somewhat subjective; however, given the ranges of these attributes considered in this study, log geometry characteristics in decreasing order of impact on the maximum that can be paid for mill-delivered logs are log length, sweep, small-end diameter under bark, taper and ovality. For logs of all diameters, the maximum that can be paid for mill-delivered logs reduces with increasing levels of taper, sweep and ovality. The analysis also revealed that the financial viability of veneering short logs (1.3 m) is challenging, suggesting 2.6 m logs lengths (or multiples thereof) need to be prioritised. Potential efficiency gains during final product manufacture (i.e. one piece cross-band for plywood manufacture) may help support the processing of the shorter logs (1.3 m) but this would likely only make up a small proportion of production and therefore would likely reflect a low commercial demand for short logs.

The modelling provides useful guidance of the potential yield from the emerging plantation mahogany timber resource as the modelled values encompass the range of log diameter, taper and log sweep that have been recently measured within the current resource, as well those log geometries expected as the resource matures. Further assessments during the next phase of the project will be complimentary to this modelling with more detailed log measurements being available and also, where the recovery of sawn and veneer material will be assessed.

Introduction

African mahogany (*Khaya senegalensis*) is an internationally important, high-value, forest tree species and early trials in northern Australia have demonstrated significant potential for the plantation species. Commercial plantation establishment commenced in the Northern Territory in 2006 with a commercial estate currently at around 14 000 hectares. A smaller plantation estate of around 1 000 hectares exists in north Queensland. These plantations have been established primarily to grow sawlogs from which high-quality and high-value sawn timber is expected.

While numerous research projects have existed to support the Australian African mahogany industry, the majority of the research effort has focused on plantation establishment and management. Research on wood properties, processing systems and target products have been limited and restricted to activities such as those reported by Zbonak *et al.* (2010) and Armstrong *et al.* (2007). Both Zbonak *et al.* (2010) and Armstrong *et al.* (2007) reported valuable base line information on wood properties, sawn timber qualities and sawn recoveries of Australian grown African mahogany. In addition, Zbonak *et al.* (2010) reported limited rotary veneer grade and recovery information. However, both of these studies were conducted on a limited number of logs, sourced from limited plantation areas and covered a spread of plantation ages. As a result, it is not possible to confidently assess the wide range of tree qualities that currently exist across the plantation estate and make informed predictions on which tree characteristics are the more desirable for fulfilling the plantations objectives. This further prevents optimum plantation management strategies from being implemented (e.g. thinning and pruning treatments) that efficiently manipulates the variation that exists within the plantations and promotes more desirable characteristics.

While the African mahogany plantations were predominately established for the production of sawlogs, the large proportion of relatively short bole trees (<3 m) and the wide range of tree diameters (including smaller diameter <30 cm, especially from thinning activities), rotary veneering may prove to be a more efficient processing method and may be better suited for a proportion of the plantation resource. While there are some variations, the rotary veneer industry predominately processes logs which are approximately 2.6 m in length which enables the manufacture of standard 2.4 m long panels. These panels are usually 1.2 m wide. There is also opportunity to process shorter 1.3 m logs to produce shorter length veneer which is often used for cross-bands in plywood panel production. These target logs lengths potentially align better with what the African mahogany plantations can supply versus sawlogs were log lengths greater than 3.3 m are preferred.

Research by the Queensland Department of Agriculture and Fisheries (DAF) has demonstrated the potential to use emerging spindleless rotary veneering technologies to process hardwood plantation and native forest logs of various sizes including sizes and qualities previously considered unmerchantable (McGavin *et al.* 2014a, b; McGavin *et al.* 2015a, b, McGavin and Leggate 2017). That research has shown that spindleless rotary veneering can recover much higher proportions of marketable product from smaller diameter and lower quality logs than can be achieved through sawing.

Two broad factors affect the recovery of marketable rotary veneer from a log. The first is log geometry (diameter, taper, sweep, ovality etc.) which influences the volume of ungraded veneer that can be recovered from a log. The second is the grade of veneer which is mainly influenced by the presence of natural characteristics (e.g. knots, gum vein, decay etc.) and process induced defects (e.g. splits) contained within the recovered veneer which may need to be removed (therefore reducing the recovered volume) to meet the grading standards for market acceptable veneer. The purpose of this report was to investigate the effect of log geometry on the financial performance of spindleless lathe rotary veneering of African mahogany plantation logs, although the findings should be transferrable to other forest resources. This study was part of an industry project entitled—"Silvicultural systems to optimise value from northern Australian Mahogany Plantations".

Research objective and analysis assumptions

The objective of this study is to investigate the effect of log geometry on the financial performance of rotary veneer production with plantation African mahogany logs. To support forest management decisions and in particular, the implementation of practices that influence the tree diameter, merchantable bole length and bole shape, along with providing guidance to log procurement decisions, the maximum that can be paid for mill-delivered logs with alternative log geometries (small-end diameter under bark (SEDUB), length, taper, sweep, and ovality) while achieving particular target gross margins per hour of operation will be determined. The analysis assumes:

1) an automated veneer production process with one operating spindleless lathe capable of peeling logs up to 2.6 m in length;

2) logs are pre-conditioned (heated) prior to being docked to length, prepared for peeling in a rounding-debarking lathe (to provide a rounded billet with bark, taper, sweep and ovality removed), and then loaded into the spindleless lathe and peeled;

3) green veneer is clipped to the desired sheet width, dried, and then visually graded in accordance with Australian and New Zealand Standard AS/NZS 2269.0:2012 (Standards Australia 2012) to produce marketable veneer. This standard provides minimum performance requirements and specifications for manufacturing structural plywood that are acceptable to users, specifiers, manufacturers, and building authorities in Australia and New Zealand. There are five veneer grades specified: A, S, B, C and D.

A-grade veneer is a high quality appearance grade veneer suitable for clear finishing. This appearance grade quality should be specified for the face veneer in plywood where surface decorative appearance is a primary consideration.

S-grade veneer is a similar specification to A-grade veneer, but some characteristics (not permissible for grade A) are allowed when specified as a decorative feature. These include knots, holes, discoloration, hobnails, and other characteristics as agreed between manufacturer and customer.

B-grade veneer is an appearance grade veneer suitable for high quality paint finishing. This face veneer quality should be specified for applications requiring a high quality paint finish.

C-grade veneer is defined as a non-appearance grade veneer with a solid surface. All open defects such as knot holes or splits are filled. Plywood with a quality C-grade face is designed specifically for applications requiring a solid non-decorative surface. An example is plywood flooring that will be overlaid with a decorative flooring surface.

D-grade veneer is defined as a non-appearance grade veneer with permitted open imperfections and is the lowest veneer appearance grade. It is designed specifically for structural applications where decorative appearance is not a requirement e.g. structural plywood bracing.

4) log preparation costs (e.g. handling, storage, pre-conditioning, and docking) per cubic metre prior to peeling, and the labour and machinery operating costs per hour of peeling, are independent of log geometry; and

5) grade recovery per unit of green veneer is consistent regardless of log geometry.

Research method

The impact of log geometry on the financial performance of a rotary veneer processing operation where spindleless lathe technology was used were estimated by examining the maximum mill-delivered log cost for logs of alternative geometries in order to achieve particular target gross margins from the sale of veneer. Marketable veneer was dried veneer which meets D-grade criteria or better in accordance with ASNZS2269.0:2012. The gross margin was defined as the market value of marketable dry-graded veneer, less the log cost. The analysis has been performed in four steps, namely:

1. Determine net recovery of marketable veneer by log geometry;
2. Develop regression models to predict total veneering time by rounded log diameter;
3. Predict the value of marketable veneer produced per hour by rounded log diameter; and
4. Calculate the maximum mill-delivered log cost for logs of alternative geometries to achieve a target gross margin.

These steps are now described in turn.

Determine net recovery of marketable veneer by log geometry

Logs arriving at the veneer processing plant are typically not cylindrical, rather they are affected by geometrical irregularities including sweep, taper and ovality. Before veneer can be recovered, the logs must be rounded; the process whereby the billet is machined using a rounding-debarking lathe to a cylinder with consistent diameter and parallel sides (McGavin et al 2014a). This process generates waste. Veneer can be recovered from the rounded log diameter until the peeler core is reached. The peeler core is a residual cylindrical core from the log centre with a diameter usually in the order of 4 cm to 5 cm. In this analysis, a peeler core of 4.5 cm diameter has been adopted, which has a volume of 1.59×10^{-3} m^3/m of log length.

Peelable log volume (PLV) in cubic metres from logs with taper, sweep and ovality, and with small-end diameter under bark (SEDUB) ranging from 0.14 m to 0.6 m in 2 cm increments, was estimated using the following equations.

$$PLV_{taper} = L * \pi * \left(\frac{SEDUB}{2}\right)^2 - CV \qquad \text{[eq. 2.1]}$$

$$PLV_{sweep} = L * \pi * \left(\frac{SEDUB - S * L}{2}\right)^2 - CV \qquad \text{[eq. 2.2]}$$

$$PLV_{ovality} = L * \pi * \left(\frac{SEDUB - \left(\frac{OV}{2} * SEDUB\right)}{2}\right)^2 - CV \qquad \text{[eq. 2.3]}$$

where L is log length (m);

π is pi;

CV is the peeler core volume (m^3) where no veneer can be recovered;

S is sweep in m/m of log length;

SEDUB is the small end-diameter under bark (m), as measured by a diameter tape around the circumference of the log; and

OV is ovality in percent, entered in the equation as a fraction, as defined in Table 5.1.

These equations were used to estimate peelable log volumes for logs with the log geometry characteristics reported in Table 5.1. The levels assessed within each log geometry characteristics were chosen to cover the predominate spread of log geometry characteristics witnessed in recent African mahogany trials. The taper peelable log volume (PLV_{taper}) equation was used to estimate peelable log volume for the two log lengths (1.3 and 2.6 m). Peelable log volumes for logs with sweep and ovality were only estimated for 2.6 m logs.

Mill-delivered log volume (MDLV) from which peelable log volume (PLV) is obtained after rounding was calculated as follows for logs with taper, sweep and ovality, and SEDUB ranging from 0.14 m to 0.6 m in 0.02 m increments.

$$MDLV_{taper} = L * \frac{\pi}{4}\left(\frac{2*SEDUB+T*L}{2}\right)^2$$ [eq. 2.4]

$$MDLV_{sweep\&ovality} = L * \pi * \left(\frac{SEDUB}{2}\right)^2$$ [eq. 2.5]

where T is log taper in m/m log length; and

all other variables are as previously defined.

Equation 2.4 was used to calculate mill-delivered log volumes for logs with taper for both log lengths examined. The term in parentheses in Equation 2.4 calculates the mean of SEDUB and large-end diameter under bark (LEDUB), where LEDUB is SEDUB + T * L. Equation 2.5 was used to calculate mill-delivered log volumes for logs with sweep or ovality. Equation 2.5 assumes no taper, thus the effect of sweep and ovality has been examined assuming SEDUB = LEDUB.

Table 5.1. Log geometry assessed

Log geometry characteristic	Units of measure	Levels assessed
Length (L)	m	2.6, 1.3
Taper (T)	m taper /m log length	0, 0.005, 0.01, 0.02, 0.04, 0.08
Sweep (S)	m sweep / m log length	0, 0.005, 0.01, 0.02, 0.04, 0.08
Ovality (OV)	%, defined as $(LSEDUB - SSEDUB)/SSEDUB$, where LSEDUB is the largest small-end diameter under bark (m), as measured across the face of the small-end of the log, and SSEDUB is the smallest small-end diameter under bark (m), as measured across the face of the small-end of the log.	0, 5, 10, 15, 20

Due to defects in the veneer sheets (from imperfections inside the log), trimming veneer to marketable dimensions and shrinkage of veneer during drying, there is further loss in processing green peeled veneer into recovered volume that meets grade quality and is therefore marketable veneer. Hence, marketable veneer volume is less than peelable log volume (PLV). The percentage net recovery of marketable veneer (NR) from mill-delivered log volume for logs ranging in SEDUB from 0.14 m to 0.6 m in 2 cm increments, is calculated as:

$$NR = \left(\frac{PLV}{MDLV}\right)/MVRPLV$$ [eq. 2.6]

where PLV is the peelable log volume estimated from Equation 2.1, 2.2 or 2.3;

MDLV is the mill-delivered log volume estimated from Equation 2.4 or 2.5; and

MVRPLV is marketable veneer recovery from peelable log volume (%).

The authors are not aware of any research trials processing African mahogany or other hardwood species using spindleless lathes that have estimated the marketable veneer recovery from peelable log volume (MVRPLV). Table 5.2 summarises net recovery (NR) of marketable veneer from mill delivered log volume (MDLV) from spindleless lathe research trials for various other hardwood resources, as well as the proportion of marketable veneer recovered by veneer grade. However, these reported estimates of net recovery combine the effects of waste due to log geometry, and defects, trimming and other losses from green peeled veneer. An estimate of marketable veneer recovery from peelable log volume is necessary to isolate the effect of log geometry on gross margins.

Table 5.2. Veneer recovery by grade from research trials where spindleless lathe technology was used

Species	Resource type[1]	Age (y)	Mean DBHOB (cm)[2]	Mean log SEDUB (cm)[3]	Net Recovery (%)[4]	Recovery by veneer grade (%)			
						A	B	C	D
Corymbia citriodora subsp. *variegata* [a]	N			19.6	45	0	0	0	100
C. citriodora subsp. *variegata* [a]	N			23.7	48	0	9	5	86
C. citriodora subsp. *variegata* [a]	N			27.8	43	0	1	11	88
C. citriodora subsp. *variegata* [b]	P	10 to 12	20.6	15.6	48	0.3	1	16.4	82.3
Eucalyptus cloeziana [b]	P	12 to 15	31.9	23.5	58	0.2	4.8	27.1	68
E. dunnii [b]	P	11	22.9	17.5	55	0	0	7.7	91.9
E. pellita [b]	P	13	28.1	20.9	55	0	1.5	10.4	86.1
E. nitens [b]	P	20 to 22	34	28.9	55	0.4	9.1	13.7	76.9
E. globulus [b]	P	13 to 16	30.6	25.7	50	0	0.9	2.3	96.8

Notes: 1. Resource type, where N is native forest and P is plantation forest.
2. Mean diameter at breast height over bark.
3. Mean SEDUB of docked logs for veneering. Note that many trees produced more than one docked log for veneering.
4. Net recovery of marketable veneer (% of MDLV).

Sources: a. McGavin and Leggate (2017).
b. McGavin *et al.* (2014a).

Empirical evidence from the spindleless lathe veneer manufacturing facility at which observations were made for this study indicated marketable veneer recovery from peelable log volume (MVRPLV) is about 60% for their operation. For a 2.6 m length, 30 cm SEDUB log with 0.01 m/m taper, setting MVRPLV to 60% results in NR of 54% (calculated with Equation 2.1, 2.4 and 2.6). This is consistent with NR estimates in Table 5.2, and in the absence of any specific African mahogany data, 60% marketable veneer recovery from peelable log volume has been adopted as the base case for analysis in this study.

Develop regression models to predict total veneering time by rounded log diameter

Data collection at a commercial veneer processing operation that has adopted spindleless lathe technology revealed that veneer production from logs with a rounded log diameter (RLD) of between 16 cm and 46 cm is limited by the rate at which the lathe can peel veneer. For the business model examined, green veneer production is assumed to be limited only by the rate at which the lathe will peel logs into veneer, which is a function of the time to load logs into the lathe and the time to peel veneer from the logs. However, it is noted that the processing of logs with large geometrical deviations (e.g. high taper, large sweep and ovality) may result in the rounding phase limiting production rather than the lathe.

Several variables not related to log geometry, including machine operator skill, can affect the time to load logs into the lathe. However, log diameter is positively related to log loading time, because at the completion of peeling a log, the log drive rollers will be closed at the peeler core position (e.g. 4.5 cm). The log drive rollers then need to retract to accept placement of the next log. The larger the diameter of the next log, the further the log drive rollers need to retract. The time required to retract the log drive rollers is greater than the time required for the log loader to position the next log ready for loading into the lathe, since the latter task is typically performed while peeling the log already in the lathe. Log loading time data was collected at a commercial spindleless lathe veneer facility for 211, 2.6 m rounded eucalypt logs that ranged in rounded log diameter (RLD) from 16 cm to 46 cm. Log loading time was measured as the time from when peeling of one log stopped to when peeling of the next log commenced.

Peeling time in seconds (PT) for the 211 rounded logs observed was estimated as follows:

$$PT = \pi * \frac{\left[\left(\frac{RLD}{2}\right)^2 - \left(\frac{CD}{2}\right)^2\right]}{VT*PS} \qquad \text{[eq. 2.7]}$$

where RLD is rounded log diameter (m);

CD is peeler core diameter (m);

VT is veneer thickness (m); and

PS is lathe operating speed (lm/second).

A lathe operating speed of 40 lm per minute (0.67 lm/second), which is a common operating speed for spindleless lathes working with many species, has been adopted for this analysis. Peeling time (PT) was calculated for two common veneer thicknesses, 2.15 mm and 3.2 mm (0.00215 m and 0.0032 m), and peeler core diameter (CD) of 0.045 m.

Total veneering time in seconds (TVT) for each log peeled to 2.15 mm and 3.2 mm veneer was estimated as the sum of observed loading time and the calculated peeling time (from Equation 2.7). A simple linear regression model was then fitted to the total veneering time data to predict total veneering time as a function of rounded log diameter (RLD). The total veneering time regression model assumes a lathe utilisation rate of 100%. That is, logs are continuously being loaded and peeled in the lathe, and there are no stoppages due to issues such as log jams, waste removal, green veneer removal, or lathe sharpening. This is unlikely in practice; however, utilization rates can vary substantially depending on many factors, including labour skill, and level of processing automation. Results from this analysis are presented on the basis of 100% utilization, because it facilitates fractional adjustment of financial performance estimates to an alternative utilization rate.

Predict the value of marketable veneer produced per hour by rounded log diameter

Marketable veneer volume produced per hour of peeling time (MVV) from logs of particular rounded log diameters (RLDs) was calculated as follows:

$$MVV = \frac{3600}{TVT} * PLV * MVRPLV \qquad \text{[eq. 2.8]}$$

where 3600 is the number of seconds in an hour;

TVT is the total veneering time in seconds for a log of a particular RLD as predicted with the regression model fitted in step 2;

PLV is peelable log volume from the rounded log estimated using Equation 2.1, 2.2 or 2.3, as appropriate; and

MVRPLV is the marketable veneer recovery from peelable log volume.

For a log with a particular SEDUB, and taper, sweep or ovality, the rounded log diameter (RLD) from which veneer can be peeled and for which total veneering time (TVT) was estimated is the numerator in parenthesis in Equations 2.1, 2.2 or 2.3, as appropriate. For example, from Equation 2.3, a 30 cm SEDUB log with 10% ovality has a rounded log diameter of 28.57 cm (0.3 m – 0.1/2 *0.3 m).

For the purposes of analysis, this study assumes veneer grade recoveries at approximately the middle of the ranges reported in Table 5.2: A-grade 0%; B-grade 5%; C-grade 15%; and D-grade 80%. Commercial dry-graded veneer values are challenging to determine, as the veneer producers are typically manufacturing engineered wood products with the veneer, and the costs of production and final market prices for these products vary substantially. In addition, Australian grown plantation African mahogany logs are yet to be processed in any significant volume to test the market value. Anecdotal information for other hardwood species indicates that 3.2 mm and 2.15 mm D-grade veneer in Australia has a wholesale value of about \$400/m^3. Engineered Wood Products Association of Australasia (2014) asserted that C-grade veneer is about 1.2 times D-grade, B-grade is 1.7 times D-grade, and A-grade is 3 times D-grade. This study has adopted these relative values for C, B and A-grade veneers, which equate to \$480/m^3, \$680/m^3 and \$1200/m^3, respectively. Marketable veneer value or revenue (R) per hour of operation has been estimated with Equation 2.9.

$$R = \sum_{g=A}^{D} MVV * GR_g * P_g \qquad \text{[eq. 2.9]}$$

where GR_g is veneer recovery by grade, g (%);

P_g is market price for veneer grade, g (\$); and

MVV is as previously defined

Calculate the maximum mill-delivered log cost for logs of alternative geometries to achieve a target gross margin

The gross margin from sale of veneer produced from logs of particular log geometries is defined as the value of marketable veneer produced, less the log cost. Log cost per cubic metre of marketable veneer (LC) for logs with log geometry characteristics examined in this study has been calculated as follows:

$$LC = \frac{MDLC}{NR} \qquad \text{[eq. 2.10]}$$

where MDLC is mill-delivered log cost (\$/m^3 of log); and

NR varies with log geometry and MVRPLV as previously defined.

Two common ways of reporting gross margins are per hour of operation (GM/h) and per cubic metre of marketable veneer (GM/m^3), which have been calculated as follows.

$$GM/h = R - LC * MVV \qquad \text{[eq. 2.11]}$$

$$GM/m^3 = \frac{R}{MVV} - LC \qquad \text{[eq. 2.12]}$$

All variables are as previously defined.

However, a more useful way to report the impact of log geometry on the financial performance of veneer manufacture is in terms of the maximum that could be paid for mill-delivered logs with particular geometries while achieving a target gross margin. The target gross margin could be stated per cubic metre of marketable veneer, but since log geometry does affect marketable veneer output per unit time and a large proportion of operating costs (e.g. labour) vary with time, adopting a target gross margin per hour is most appropriate. All non-log veneer manufacturing costs, including the desired profit margin, need to be covered by the target gross margin per hour (GM/h_{target}). With a target gross margin determined, the maximum that can be paid for mill-delivered logs of a particular log geometry, $MDLC_{max}$ (in $/m^3 of log), is estimated as follows:

$$MDLC_{max} = R - \frac{GM/h_{target}}{MDLV\left(\frac{3600}{TVT}\right)} \qquad \text{[eq. 2.13]}$$

where the denominator in the second term calculates the volume of mill-delivered logs of a particular geometry processed per hour. Mill delivered log volume (MDLV) is estimated from Equation 2.4 or 2.5 as appropriate and 3600 is the number of seconds in an hour. Total veneering time (TVT in seconds) is for the rounded log derived from the mill-delivered log of a particular geometry (as described with Equation 2.8).

Marketable veneer recovery from peelable log volume $MDLC_{max}$ provides a simple metric with which to assess the impact of log diameter, length, taper, sweep and ovality on the financial performance of veneer manufacture. The sensitivity of $MDLC_{max}$ to marketable veneer recovery from peelable log volume (alternative levels 50% and 70%), veneer lathe utilisation rate (60% and 80%) and veneer market price (D-grade prices of \$400/m^3 ± \$50/m^3 and ± \$100/m^3) has been examined.

Results

Net recovery of marketable veneer by log geometry

Net recovery (NR) from mill-delivered 2.6 m logs with SEDUB ranging from 14 cm to 60 cm is presented for logs with taper in Figure 5.1, with sweep in Figure 5.2, and with ovality in Figure 5.3. Net recovery of cylindrical logs is asymptotic with marketable veneer recovery from peelable log volume. These figures highlight the positive relationship between log SEDUB and net recovery, and the negative relationship between log taper, sweep and ovality, and net recovery. Sweep has the greatest impact on net recovery and ovality the least impact. Log geometry does substantially affect gross margins in veneer production. For example, 49% of log volume will be converted into marketable veneer from a 30 cm SEDUB log with 0.02 m/m taper, relative to 59% from a cylindrical log with the same SEDUB. This equates to 20% less marketable veneer being produced from the log with taper.

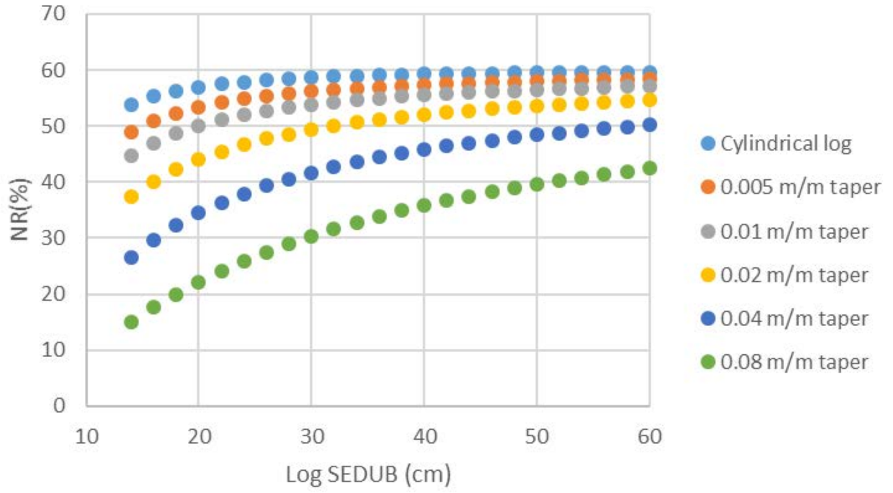

Figure 5.1. Net recovery of marketable veneer from 2.6 m logs by SEDUB and log taper

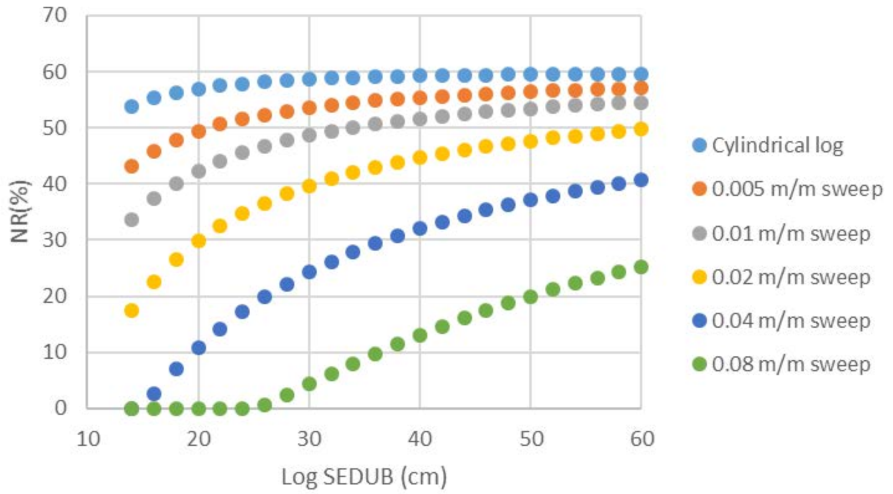

Figure 5.2. Net recovery of marketable veneer from 2.6 m logs by SEDUB and sweep

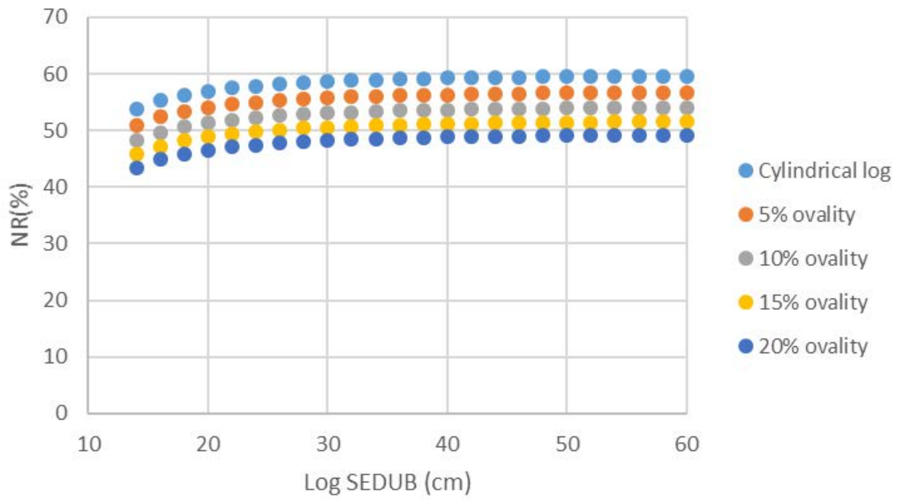

Figure 5.3. Net recovery of marketable veneer from 2.6 m logs by SEDUB and ovality

Net recovery from 1.3 m logs is not illustrated, but gross margins from 1.3 m logs are reported later in this report.

Total veneering time by rounded log diameter

Observed log loading time ranged from 8 to 21 seconds. Peeling time (PT) for the observed logs was calculated with Equation 2.7, and Figure 5.4 presents total veneering time (TVT) for these rounded logs for 3.2 mm veneer. The linear regression models fitted to total veneering time for 2.15 mm veneer (not illustrated) and 3.2 mm veneer are, respectively:

-40.165 + 3.4203 RLD (R^2 = 0.9714); and

-25.641 + 2.4229 RLD (R^2 = 0.9579).

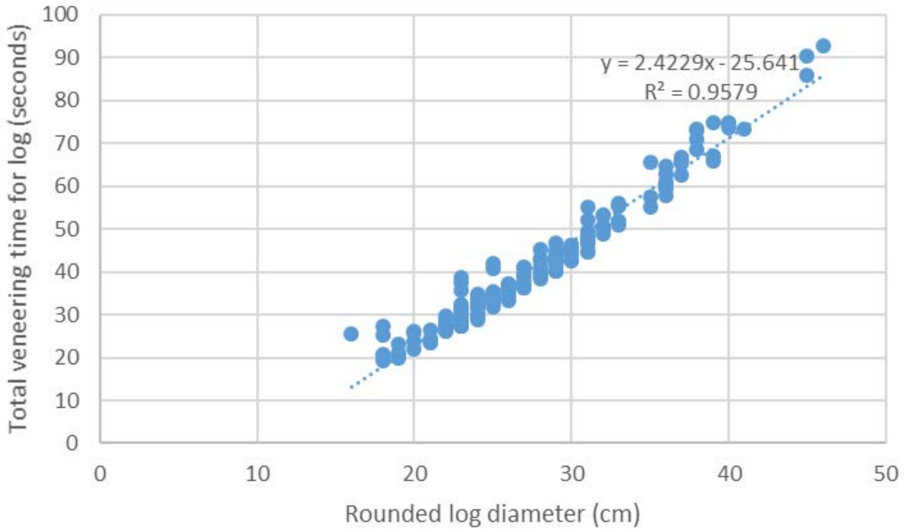

Figure 5.4. Total veneering time by rounded log diameter for 3.2 mm thick veneer peeled at 40 lm per minute

Volume and value of marketable veneer produced per hour by rounded log diameter

Marketable veneer volume produced per hour of peeling (MVV) and marketable veneer value per hour of operation (R) are presented in Figure 5.5 for 2.15 mm and 3.2 mm veneer produced from 2.6 m logs[1] with rounded log diameters (RLDs) ranging from 18 cm to 60 cm. Volumes and values for 2.15 mm veneer are lower than for 3.2 mm veneer because peeling time per cubic metre of veneer is longer for 2.15 mm veneer. Given the recovery of veneer by grade in Table 5.1, and the veneer prices by grade adopted for this study, the average value of marketable veneer (R/MVV) is \$426/m^3. The slightly U-shaped relationship of volume and value with rounded log diameters arises because of the short loading time for small rounded logs. As rounded log diameter increases, loading time increases, and for smaller rounded log diameter logs, this additional loading time is not offset by the additional veneer volume produced from the log. For example, 18 cm and 32 cm rounded log diameter logs produce the same volume of 2.15 mm veneer per hour, and 18 cm and 24 cm rounded log diameter logs produce the same volume of 3.2 mm veneer per hour.

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[1] If 1.3 m logs are processed rather than 2.6 m logs, marketable veneer volume produced is halved, as loading and peeling time does not change.

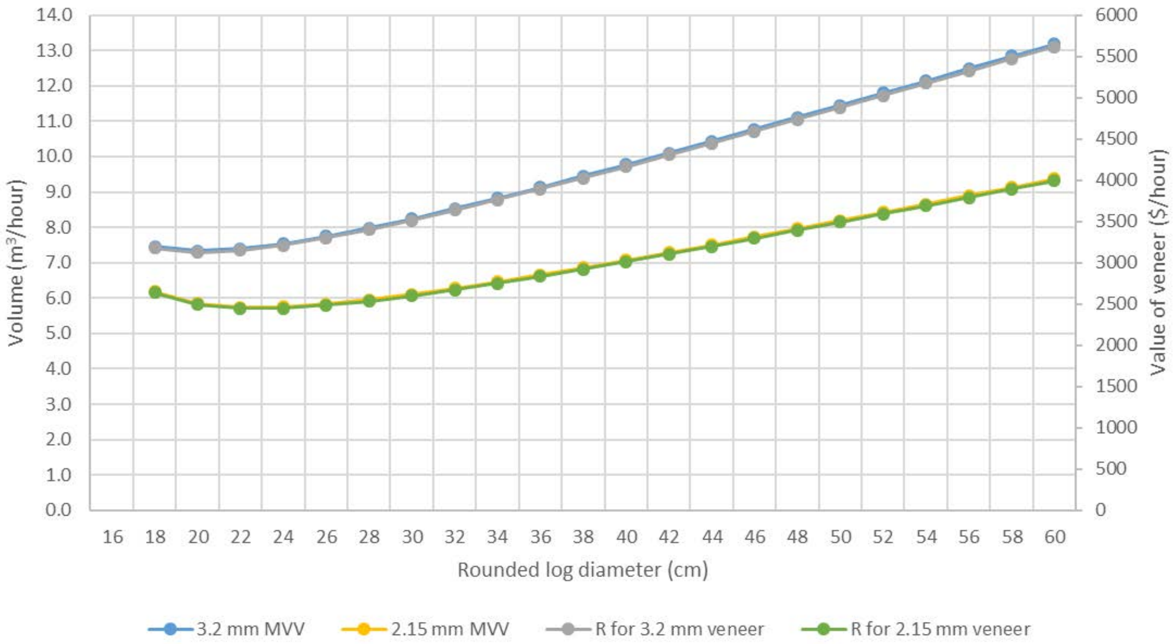


Figure 5.5. Veneer volume and value per hour of 2.15 mm and 3.2 mm veneer produced from 2.6 m logs

Maximum mill-delivered log cost for logs of alternative geometries to achieve a target gross margin

This section presents the impact of log geometry on the financial performance of spindleless lathe veneering as follows. First, gross margins and the maximum mill-delivered log cost ($MDLC_{max}$) for perfectly cylindrical logs are reported for 3.2 mm veneer produced from 2.6 m logs. This represents the most desirable log geometry for veneering (i.e. longer logs with zero taper, zero sweep and zero ovality). LEDUB equals SEDUB, and there is effectively zero log rounding waste. $MDLC_{max}$ for 2.15 mm veneer is then presented for comparison.

Second, the sensitivity of the maximum mill-delivered log cost ($MDLC_{max}$) for 2.6 m cylindrical logs to key analysis parameters – lathe utilisation rate, marketable veneer recovery from peelable log volume (MVRPLV) and veneer market price (P) – is assessed. Third, the effects of sweep, ovality and log length on $MDLC_{max}$ are examined.

Gross margins and the maximum mill-delivered log cost for 2.6 m cylindrical logs

In this analysis, 2.6 m cylindrical logs peeled to 3.2 mm thick veneer with a marketable veneer recovery from peelable log volume (MVRPLV) of 60% serve as the benchmark against which logs with alternative geometries are compared. Figure 5.6 presents GM/h for 2.6 m cylindrical logs with SEDUB ranging from 20 cm to 60 cm, given mill delivered log cost (MDLC) is between $80/m^3 and $280/m^3. The increasing gross margins with increasing SEDUB arises because the proportion of log volume that is peelable is higher for larger SED logs (Figure 5.1), and because a larger volume of larger SEDUB logs can be processed per unit of time (Figure 5.5). At $80/m^3 mill-delivered log cost, gross margins range from $2100/h for 20 cm SED logs to $3850/h for 60 cm SEDUB logs. Gross margins per hour for logs of all SEDUB examined are minimal at a mill-delivered log cost of $240/m^3. In the Australian log market, mill-delivered log costs typically rise with log diameter, so veneer manufacturers face a trade-off between higher mill-delivered log cost and higher gross margins per unit time for large diameter logs, and lower mill-delivered log cost and lower gross margins per unit time for small diameter logs.

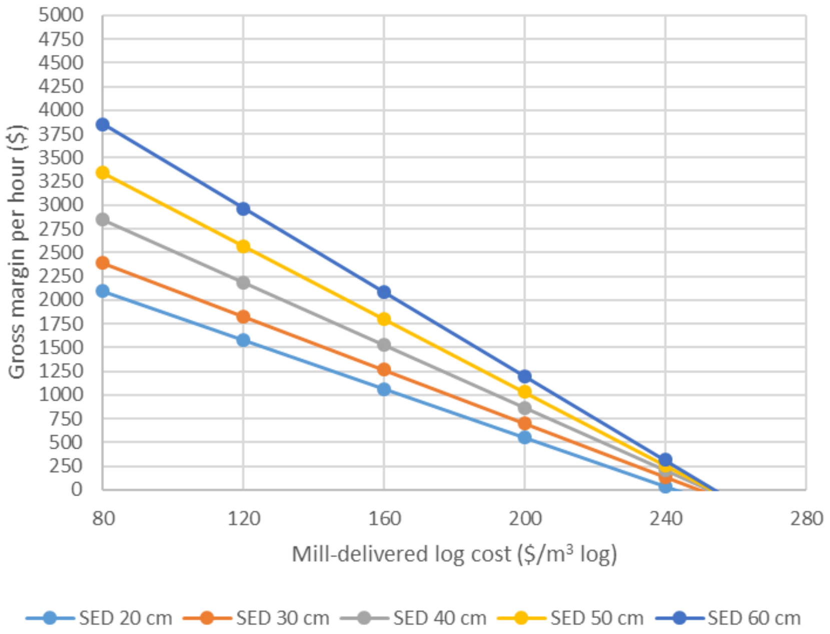


Figure 5.6. Gross margins per hour for 3.2 mm veneer by mill-delivered log cost and SEDUB for 2.6 m cylindrical logs

Figure 5.7 illustrates GM/m^3 for 2.6 m cylindrical logs. At a mill-delivered log cost of \$80/m^3, the gross margins range from \$286/m^3 of marketable veneer for 20 cm SEDUB logs, to \$292/m^3 of marketable veneer for 60 cm SEDUB logs. Figure 5.7 disguises the large differences in gross margins per hour presented in Figure 5.6, indicating that the difference in gross margins per hour between small and large diameter cylindrical logs is predominantly due to the larger volume of larger SEDUB logs that can be processed per hour, not the higher proportion of log volume that can be peeled from larger SEDUB logs.

Figure 5.8 presents $MDLC_{max}$ to generate particular gross margins per hour of peeling with 2.6 m cylindrical logs. For example, in order to earn gross margins of \$1000/h (i.e. GM/h_{target} = \$1000), the maximum that can be paid for 20 cm SEDUB logs is \$165/m^3, and the maximum for 60 cm SEDUB logs is \$209/m^3. The format of Figure 5.9 is useful for supporting log procurement decisions, and throughout the remainder of the report, this format has been adopted to facilitate comparison of the effects of log geometry on gross margins and the maximum that can be paid for mill-delivered logs.

Figure 5.8 is for a lathe utilization rate of 100%. If lathe utilization is actually 50%, then the gross margins on the x-axis are halved. For example, in order to earn gross margins of \$500/h, the maximum that can be paid for 20 cm SEDUB logs is \$165/m^3, and the maximum for 60 cm SEDUB logs is \$209/m^3. This illustrated fractional conversion for Figure 5.9 can be performed for any utilisation rate; nevertheless, the sensitivity of $MDLC_{max}$ to two plausible lathe utilisation rates, 60% and 80%, is described in the next section.

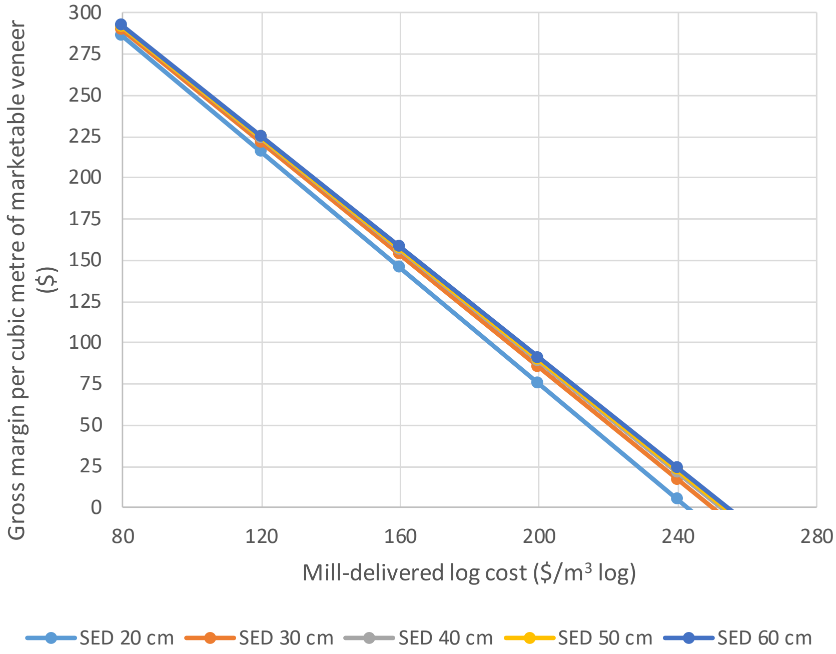


Figure 5.7. Gross margins per cubic metre of 3.2 mm marketable veneer by mill-delivered log cost for 2.6 m cylindrical logs

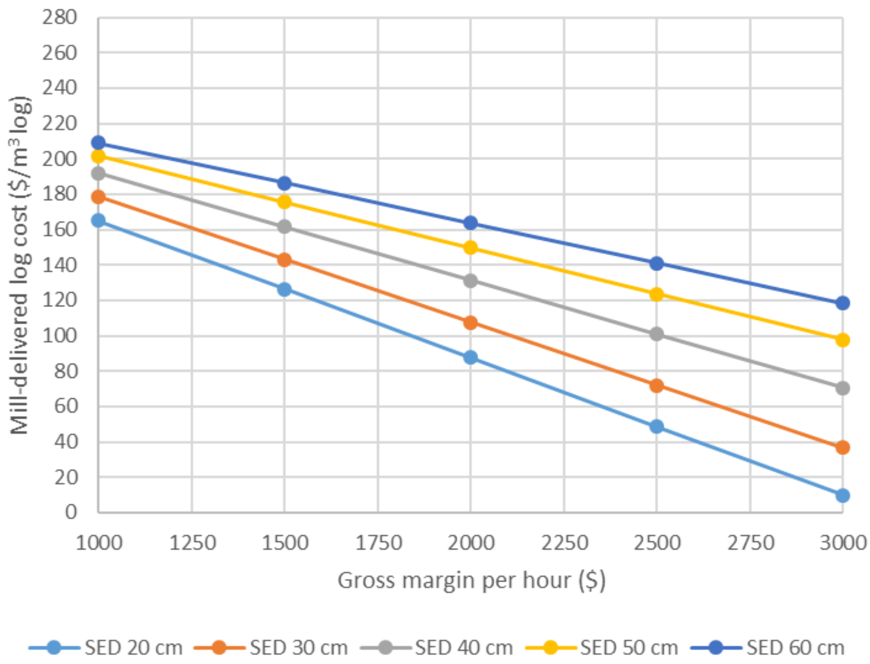


Figure 5.8. Maximum mill-delivered log cost to achieve particular target gross margins per hour peeling 3.2 mm veneer from 2.6 m cylindrical logs

If market price per cubic metre of veneer does not vary with veneer thickness, then gross margins per cubic metre of veneer produced are not affected by veneer thickness[2]. However, thinner veneer will require longer peeling time per cubic metre of veneer, and therefore less veneer will be produced in any given time period (Figure 5.5). The reduction in production is greater for larger SEDUB logs, because log loading time, which is not affected by veneer

[2] Theoretically, the same volume of veneer can be peeled from a log regardless of veneer thickness.

thickness, is a smaller fraction of total peeling time for larger logs. As illustrated in Figure 5.9, the slower peeling time per cubic metre of 2.15 mm veneer results in $MDLC_{max}$ to achieve particular gross margins per hour of between about $20/m^3 to $60/m^3 lower than for equivalent SEDUB logs peeled to 3.2 mm veneer thickness (Figure 5.8). At any positive mill delivered log cost (MDLC), it is not possible to earn gross margins exceeding about $2500/h with 20 cm and 30 cm SEDUB logs.

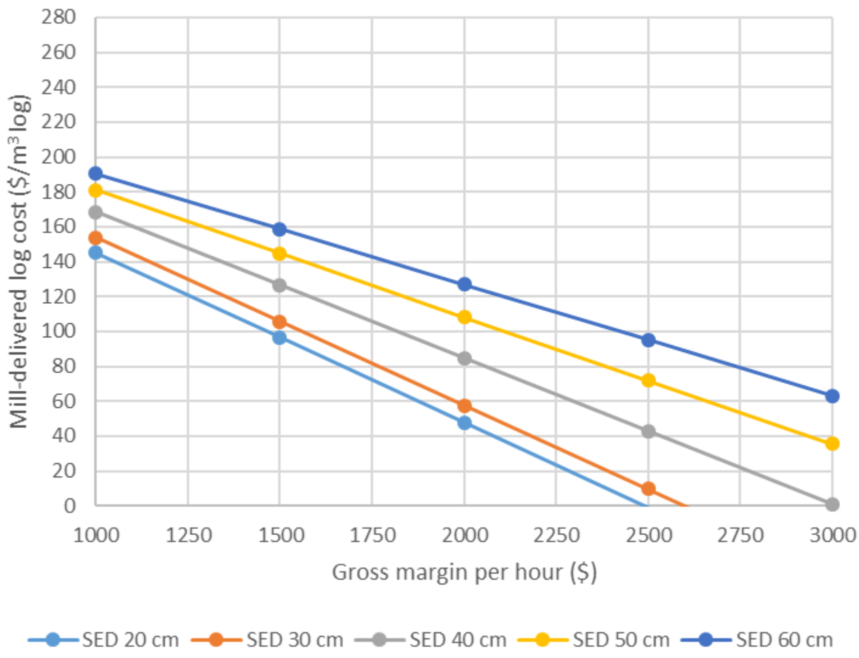


Figure 5.9. Maximum mill-delivered log cost to achieve particular gross margins per hour of operation for 2.15 mm veneer from 2.6 m cylindrical logs with MVRPLV of 60%

Unless otherwise specified, throughout the results that follow, lathe utilisation rate is 100%, MVRPLV is 60%, veneer thickness is 3.2 mm and log length at 2.6 m.

Sensitivity of maximum mill-delivered log cost to utilisation rate, the proportion of peelable log volume recovered as marketable veneer (MVRPLV) and veneer market price

Figure 5.11 illustrates the sensitivity of $MDLC_{max}$ to lathe utilisation rates of 60% and 80%. A lathe utilisation rate of 60% means the marketable veneer volume (MVV) and revenues per hour (R) are 60% of the levels illustrated in Figure 5.5, and Figure 5.10 indicates this substantially lowers $MDLC_{max}$. For example, in order to earn gross margins of $1000/h, the maximum that can be paid for 20 cm SEDUB logs is $113/m^3, and the maximum for 60 cm SEDUB logs is $179/m^3, which are 32% and 14% lower, respectively, than when utilisation rate is 100%. $MDLC_{max}$ for smaller diameter logs is more sensitive to utilisation rate than for larger diameter logs, because the target gross margin per hour is a larger proportion of R for smaller logs.

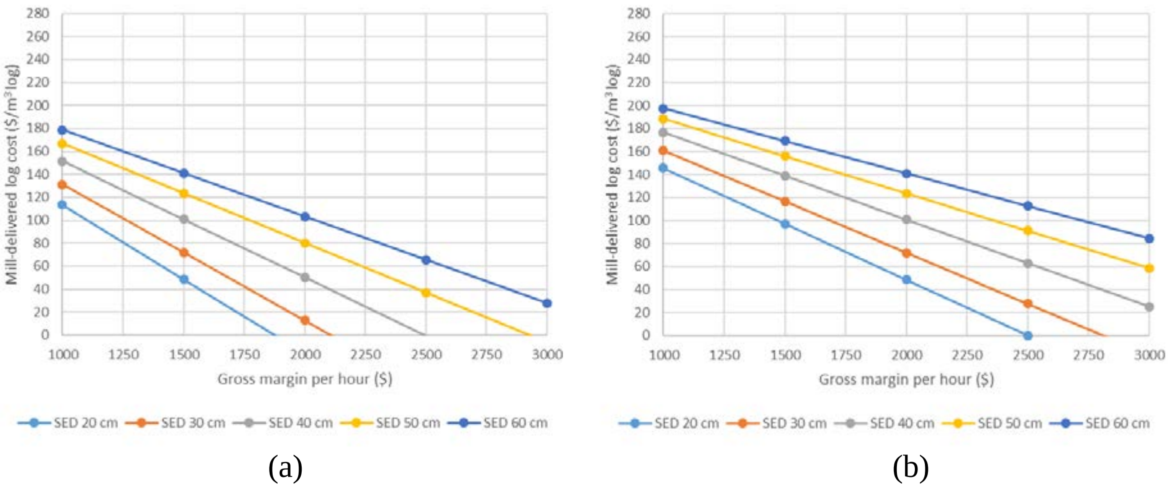


Figure 5.10. Sensitivity of maximum mill-delivered log cost to lathe utilisation rate
Notes: (a) lathe utilisation rate is 60%; and (b) lathe utilisation rate is 80%

Figure 5.11 reveals the sensitivity of $MDLC_{max}$ to plausible alternative levels of MVRPLV. When MVRPLV is 50%, maximum mill-delivered log costs fall by about $40/m^3 for all assessed SEDUB and target gross margins, relative to when MVRPLV is 60%. $MDLC_{max}$ increases by about $40/m^3 when MVRPLV is 70%, relative to when MVRPLV is 60%.

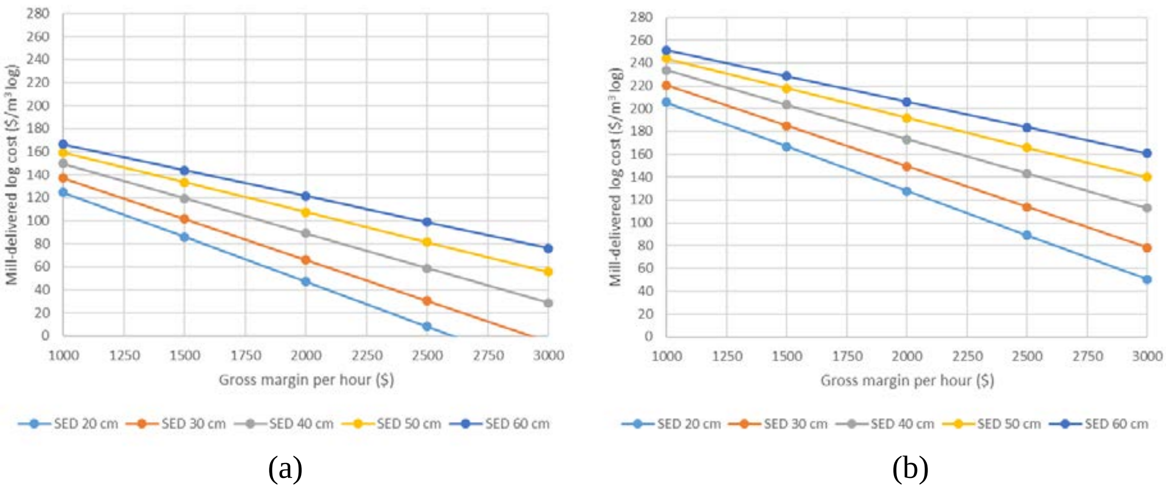


Figure 5.11. Sensitivity of maximum mill-delivered log cost to marketable veneer recovery from peelable log volume (MVRPLV)
Notes: (a) MVRPLV is 50%; and (b) MVRPLV is 70%

An analysis has also been performed to assess the sensitivity of $MDLC_{max}$ to ±$50/m^3 and ±$100/m^3 changes in D-grade veneer market price, with the same proportionate mark-up for C-grade and B-grade veneer as described for the base case. Figure 5.12 presents that sensitivity, indicating that $MDLC_{max}$ changes by the level of veneer market price change multiplied by net recovery (NR). For cylindrical logs, net recovery varies little with SEDUB; hence the illustrated change in $MDLC_{max}$ is consistently about ±$30/m^3 for ± $50/m^3 in veneer price for all SEDUB examined, and ±$60/m^3 for ±$100/m^3 change in veneer price (i.e. change in $MDLC_{max}$ = NR multiplied by the change in veneer price). As net recovery reduces when logs have taper, ovality or sweep, the sensitivity of $MDLC_{max}$ to veneer price will decrease for logs that are less cylindrical.

Impact of log taper on maximum mill-delivered log cost

Figure 5.13 illustrates the impact of taper on $MDLC_{max}$. Panel (a) repeats Figure 5.8 to better facilitate comparison with zero taper, cylindrical logs. To achieve gross margins of \$2000/h, the $MDLC_{max}$ for mill-delivered logs with 0.01 m/m taper (panel c) is about \$10/m^3 less than for logs of the same SEDUB with zero taper. At a gross margin of \$2000/h, the $MDLC_{max}$ for logs with 0.08 m/m taper is about \$50/m^3 lower than for logs with zero taper. To put this into context, a 2.6 m, 20 cm SEDUB log with 0.08 m/m taper, has a LEDUB of 40.8 cm. Thus, much waste is generated when these logs are rounded to the SEDUB. The effect of 0.08 m/m taper on $MDLC_{max}$ is similar to MVRPLV falling from 60% to 50%.

Further examination of Figure 5.13 reveals that SEDUB has a greater effect on $MDLC_{max}$ than taper. This is evidenced by the difference in $MDLC_{max}$ between 20 cm and 60 cm SEDUB logs in panel (a) being greater than the difference in $MDLC_{max}$ between logs with zero taper (panel a) and 0.08 m/m taper (panel f), but having the same SEDUB.

Impact of sweep on maximum mill-delivered log cost

Figure 5.14 illustrates the impact of sweep on $MDLC_{max}$. Panel (a) presents the cylindrical log case for comparison. Mill-delivered log costs for any particular gross margin are considerably lower for logs with sweep than for logs with the same level of taper. This is because of the much greater impact of sweep on net recovery relative to taper, as highlighted by comparing Figures 5.1 and 2.2. For example, $MDLC_{max}$ for 20 cm and 60 cm SEDUB logs with 0.01 m/m sweep at a gross margin of \$2000/h is \$19/m^3 and \$17/m^3 lower than for cylindrical logs, respectively. At 0.04 m/m sweep, positive gross margins cannot be earned with 20 cm SEDUB logs, and $MDLC_{max}$ for a 60 cm SEDUB log while earning a gross margin of \$2000/h is \$62/m^3 lower than for a cylindrical log. At 0.08 m/m sweep, positive gross margins cannot be earned with 30 cm SEDUB logs.

In Figure 5.14, panel (d), the mill-delivered log cost schedule for 20 cm SEDUB logs is noticeably flatter than for larger SEDUB logs. This arises because 20 cm SEDUB mill-delivered logs with 0.02 m/m sweep are rounded to only 14.8 cm for peeling, resulting in considerably shorter predicted total veneering time per cubic metre of veneer (from the TVT regression model) than for larger mill-delivered logs. Since the smallest observed rounded log was 16 cm, this result should be applied with caution.

Figure 5.14 suggests that sweep has a greater effect on $MDLC_{max}$ than SEDUB. The difference in $MDLC_{max}$ between 20 cm and 60 cm SEDUB logs in panel (a) is less than the difference in $MDLC_{max}$ between logs with zero taper (panel a) and 0.08 m/m sweep (panel f), but having the same SEDUB.

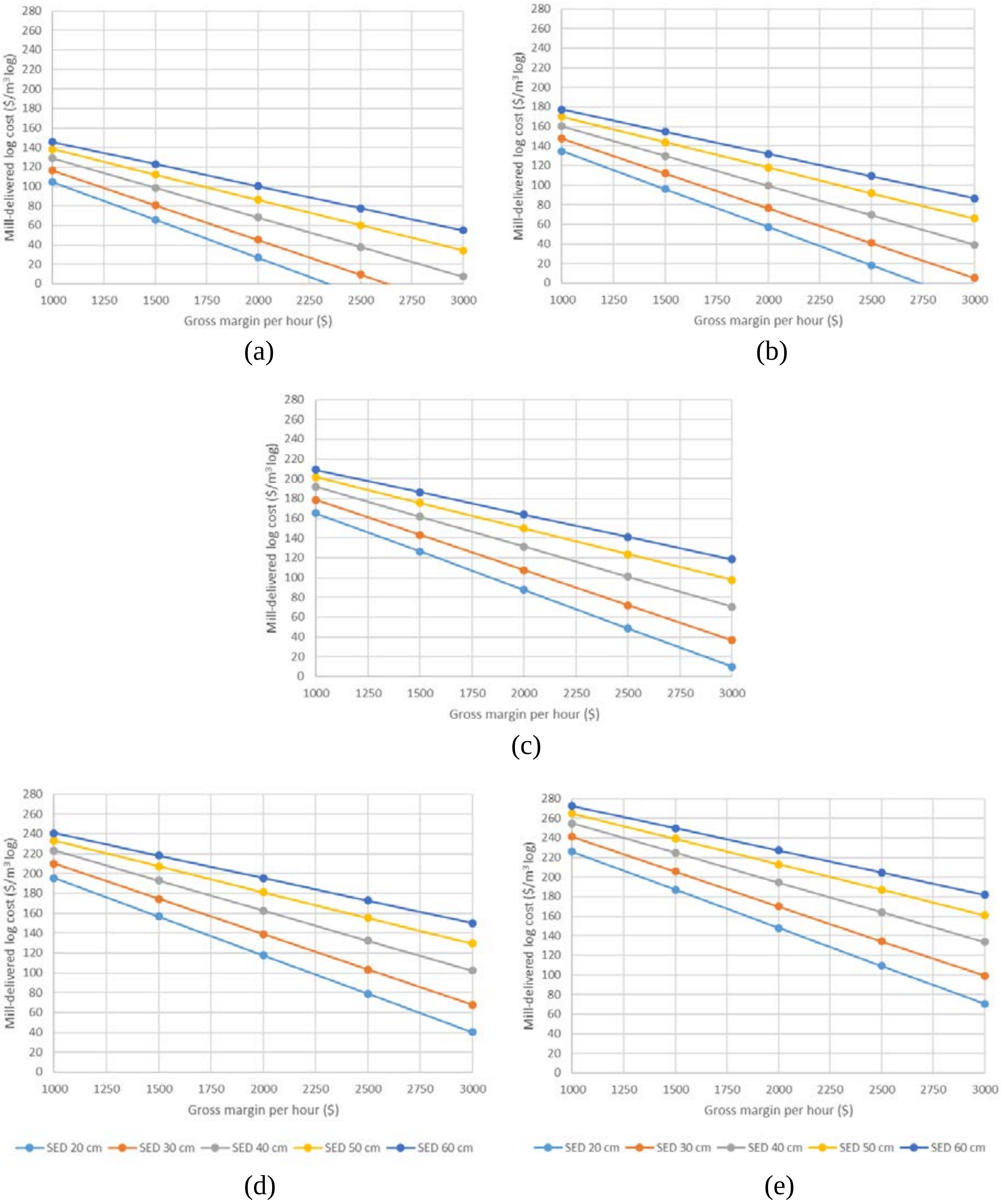


Figure 5.12. Sensitivity of maximum mill-delivered log cost to market price of veneer

Notes: (a) D-grade veneer $300/m^3; (b) D-grade veneer $350/m^3; (c) D-grade veneer $400/m^3 (base case); (d) D-grade veneer $450/m^3; and (e) D-grade veneer $500/m^3.

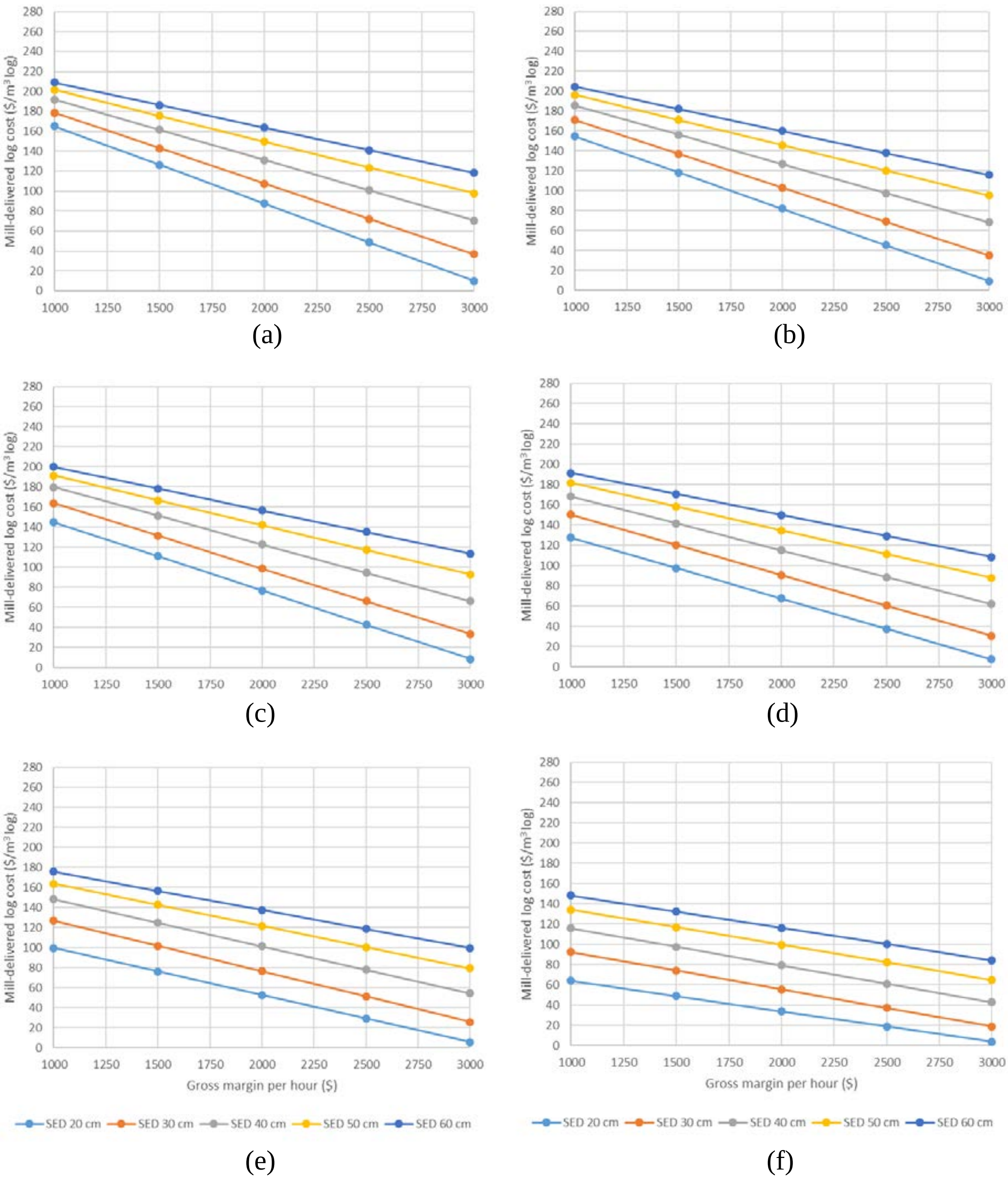
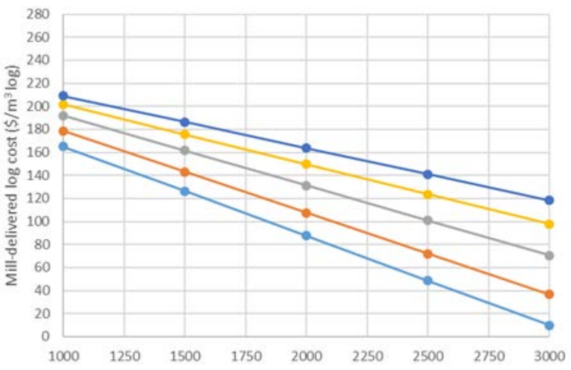
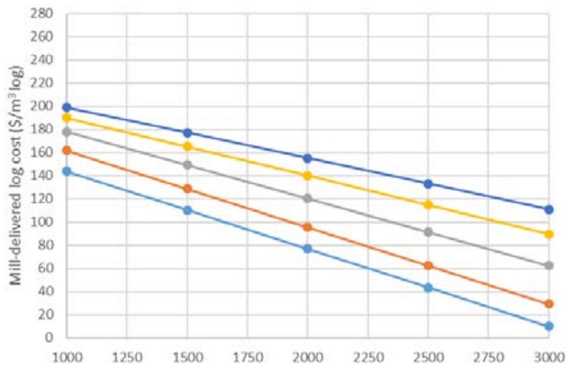


Figure 5.13. Impact of taper on maximum mill-delivered log cost to achieve particular gross margins per hour

Notes: (a) cylindrical log, (b) 0.5 cm/m taper, (c) 1 cm/m taper, (d) 2 cm/m taper, (e) 4 cm/m taper, and (f) 8 cm/m taper.



(a)



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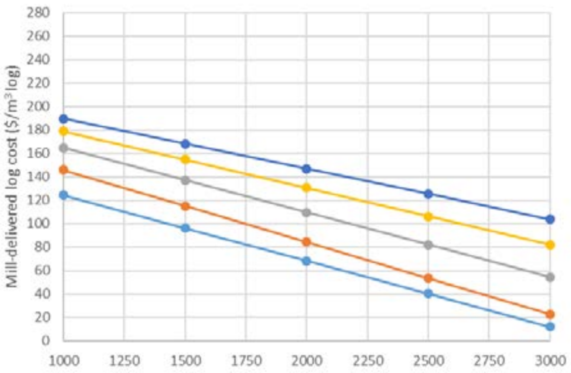

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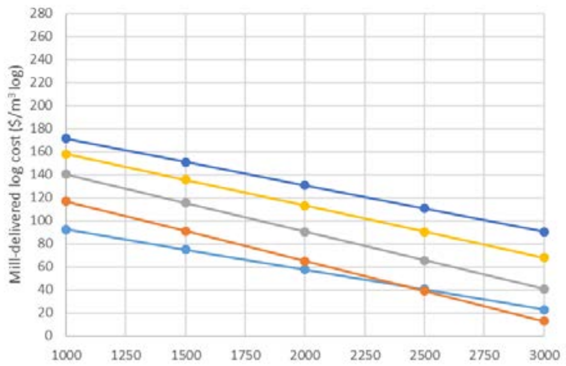
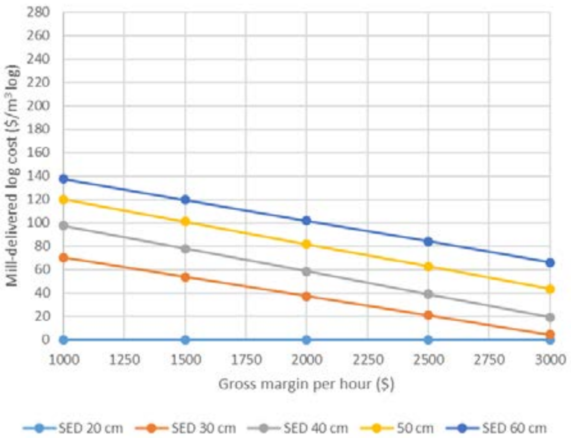
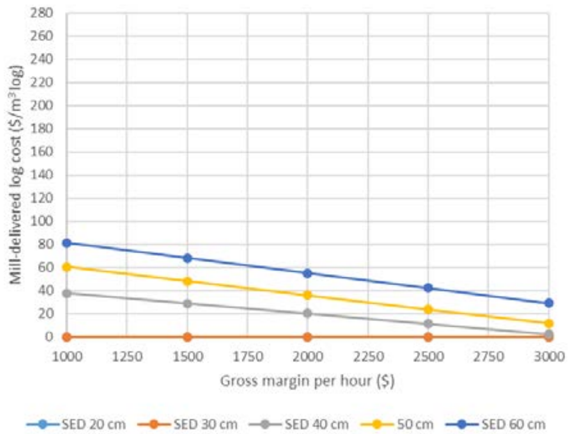


(d)



(e)



(f)

Figure 5.14. Impact of sweep on maximum mill-delivered log cost to achieve particular gross margins per hour

Notes: (a) cylindrical log, (b) 0.5 cm/m sweep, (c) 1 cm/m sweep, (d) 2 cm/m sweep, (e) 4 cm/m sweep, and (f) 8 cm/m sweep.

Impact of ovality on maximum mill-delivered log cost

Figure 5.15 presents the impact of ovality on $MDLC_{max}$. For the levels of ovality examined, the impact is small relative to the projected impact of taper and sweep, and this is explained by the relatively high net recovery from logs with ovality (compare Figures 5.1, 5.2 and 5.3). At 20% ovality (panel e), $MDLC_{max}$ for 20 cm SEDUB logs while maintaining $2000/h gross margin is $14/m^3 lower than for cylindrical logs (panel a). This is similar to the level of impact on $MDLC_{max}$ for 20 cm SEDUB logs with 0.01 m/m sweep or 0.02 m/m taper. The difference in $MDLC_{max}$ between 20% ovality and cylindrical 60 cm SEDUB logs is $35/m^3. This is similar to the level of impact on $MDLC_{max}$ for 60 cm SEDUB logs with 0.02 m/m sweep or 0.04 m/m taper.

Figure 5.15 also reveals that SEDUB has a greater effect on $MDLC_{max}$ than ovality. This is evidenced by the difference in $MDLC_{max}$ between 20 cm and 60 cm SEDUB logs in panel (a) is greater than the difference in $MDLC_{max}$ between logs with zero ovality (panel a) and 20% ovality (panel e), but having the same SEDUB.

Impact of log length on maximum mill-delivered log cost

Shorter log lengths reduce the volume of veneer produced per unit of time, which reduces gross margins per unit of time relative to peeling with longer log lengths. Figure 5.16 illustrates the maximum that can be paid for 1.3 m logs with alternative rates of taper to achieve particular gross margins per hour. The impact of taper on $MDLC_{max}$ of short logs is minimal compared to longer logs. Panel (a) in Figure 5.16 represents a 1.3 m log with zero taper. Relative to 2.6 m logs with zero taper, the maximum that can be paid for 1.3 m logs while earning a gross margin of $1000/h is $78/m^3 lower for 20 cm SEDUB logs and $45/m^3 lower for 60 cm SEDUB logs. Panel (a) also reveals that with 1.3 m logs, gross margins of $2000/h are only technically possible with logs at least 40 cm SEDUB. Cylindrical logs of 1.3 m by 40 cm, 50 cm or 60 cm SEDUB, would have to be delivered to the mill for only $10/m^3, $45/m^3 and $75/m^3, respectively, in order to gross $2000/h. This is a similar level of impact on $MDLC_{max}$ as 0.08 m/m sweep with 2.6 m logs.

When rates of taper of logs are less than 0.02 m/m, 2.6 m logs always generate higher gross margins than 1.3 m logs when they have the same mill-delivered log cost. However, close examination of the gross margins for 1.3 m and 2.6 m logs reveals that, at rates of taper of at least 0.02 m/m, the gross margins per hour of operation from 1.3 m logs sometimes exceed the gross margins from 2.6 m logs when these logs have the same mill delivered log costs. That is, the wood waste associated with rounding 2.6 m logs with high rates of taper results in such a large reduction in net recovery relative to a 1.3 m log, that 1.3 m logs generate higher gross margins per hour. Processing veneer from 1.3 m logs can also result in some final product manufacturing efficiencies, for example, where one piece cross-bands are used in plywood manufacture, however this only makes up a small proportion of panel manufacture. This may support the processing of short logs even if the processing economics are not as favourable compared to longer logs. Cross-band veneers are also sourced as a recovery product from longer veneers and therefore the demand (and often value) of short veneers is lower compared to longer veneers (i.e. sourced from 2.6 m logs).

Tables 5.3 and 5.4 present the gross margins per hour of operation for 2.6 m and 1.3 m logs respectively. Table 5.5 reports gross margins by log SEDUB and mill delivered log cost (MDLC) for rates of taper of 0.02 m/m, 0.04 m/m and 0.08 m/m. Blue-shaded cells indicate negative gross margins per hour from both 2.6 m and 1.3 m logs. Green shaded cells indicate that 2.6 m logs generate positive gross margins that are higher than for 1.3 m logs. Brown shaded cells indicate that 1.3 m logs generate positive gross margins that are higher than for

2.6 m logs. In the cases where 1.3 m logs generate higher returns than 2.6 m logs, the gross margins never exceed \$710/h.

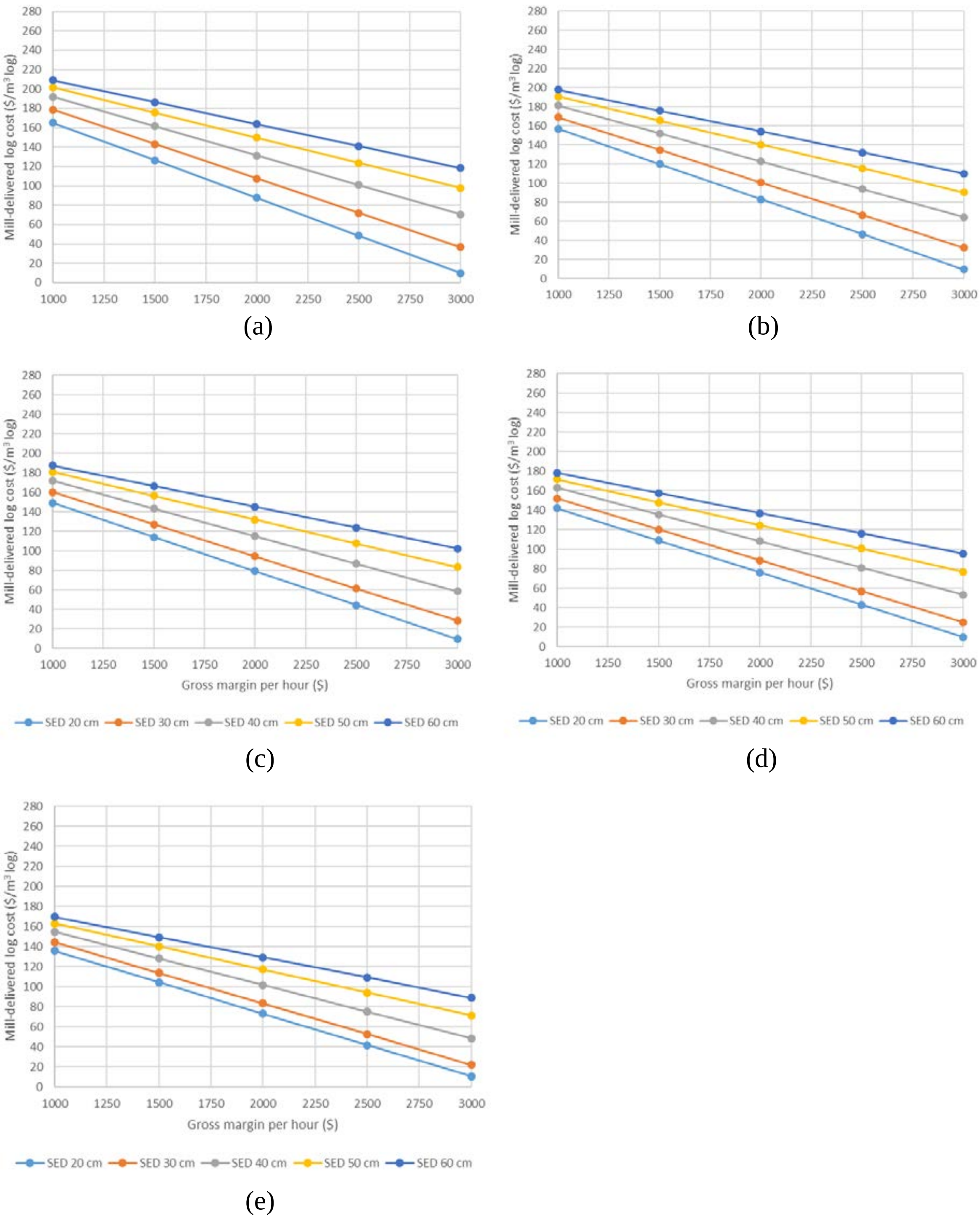
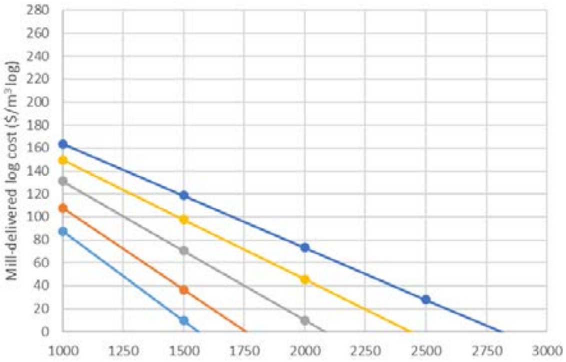
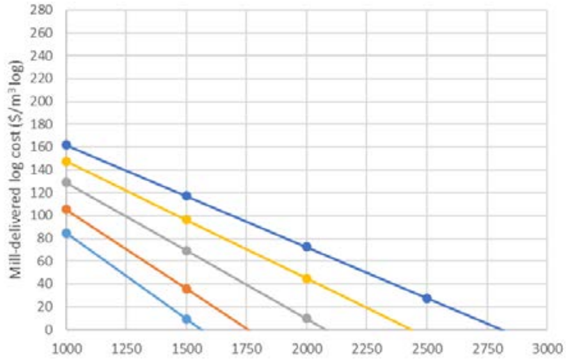


Figure 5.15. Impact of ovality on maximum mill-delivered log cost to achieve particular gross margins per hour

Notes: (a) cylindrical log, (b) 5% ovality, (c) 10% ovality, (d) 15% ovality, (e) 20% ovality.



(a)



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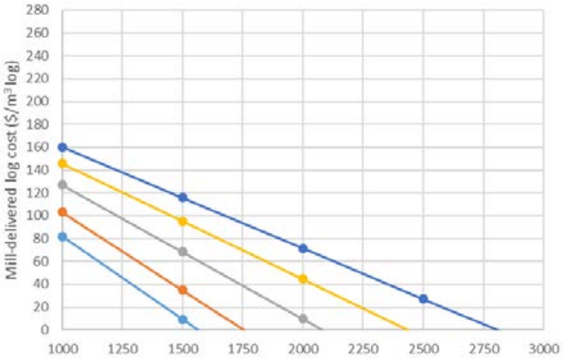

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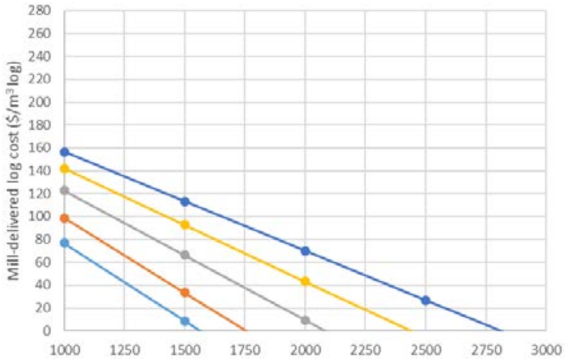

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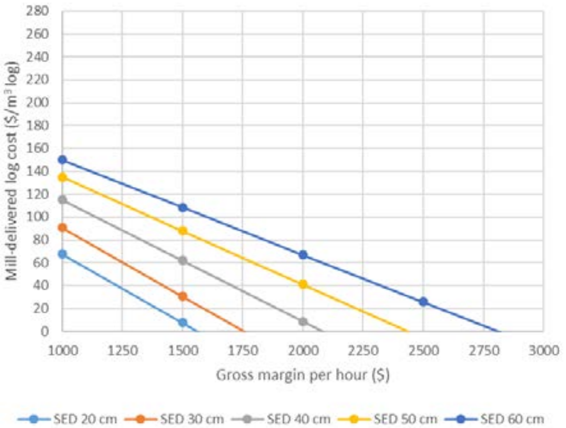

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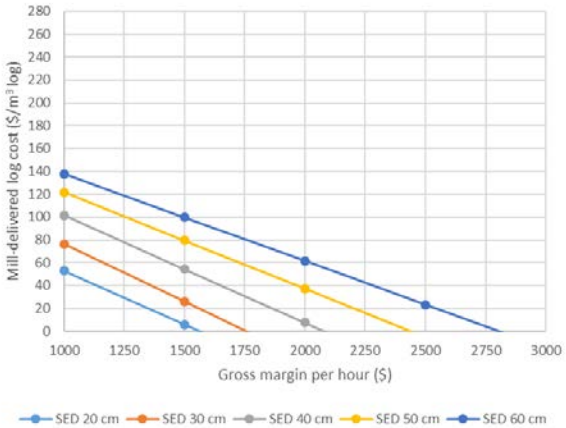

(f)

Figure 5.16. Impact of log length (1.3 m logs) and taper on maximum mill-delivered log cost to achieve particular gross margins per hour

Notes: (a) zero taper, (b) 0.5 cm/m taper, (c) 1 cm/m taper, (d) 2 cm/m taper, (e) 4 cm/m taper, and (f) 8 cm/m taper.

Table 5.3. Gross margins per hour of operation with 2.6 m logs

SED (cm)	Taper (cm/m)	Gross margin per hour ($) of operation by mill-delivered log price ($/m^3)					
		80	120	160	200	240	280
20	2	1 793	1 126	459	-207	-874	-1 541
20	4	1 421	568	-286	-1 139	-1 992	-2 845
20	8	466	-864	-2 194	-3 525	-4 855	-6 186
30	2	2 177	1 508	840	171	-497	-1 166
30	4	1 931	1 140	348	-443	-1 234	-2 026
30	8	1,338	250	-837	-1 925	-3 013	-4 101
40	2	2 662	1 910	1 159	407	-344	-1 096
40	4	2 457	1 603	749	-106	-960	-1 814
40	8	1 979	887	-206	-1 298	-2,391	-3 484
50	2	3 171	2,317	1 463	609	-245	-1 099
50	4	2 986	2 039	1 093	146	-800	-1 747
50	8	2 566	1 409	253	-904	-2 061	-3 217
60	2	3 690	2 726	1 762	797	-167	-1 131
60	4	3 516	2 466	1 415	365	-686	-1 737
60	8	3 130	1 887	643	-601	-1 845	-3 088

Table 5.4. Gross margins per hour of operation with 1.3 m logs

SED (cm)	Taper (cm/m)	Gross margin per hour ($) of operation by mill-delivered log price ($/m^3)					
		80	120	160	200	240	280
20	2	977	683	390	96	-197	-490
20	4	897	563	230	-104	-437	-771
20	8	710	284	-143	-569	-996	-1 423
30	2	1 143	837	530	223	-83	-390
30	4	1 088	754	420	86	-249	-583
30	8	966	570	174	-222	-617	-1 013
40	2	1,378	1 026	674	321	-31	-383
40	4	1,331	955	579	204	-172	-548
40	8	1 228	801	374	-53	-480	-907
50	2	1 629	1 223	818	412	7	-398
50	4	1 585	1 158	731	305	-122	-549
50	8	1 493	1 020	546	73	-400	-873
60	2	1 905	1 454	1 002	550	98	-353
60	4	1 886	1 424	962	501	39	-423
60	8	1 845	1,363	881	399	-83	-565

Table 5.5. Optimal log length to maximise gross margins per hour of operation

SED (cm)	Taper (cm/m)	Gross margin per hour ($) of operation by mill-delivered log price ($/m^3)					
		80	120	160	200	240	280
20	2	1,793	1,126	459	96	<0	<0
20	4	1,421	568	230	<0	<0	<0
20	8	710	284	<0	<0	<0	<0
30	2	2,177	1,508	840	223	<0	<0
30	4	1,931	1,140	420	86	<0	<0
30	8	1,338	570	174	<0	<0	<0
40	2	2,662	1,910	1,159	407	<0	<0
40	4	2,457	1,603	749	204	<0	<0
40	8	1,979	887	374	<0	<0	<0
50	2	3,171	2,317	1,463	609	7	<0
50	4	2,986	2,039	1,093	305	<0	<0
50	8	2,566	1,409	546	73	<0	<0
60	2	3,690	2,726	1,762	797	39	<0
60	4	3,516	2,466	1,415	399	<0	<0
60	8	3,130	1,887	708	182	<0	<0

Notes: Blue-shaded cells indicate negative gross margins from both 2.6 m and 1.3 m logs. Green shaded cells indicate that 2.6 m logs generate positive gross margins that are higher than for 1.3 m logs. Brown shaded cells indicate that 1.3 m logs generate positive gross margins that are higher than for 2.6 m logs.

Discussion and conclusions

The maximum that can be paid for mill-delivered logs while earning a particular target gross margin ($MDLC_{max}$) is the metric used in this study to estimate the impact of log geometry and the potential value of logs with different geometrical characteristics. $MDLC_{max}$ is positively related to SEDUB, because net recovery of marketable veneer from log volume increases with SEDUB. $MDLC_{max}$ is negatively related to taper, sweep and ovality, because net recovery decreases with these log characteristics. $MDLC_{max}$ is positively related to log length, because more veneer can be peeled per unit of time, resulting in 2.6 m logs being more favourable than 1.3 m logs in most situations. A comparison of the relative importance of alternative log geometry characteristics on $MDLC_{max}$ is necessarily somewhat subjective. However, given the ranges of these attributes considered in this study, log geometry characteristics can be arranged in decreasing order of impact on $MDLC_{max}$ as follows:

1. length;
2. sweep;
3. SEDUB;
4. taper; and
5. ovality.

The analysis confirmed that spindleless lathe veneer manufacture can generate gross margins of at least $2000/h (100% utilisation rate) even with relatively cylindrical 20 cm and 30 cm SEDUB logs at mill-delivered log costs of $80/m^3 to $110/m^3. This does suggest spindleless lathe veneer manufacture could present opportunities for utilisation of even small diameter hardwood plantation logs such as those resulting of mid-rotation thinning operations. However, short (1.3 m) logs, while being advantageous in some scenarios (e.g. increasing potential recovery where log taper is high) only generate gross margins of $2000/h when

SEDUB is at least 40 cm SEDUB, and mill-delivered log costs are between \$10/m^3 (for 40 cm logs) and \$75/m^3 (for 60 cm logs). Thus, spindleless lathe veneering with short log lengths is financially challenging suggesting 2.6 m logs lengths (or multiples thereof) need to be prioritised.

The utility of this report is in the practical application of findings to guide both forest management decisions and also log procurement decisions. For example, silvicultural activities that target the manipulation of the merchantable tree bole and diameter can be guided by characteristics that are valued by the veneer processing industry. As an example for log procurement, suppose the business model of a particular veneer manufacturer demands that gross margins of at least \$1000/h are earned to cover all non-log costs (e.g. labour and energy) and the desired profit margin. The utilisation rate of the lathe is 50%. In Figures 5.13 to 2.16, a gross margin \$2000/h for a utilisation rate of 100%, is interpreted as \$1000/h with a 50% utilisation rate. Table 5.6 represents the log market faced by the firm. For simplicity, log costs vary by SEDUB and log length only, where 1.3 m logs are half the log cost per cubic metre of 2.6 m logs of the same SEDUB.

Table 5.6. Hypothetical log market faced by a veneer manufacturer and optimal log purchases

SEDUB	Log cost (\$/m^3) [a]	Financially viable log purchases by log geometry															
		1.3 [b]	Cyl [c]	Taper (mm/m)					Sweep (mm/m)					Ovality (%)			
				5	10	20	40	80	5	10	20	40	80	5	10	15	20
20	80																
30	100																
40	120																
50	150																
60	180																

Notes: a. The reported mill-delivered log costs are for 2.6 m logs. Log costs for 1.3 m logs are assumed to be half the indicated 2.6 m log cost.

b. 1.3 m logs. Even cylindrical 1.3 m logs are not financially viable purchases at half the listed 2.6 m log cost per cubic metre.

c. Cylindrical 2.6 m logs, i.e. no taper, sweep or ovality.

In Figures 5.13 to 2.16, the appropriate gross margin per hour is located on the x-axis, and the $MDLC_{max}$ can be read from the y-axis where the selected gross margin intersects the downward sloping maximum log cost schedule. If $MDLC_{max}$ is greater than the log cost in Table 5.4, then logs with that geometry are a financially viable purchase for veneer manufacture. The shaded cells in Table 5.6 indicate financially viable purchases in this scenario, which are relatively straight 2.6 m logs up to 40 cm SEDUB. Short (1.3 m) logs and 60 cm SEDUB logs are never financially viable purchases in this scenario.

Log geometry does substantially affect the financial performance of veneer manufacture. Sensitivity analyses on lathe utilisation rate, the marketable veneer recovery from peelable log volume (MVRPLV) and veneer market price also revealed that $MDLC_{max}$ is highly sensitive to these parameters. Context-specific research should be performed to determine appropriate levels for these parameters when evaluating particular spindleless lathe operations. Although veneer thickness is not a log geometry characteristic, it is notable that $MDLC_{max}$ is strongly positively related to veneer thickness, because thicker veneer takes less time to peel per cubic metre. This suggests firms should minimise production of thinner veneer, unless thinner veneer commands substantial market price premiums.

The modelling undertaken in this study provides useful guidance of the impact of log geometry on the recovery and hence value of African mahogany grown in the Northern Territory and Queensland as the log dimensions and parameters modelled cover the range of log geometries reported in previous studies. As the recent studies have focused mainly on logs from early to mid-rotation plantation trees, the small end diameter under bark (SEDUB), which provides an estimate of the rounded diameter of the logs, is at the lower end of the values modelled from all the assessed logs (Figure 5.3, Tables 5.7 and 5.8). For example, the diameter of logs at approximately half the target final harvest age (or less) from the Douglas Daly (Table 5.8) are at the lower end of the modelled values. The significant increase in SEDUB for the trees that were thinned early relative to unthinned trees at the Wallaroo plantation (Table 5.8) is particularly important as it indicates that in addition to reducing water stress in the thinned stands, there are significant advantages with the larger diameter logs that results.

The taper values for the measured trees appears to be at the mid to lower end of the modelled values. The taper appears to be lower in the older trees (Table 5.7) relative to younger trees (Table 5.8). While the data are not presented the taper in logs above 3 m in the recent sampling from the Douglas Daly were approximately half of the values from the butt logs indicating that rounding losses will be les in logs from the upper parts of the boles and from older trees.

Currently there are only limited data on log sweep, and the data available indicate that sweep is quite variable in 14 y.o. (Katherine) and 18-20 y.o. (Burdekin) mahogany (Table 5.7). The values for sweep in the earlier study (Zbonak *et al.* 2010, Table 5.7) were towards the lower end of the modelled values and suggests that sweep will not severely influence veneer recovery from plantation mahogany at the projected harvest age of approximately 20 years.

Table 5.7 Log dimensions, taper and sweep for logs from the Burdekin (Qld) and Katherine (NT) regions sampled in 2009 (Data from Zbonak *et al.* 2010)

Site	Age (yrs.)	n		LEDUB (cm)	SEDUB (cm)	Taper (cm/m)	Sweep (cm/m)
Burdekin	18-20	9	Mean	33.0	24.2	2.0	1.1
			Range	25.2-44.4	17.6-31.7	0.5-4.8	0.2-3.3
				LEDOB (cm)	SEDOB (cm)	Taper (cm/m)	Sweep (cm/m)
Katherine Fox Rd	14	9	Mean	28.4	20.9	2.5	0.9
			Range	20.1-43.3	15.5-35.1	0.2-4.3	0.1-2.4.

Notes: a. The log lengths of the Katherine logs were approximately 3 m and hence matches the later sampling from the Douglas Daly region (Table 5.8). The length of the Burdekin logs were longer and varied from approximately 4 to 6 m.

b. The log diameter values for the Katherine sourced logs are over bark measurements and hence would need to be reduced by approximately 2-3 cm to provide an estimate of the under bark diameters.

Table 5.8 Log dimensions and taper for butt logs (0.3 - 3.0 m) from the Douglas Daly region sampled in 2017 as part of the FWPA Mahogany Silviculture Project

Site	Age (yrs.)	n		LEDUB (cm)	SEDUB (cm)	Taper (cm/m)
NTT Why Not		9	Mean	29.6	20.6	3.8
			Range	20.4-34.8	18-23.5	2.9-4.6
KBC Hippo		9	Mean	29.8	19.1	3.9
			Range	25.6-35.3	17-21.3	2.4-5.0
Stray Wallaroo(300)	9	16	Mean	24.7	16.2	3.2
			Range	21.8-28.8	13.9-20.2	2.6-4.0
Stray Wallaroo(800)	9	16	Mean	17.4	11.1	2.6
			Range	14.8-21.5	8.1-14.2	1.8-3.3

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Section 6: Process and grade recovery potential

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Summary

An industrial African mahogany plantation estate of approximately 15 000 hectares exists in northern Australia. With most of these plantations requiring thinning to ensure sustainable growth (see Section 2), there was increasing interest in understanding the potential volume and grades recovered from different processing methods of young small dimension juvenile material produced from the thinning. Forty-eight trees were harvested from four different operational plantation areas that represented a range of ages, growth rate and climate. The harvested trees yielded 56 logs with 32 logs processed into rotary veneer using spindleless lathe technology and 24 logs processed into sawn boards using traditional sawing techniques. The logs displayed variable but high levels of taper and sweep.

Dry veneer recoveries between 56% and 73% of log volume where achieved with the variation mostly explained by log diameter and form. Net veneer recovery ranged between 42% and 55% of log volume. The proportion of veneers with better grade qualities cate increased with age and coincided with the oldest material having the lowest proportion of material with compression related defects. This site (Windermere, NQ age 19 years) produced more than 30% of veneers achieving C-grade or better, which is considered an industry benchmark for saleable product manufacture (Engineered Wood Products Association of Australasia, Available at URL: http://ewp.asn.au/). Veneer defects which had the most impact on limiting grade included compression, surface roughness and grain breakout. Veneer compression resulting in a wavy and an undulating surface, has the potential to reduce the usability and therefore value of African mahogany veneer recovered from plantation thinnings.

Sawn board recovery ranged between 35% and 49% with the variation mostly explained by log diameter and form. The sawn-dried-dressed recovery was low with less than 20% of the log volume representing a potential saleable product in accordance with Australian Standard *AS2796.2:2006*. Defects including wane, heart shake, pith and knots reduced the potential grade recovery and are all common defects that result from sawing relatively small-diameter plantation hardwood logs. A board distortion analysis was undertaken independent of the grade assessment and was measured on full length boards. All sites demonstrated a high presence of board distortion which negatively impacts the efficiency of processing along with product recovery. Applying the distortion limits for strip flooring, less than 50% of the recovered boards would meet the distortion requirements of this product group. It could be possible that the mechanism influencing board distortion (twist, spring and bow) in sawn boards may also be influencing the severity of compression in veneer.

The phenomenon causing the compression in the veneer and distortion in the sawn boards is not well understood and may be influenced by genetics, growth cycles, log form characteristics (resulting in veneers or boards containing zones of different wood ages), wood structure (reaction wood) or by processing protocols (e.g. lathe setup, pre-treatment conditions etc.), or most likely, a combination of factors. A focused study to further understand this phenomenon will be critical in developing management strategies. Determining whether these issues occur in older, larger dimension logs that are likely to be produced at clearfell will also be important. Encouragingly the recovery of higher-grade veneer products increased with increasing age.

Introduction

African mahogany (*Khaya senegalensis*) is an internationally important, high-value, forest tree species and early trials in northern Australia have demonstrated significant potential for the plantation species. Commercial plantation establishment commenced in the Northern Territory in 2006 with a commercial estate at around 14 000 hectares. A smaller plantation estate of around 1 000 hectares exists in north Queensland. These plantations have been established primarily to grow sawlogs from which high-quality and high-value sawn timber is expected.

While numerous research projects have existed to support the Australian African mahogany industry, the majority of the research effort has focused on plantation establishment and management. Research on wood properties, processing systems and target products have been limited and restricted to activities such as those reported by Zbonak *et al.* (2010) and Armstrong *et al.* (2007). Both Zbonak *et al.* (2010) and Armstrong *et al.* (2007) reported valuable base line information on wood properties, sawn timber qualities and sawn recoveries of Australian grown African mahogany. In addition, Zbonak *et al.* (2010) reported limited rotary veneer grade and recovery information. However, both of these studies were conducted on a limited number of logs, included a range of plantation ages and were sourced from plantations that potentially don't represent the growth and from expected from a larger 'commercial' plantation resource.

Previous research undertaken by the Queensland Department of Agriculture and Fisheries (DAF) has demonstrated the potential to use emerging spindleless rotary veneering technologies to process hardwood plantation and native forest logs of various sizes, and qualities previously considered un-merchantable (McGavin *et al.* 2014a and b, McGavin *et al.* 2015a and b, McGavin and Leggate 2017). That research has shown that spindleless rotary veneering can recover much higher proportions of marketable products from smaller diameter and lower quality logs than can be achieved through sawing.

Limited information exists about the suitability and efficiency of these processing approaches for plantation grown African mahogany. Similarly, there is limited understanding of the product quality and variation of qualities that are recovered from these processes. Furthermore, it is unclear how the variation between plantations and the plantation management approaches impacts the volume and quality of the product recovered. Without a clearer understanding of these variables, it is difficult for industry to make informed decisions regarding optimal plantation management regimes (e.g. silviculture) and to identify the most profitable markets that best suits the Australian plantation African mahogany resource.

This study, using logs sourced from mid-rotation plantations that provide a range of age, growing area, climate and growth rate; compares the recovery rates and the product quality of wood product from traditional sawing approaches to that produced using a spindleless veneer processing system. More specifically, the study targeted 'superior' trees in terms of diameter and form, to provide an insight into the upper benchmark recovery and grade values that may be possible to achieve from mid rotation thinning.

Research method

Plantation Resource

Four African mahogany plantation sites were selected to enable sampling from a range of environmental conditions and silvicultural management regimes. Two sites were located in the Douglas Daly Region, Northern Territory (Why Not and Kumbyechants); one north of

Cooktown, Queensland (Elderslie); and one at Bowen, Queensland (Windermere). The Windermere plantation at Bowen was a small agroforestry planting in which the Queensland Government had established a thinning research trial in 2011. The other three plantations are within industrial plantings.

In alignment to the study's objective, trees of superior quality (i.e. high growth rate and form) were targeted that represent the upper 5-10% of tree size and log quality (as judged by straightness, lack of deformities, branching defects etc.). This selection protocol was followed for Why Not and Kumbyechants plantations, and the Elderslie plantation. However, due to the need to maintain the integrity of the thinning trial at Windermere, only average sized trees that were to be removed in a subsequent thinning operation (rather than superior trees) were available for sampling. The tree form at this site was described as 'good' with the sampled trees considered to conform to the log quality requirements of the study.

The climate varies between the four sites with the Cooktown site being the wettest of the four sites and Bowen the driest site. Climate estimates from the Data Drill system for the Douglas Daly sites indicate that these sites are midway between the two Queensland sites (Table 6.1). Within the Douglas Daly region the more northern Kumbyechants site had a higher rainfall than the southern Why Not site, however this difference is relatively small and local knowledge indicates that the more southern site may have around 200 mm less annual rainfall.

Table 6.1. The climatic characteristics for the four sample sites

	Why Not, Douglas Daly, NT	Kumbyechants, Douglas Daly, NT	Windermere, Bowen, Qld	Elderslie, Cooktown, QLD
Mean Max Temp (^{0}C)	34.2	34.3	28.6	28.9
Mean Min Temp (^{0}C)	20.3	20.5	19.4	22.3
Annual Rainfall (mm)	1365	1434	826	1562
Annual Evaporation (mm)	2506	2497	2056	2032
Climate Wetness Index (Rainfall/Evaporation)	0.54	0.57	0.41	0.76

Source: Queensland Government, https://legacy.longpaddock.qld.gov.au.

Table 6.2 presents the silvicultural history for each site. With the harvesting of study trees occurring between May and July 2017, the Windermere plantation at Bowen was the oldest at 19 years-old, and the youngest was Kumbyechants at 7.5 years-old. The Why Not and Elderslie plantations were similar ages at 11 and 13 years-old respectively. All sites were thinned and pruned at various stages.

Table 6.2. Plantation silvicultural history

	Why Not, Douglas Daly, NT	Kumbyechants, Douglas Daly, NT	Windermere, Bowen, Qld	Elderslie, Cooktown, QLD
Planting date	Early 2006	Jan 2010	June 1998	2004
Planting density (sph)	460	1170	666	470
Thinning (NCT) age	August 2013	July 2013	2011	September 2011
Density (sph)	280	510	250	320
Pruning	2011 to 3.5 m 2013 to 4.5 m	May 2014 to 3.4 m	2004 to 3.5 m 2006 to 4.5 m	2010 to 4.5 m
Fertilizer – year and application	1x Application 2010 27 kg N/ha 17 kg P/ha 25 kg K/ha	4x Applications 2010-2014 Total N ~70 kg/ha Total P ~85 kg/ha	Nil	1x Application 2007 18 kg N/ha 12 kg P/ha 15 kg K/ha

Tree harvesting, log merchandising and allocation

The selected trees were merchandised (prepared) immediately after harvesting to provide a target log length of approximately 3 m. Logs were end-sealed as soon as possible after merchandising and transported to Queensland Department of Agriculture and Fisheries (DAF), Salisbury Research Facility in Brisbane, Queensland. The time between harvesting and delivery to the Salisbury Research Facility was minimised to limit log degrade.

The allocation of logs within each plantation batch to processing method (either peeling or sawing) was made by ranking each log by small-end diameter and then systematically allocating each log to a processing method with two logs allocated to sawing for each log allocated to peeling (Figure 6.1). This ensured a reasonable distribution of the available log diameters between the two processing methods.

Logs allocated to veneer processing were further merchandised to provide two 1.5 m peeler billets per log (Figure 6.2). Logs allocated to sawmilling were not merchandised further unless severe defects outside the original log selection guidelines were identified. This resulted in similar log/billet numbers for each processing method, although the total log volume of peeler billets were much less due to the shorter log length.

The following parameters were measured on each sawlog and peeler billet:

- Large-end diameter under bark or *LEDUB* (m) – measured from the circumference with a diameter tape;
- Small-end diameter under bark or *SEDUB* (m) – measured from the circumference with a diameter tape;
- Log length or *L* (m) – measured using a length tape;
- Log sweep deviation or *a* (mm) – measured as the maximum distance on the curved side of a log when a line is extended between the log ends and specifically used to calculate log sweep (see Equation 3.2 below);
- Shortest small-end diameter or *SD* (m) – the shortest small-end diameter measured using a steel rule;
- Longest small-end diameter or *LD* (m) – the longest small-end diameter measured using a steel rule.

From the measured data, the following characteristics were measured:

Log volume, V (m^3) was derived for each log and was calculated as follows:

$$V = \left(\frac{SEDUB + LEDUB}{2}\right)^2 \times \pi \times L \qquad \text{[eq. 3.1]}$$

where V is the individual green log volume (m^3);

π is 3.141593; and

All other variables are previously defined.

Log sweep, S (mm/m), was calculated as the rate of deviation per lineal meter of log length and was calculated as follows:

$$S = \frac{a}{L} \qquad \text{[eq.3.2]}$$

All variables are previously defined.

Log ovality, O (%), was calculated as the difference between longest small-end diameter (LD) and the shortest small-end diameter (SD) as a proportion of the longest small-end diameter (LD), expressed as a percentage, and was calculated as follows:

$$O = \frac{LD - SD}{LD} \times 100 \qquad \text{[eq. 3.3]}$$

All variables are previously defined.

Log taper, T (mm/m) was calculated as the change in diameter per lineal meter of log length and was calculated as follows:

$$T = \left(\frac{LEDUB - SEDUB}{L}\right) \qquad \text{[eq. 3.4]}$$

All variables are previously defined.

Figure 6.1. Elderslie sourced logs being measured

Figure 6.2. Windermere logs allocated to veneering

Rotary veneer processing

Log conversion

Peeler billets allocated to rotary veneer processing were processed using a semi-industrial scale spindleless veneer lathe (Figure 6.3). The lathe is capable of processing billets up to 1300 mm in length and 500 mm in diameter. The minimum peeler core size is 40 mm. For the study, a nominal dried veneer thickness of 2.5 mm was selected. The peeler billets were pre-heated prior to peeling using saturated steam until the billet cores reached approximately 65 ^{0}C. Immediately after being pre-heated, billets were docked to 1300 mm billet lengths, debarked and rounded in a dedicated rounding lathe before being peeled into veneer (Figure 6.4).

Figure 6.3. African mahogany veneer produced from a semi-industrial scale spindleless veneer lathe

Figure 6.4. Debarked and rounded billets ready for veneer processing

Veneer Management

The resulting veneer ribbon was sequentially clipped to sheets with a 1 350 mm maximum width. Veneer sheets were labelled with a unique identifier and seasoned with a commercial veneer jet-box drier using the factory's standard practices with a target moisture content of 8%.

The following parameters were measured on the veneer sheets:

- Dried veneer thickness (*DT*)—the mean thickness of each dried veneer sheet, measured using a dial thickness gauge at four locations along the sheet length; and
- Dried veneer width (*DW*)—the width (perpendicular to grain) of each dried veneer sheet.

Veneer grading

Veneer quality was assessed by visual grading in accordance with Australian and New Zealand Standard *AS/NZS 2269.0:2012* (Standards Australia 2012). This standard is widely adopted across the Australian veneer industry and follows the same principles as other international veneer visual grading classification systems. The standard separates structural veneer into four veneer surface qualities (A, B, C and D-grade) and a reject grade according to severity and concentration of imperfections and defects. The grades are summarised as follows:

- A-grade veneer is a high-quality appearance grade veneer suitable for a clear finish.
- B-grade veneer is an appearance grade veneer suitable for high-quality painted finish.
- C-grade veneer is defined as a non-appearance grade veneer with a solid surface.
- D-grade veneer is defined as a non-appearance grade veneer with permitted open imperfections where decorative appearance is not a requirement.

The grading process was undertaken by a minimum of two experienced graders to minimise variation with defect definition and measurement, and to ensure consistent assessment.

The *AS/NZS2269.0:2012* doesn’t include a specific provision for grading veneer for compression or flatness, rather the acceptance of the defect is managed during the manufacturing process (i.e. veneer industry understanding of the severity of compression and waviness that can be managed through the process without causing problems with drying, bonding and pressing) and the effects of the defect (e.g. splits, poor bonds, panel products which aren’t flat etc.) are managed in the final product grading rather than at the veneer stage.

As part of the veneer assessment process, two experienced veneer industry experts were invited to comment on the presence and severity of compression in the recovered veneers. Serious concerns were raised from both indicating that the majority of veneer may be commercially unusable. To quantify the compression severity, the recovered veneer sheets were graded in line with the A to D-grade criteria (i.e. even the veneers affected by severe compression were graded as D-grade) with the additional segregation of D-grade veneers into a 1 to 4 category (with 1 being better than 4).

Veneer recovery

Four recovery calculation methods were used: dry veneer recovery, gross veneer recovery, net veneer recovery, and graded veneer recovery.

Dry veneer recovery provides a useful measure of the maximum recovery, taking into account log geometry (e.g. sweep, taper, circularity), lathe limitations (e.g., peeler core size) and the drying process (e.g. veneer shrinkage, etc.). Dry veneer recovery disregards internal log quality. Dry veneer recovery (DR as %) was calculated as follows:

[eq. 3.5]

$$DR = \frac{L \times \sum_{veneer}(DT \times DW)}{\sum_{billet} V} \times 100$$

where DT is the average dry veneer thickness of each veneer (m);

DW is the dry veneer width (m, perpendicular to grain); and

All other variables are previously defined.

Gross veneer recovery provides a useful measure of the maximum recovery of dried veneer that meets the quality specifications of *AS/NZS 2269.0:2012* (A-grade to D-grade). This recovery includes the losses accounted for in dry veneer recovery but also includes additional losses from visual grading (*i.e.,* veneer which failed to meet grade). Gross veneer recovery (*GSR* as %) was calculated as follows:

[eq. 3.6]

$$GSR = \frac{L \times \sum_{veneer}(DT \times GRW)}{\sum_{billet} V} \times 100$$

where GRW is the width (m, perpendicular to grain) of dried veneer that meets the grade requirements of A, B, C, and D grades in accordance with *AS/NZS 2269.0:2012*; and

All other variables are previously defined.

Net veneer recovery provides a useful measure of process efficiency, as it identifies the saleable product, taking into account the product manufacturing limitations. Net veneer recovery includes the losses accounted for in gross veneer recovery and also includes the additional losses due to the trimming of veneer before, during, and after product manufacture. The loss incurred when veneer sheets are reduced in width to the final product size is known as a trimming factor. In this study the trimming factor was 0.94. This corresponds to reducing the veneer sheet width perpendicular to the grain from 1 275 mm to 1 200 mm. The veneer sheet parallel to the grain was systematically reduced from 1 300 mm to 1 200 mm. Net veneer recovery (*NR* as %) was calculated as follows:

$$NR = GSR \times 0.94 \times \frac{1200}{1300}$$ [eq. 3.7]

Thus,

$$NR = GSR \times 0.869$$

Graded veneer recovery is the net veneer recovery for each grade as defined by *AS/NZS2269.0:2012* (*i.e.,* A, B, C, or D grades). Graded veneer recovery was calculated for each grade quality and is defined as NR_A, NR_B, NR_C, and NR_D.

Sawmill processing

Log conversion

The logs allocated to sawmilling were processed using a Kara-Master processing system (Figure 6.5). The sawing approach adopted for the study mirrored common commercial processing strategies used in many modern hardwood sawmills and targeted predominately two different nominal board dimensions – being 100 mm x 25 mm and 150 mm x 25 mm.

These board dimensions are commonly targeted by the Australian hardwood sector due to their suitability for flooring and joinery type products. Smaller dimension 100 mm x 20 mm and 150 mm x 20 mm boards were also recovered as a means to further maximise recovery with these nominal dimensions being suitable for products such as internal panelling etc. Boards were sawn at a dimension slightly greater than the nominal dimension to allow for shrinkage during drying.

Recovered boards were labelled with a unique identifier before having any obvious want and wane removed from the board ends. Board dimensions (nominal width and thickness, and board length) were recorded. Boards were then seasoned using conventional techniques which included a short period of air-drying followed by mild kiln drying to a target moisture content of 10%.

Figure 6.5. African mahogany logs being processing into sawn boards

Sawn timber grading

Dried boards were graded to Australian Standard *AS2796.2:2006* (Standards Australia 2006). This standard is well accepted by the Australian hardwood timber industry and segregates sawn and milled products into three grade qualities; Select Grade (highest quality), Medium Feature Grade and High Feature Grade (lowest quality). Each board was visually graded to all three grades individually to determine the grade recovery of each specific grade. The most influential defect type that caused boards to be down-graded/rejected was also recorded. Note that other grade limiting defects may have also been present, however only the most influential defects were recorded. A minimum piece length was set at 900 mm.

At the time of grading, board distortion characteristics (*i.e.* twist, spring and bow) were measured on the boards in their original length. Reducing board lengths by docking as part of a commercial grading process would be expected to reduce the severity of board distortion present in the final 'graded' board dimension. As the boards were only 'hypothetically' docked during the grading process, board distortion limits were not included in the grade recovery analysis, rather they are analysed separately.

Sawn timber recovery

Three recovery calculation methods were used: sawn recovery (*SR*) %, sawn-graded recovery (SGR) and dried-dressed recovery (*DDR*). Sawn recovery, *SR* (%), provides a useful measure of the percentage of log volume converted into boards from the sawing process (mainly influenced by log size and geometry, and processing equipment). The sawn recovery was calculated for each log as follows:

$$SR = \frac{\sum_{board}(W \times T \times L)}{\sum_{log} V} \times 100 \qquad \text{[eq. 3.8]}$$

where *W* is the sawn board nominal dried width (m);

T is the sawn board nominal dried thickness (m); *L* is the sawn board length (m); and

All other variables are previously described.

Sawn graded recovery, SGR (%), includes the losses accounted for in sawn recovery but also includes the losses that occur through the grading process (e.g. due to presence of internal log imperfections and defects). The sawn graded recovery was calculated as follows:

$$SGR = \frac{\sum_{board}(W \times T \times L)}{\sum_{log} V} \times 100 \qquad \text{[eq. 3.9]}$$

Dried-dressed recovery, DDR (%), includes the losses accounted for in sawn and sawn graded recoveries but also includes the additional losses due to dressing (or machining) to a final dimension e.g. tongue and groove flooring. The dried-dressed recovery was calculated as follows:

$$DDR = \frac{\sum_{board}(DDW \times DDT \times L)}{\sum_{log} V} \times 100 \qquad \text{[eq. 3.10]}$$

where *DDW* is the board nominal width (m) after drying and dressing;

DDT is the board nominal thickness (m) after drying and dressing;

L is the board length (m); and

All other variables are previously defined.

Results and discussion

Resource

Thirty-nine trees were harvested for the study from the four plantations. Table 6.3 provides comparative details of the trees present in the wider plantation and the selected trees harvested for the study. This confirms the strategy of selecting the superior quality trees for the study as demonstrated by the higher mean DBHOB of sampled trees compared with the wider plantation trees for Why Not, Kumbyechants and Elderslie plantations. Only average sized trees were selected from the Windermere plantation.

Table 6.3. Sampled tree characteristics relative to surrounding trees

	Why Not, Douglas Daly, NT	Kumbyechants, Douglas Daly, NT	Elderslie, Cooktown, QLD	Windermere, Bowen, Qld
Mean DBHOB of plantation trees (mm)	228	176	250	257
Mean DBHOB of sampled trees (mm)	268	255	356	253
Mean height of plantation trees (m)	13.3*	11.0	15.5*	**
Mean height of sampled trees (m)	12.5	13.3	**	11.1
Number of tree samples	9	9	9	12

Notes: Top height rather than mean height was recorded.
Data not collected or not available at time of reporting

From the harvested trees, 56 logs (6.376 m³) resulted after final merchandising with 32 logs (1.918 m³) being allocated to rotary veneer processing and 24 logs (4.458 m³) allocated to sawmilling (Table 6.4). The method of log allocation ensured that there was minimal variation in log SEDUB between the two processing methods (sawing and rotary peeling). The variation in average log volume between the two processing methods is explained by the shorter log length used for rotary peeling (1.3 m versus approximately 3.0 m used for sawing).

The logs sourced from Elderslie were the largest in diameter and the Windemere logs were the smallest (Table 6.4). This is despite the Windemere trees being 6 years older than the Elderslie trees (19 years-old versus 13 years-old). Even though the selected Why Not trees were of similar age to the Elderslie trees, the Why Not logs were much smaller and more similar in size to the Kumbyechants selected logs, despite the latter being approximately 3.5 years younger (7.5 years-old).

The variation in selected log diameter between sites would obviously be influenced by various factors resulting in tree growth rate differences between the sites. However, the variation in tree selection strategy between Windermere and the other sites also means that the selected log sizes can't alone be used to compare the tree growth performance. For example, while the logs sourced from Elderslie were the largest in diameter and the Windemere logs were the smallest, the mean tree DBHOB at the Windermere plantation is actually larger than Elderslie (257 mm and 250 mm respectively). At least part of the variation in size of logs from Windermere compared to the other sites can be explained by the average size trees selected from this site for the study compared to the superior trees selected from the other sites.

Table 6.4. Log characteristics

	Processing method	Number of logs	Average log length (m)	Average log small-end diameter under bark (mm)	Average log volume (m³)	Total log volume processed (m³)
Why Not, Douglas Daly, NT	Sawing	6	3.1	216 (13.7)	0.1494	0.8964
	Peeling	7*	1.3	219 (17.2)	0.0551	0.3856
Kumbyechants, Douglas Daly, NT	Sawing	6	2.9	220 (22.9)	0.1491	0.8945
	Peeling	7*	1.3	200 (24.2)	0.0490	0.3436

Elderslie, Cooktown, QLD	Sawing	6	3.1	307 (52.0)	0.3148	1.8890
	Peeling	6	1.3	291 (33.5)	0.1007	0.6030
Windermere, Bowen, Qld	Sawing	6	3.0	187 (19.6)	0.1296	0.7777
	Peeling	12	1.3	197 (18.5)	0.0487	0.5848

Notes: Standard deviation presented in parentheses
One log yielded 3 peeler billets after final merchandising, while the balance yielded 2 peeler billets

Figures 6.6 to 6.8 illustrate the variation in log taper, log sweep and log small-end ovality for the selected logs from each site. The results highlight the relatively large taper that exists when this species is at a relatively young age, regardless of site and growing condition. The taper in these logs was well over triple of what would be expected from other plantation hardwood species (e.g. *Eucalyptus* and *Corymbia* spp.) (McGavin *et al.* 2014a). There was little variation in the mean log taper between the sites (range 31-37 mm/m) and the median values for taper varied from 29 to 33. The variation in taper within each site was much higher that the variation between the sites (Figure 6.6). There may be opportunities to reduce this wide variation through future selection and tree breeding programs that target more desirable tree form and properties.

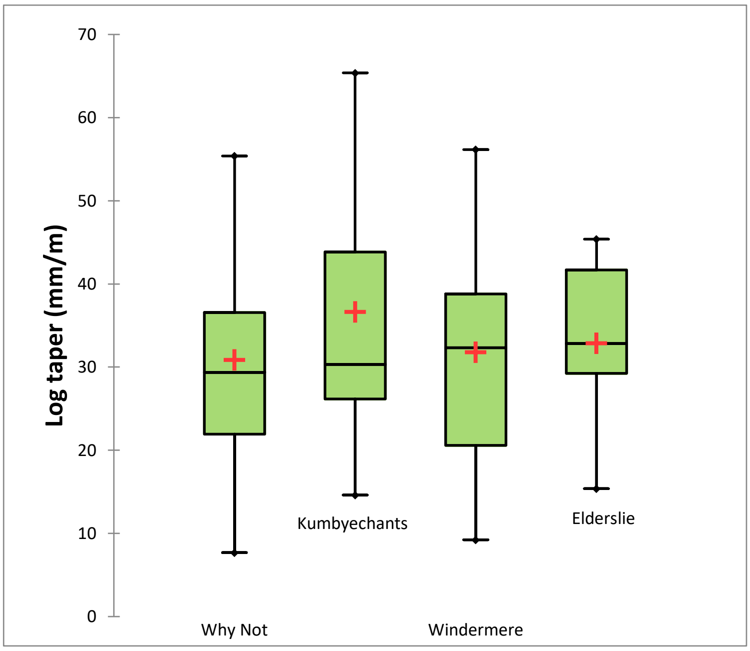

Figure 6.6. Log taper
Notes: Why Not *n*=13, Kumbyechants *n*=13, Windermere *n*=18, Elderslie *n*=12

Similarly, the log sweep is high, especially given the log selection criteria that provided superior quality trees based on log size and form. The average sweep recorded for each plantation site exceeded the maximum sweep permissible by an Australian commercial veneer processor within their in-house log grading specification. The variation within the sites was high and particularly so for the trees from Windermere. This may reflect the different selection protocol for this site where average rather than superior trees were sampled due to constraints with the thinning trial from which this material was taken.

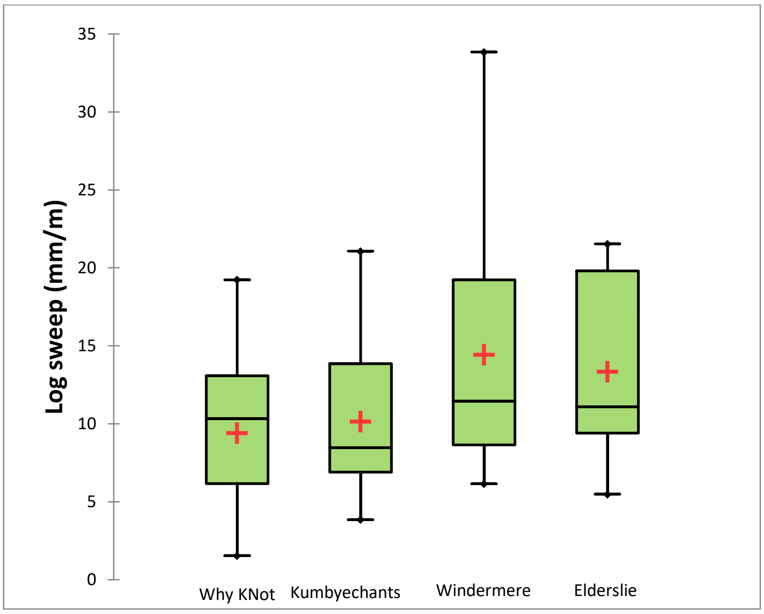

Figure 6.7. Log sweep

Notes: Why Not *n*=13, Kumbyechants *n*=13, Windermere *n*=18, Elderslie *n*=12

Log ovality was shown in Section 5 to have less impact on recovery compared with sweep and taper, however still has a significant negative impact. The impact of ovality is probably greater for veneer processing compared to sawmilling as essentially no useable veneer can be recovered from the log until it is rounded to a cylinder with consistent diameter and parallel sides (e.g. ovality removed). Sawmilling is potentially more flexible in recovering product from logs which are oval. The presence of log ovality in the four samples plantation showed wide within-site variation and similar mean ovality values between 5% and 7% (Figure 3.8).

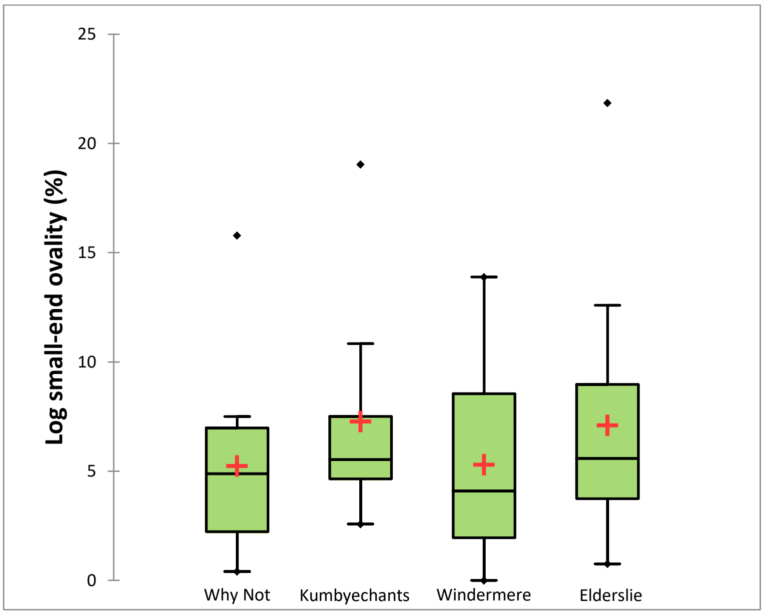

Figure 6.8. Log small-end ovality

Notes: Why Not *n*=13, Kumbyechants *n*=13, Windermere *n*=18, Elderslie *n*=12

As reported in Section 5 increasing log taper, log sweep and ovality all negatively affects, not only the potential product recovery that can be achieved from a resource, but also has significant impacts on the financial viability of a commercial operation (e.g. reduces the log price that processors are able to pay, increases cost of production etc.).

Rotary veneer processing

Figure 6.9 shows the recovery of dry veneer from each of the plantations. As the calculation method for dry veneer recovery doesn't include grading for defects (internal billet features), most of the variation in recovery between plantations can be explained by the log geometry (diameter and form deviation from a cylindrical column) rather than other factors such as tree age, wood quality or impacts of silviculture (refer to Section 5).

The Why Not billets yielded the highest recovery with 73%, followed by the Kumbyechants and Elderslie billets with 68% (Figure 6.9 and Table 6.5). Despite Elderslie billets having the highest mean diameter, these billets did not result in the highest recovery. The higher dry veneer recovery which resulted from the Why Not billets can be explained by the influence of the lowest average log taper, lowest average log sweep and lowest average log ovality meaning that less of the billet volume is lost during the billet rounding phase where no veneer can be recovered. The Elderslie billets still produce more veneer volume per billet though. The Windemere billets produced the lowest dry veneer recovery (56%) which is expected given these billets had the smallest diameter and the highest ranking for log sweep. Although the log taper and ovality results for the Windemere billets were comparable to the other sites, there is more of a negative impact due to the smaller billet diameters (i.e. the ratio of sweep to diameter is greater). Other log form factors that can influence dry veneer recovery are stem fluting, hollows etc.

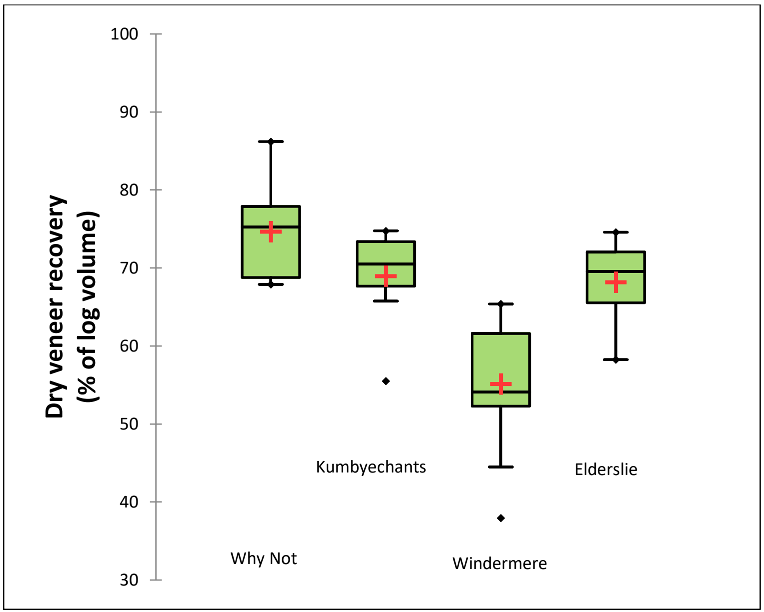

Figure 6.9. Dry veneer recovery

Notes: Why Not *n*=13, Kumbyechants *n*=13, Windermere *n*=18, Elderslie *n*=12

While the dry veneer recovery (dried, ungraded veneer) from the Why Not billets benefited from good comparative billet form, the benefit of the larger diameter Elderslie billets did aid in the gross veneer recovery (dried and graded veneer) with 63% of log volume being recorded, the highest from the four plantation sites (Table 6.5).

In order to separate the internal billet imperfections from the billet geometry, the gross recovery presented as the percentage of dry veneer volume (rather than log volume) provides a useful comparison (Table 6.5). The Elderslie billets yielded the highest recovery (93%) indicating a lower proportion of the recovered veneers were negatively affected by internal billet defects. The larger diameter logs may have also assisted in the defects being less concentrated and more distributed within the recovered veneer. The Windermere veneer ranked second with 87% recovery. Why Not veneer ranked lowest with 71% recovery, essentially losing the benefits gained at the dry veneer recovery stage. This indicates that the recovered veneer from this site contained levels of defects and imperfections that negatively affected the grade quality compared to the other sites.

The net recovery presents the percentage of the billet volume which is marketable (veneer which is dried, grade and trimmed to a nominal final product dimension). The Elderslie billets achieved the highest net recovery at 55%, attributed to the larger billet diameter and less internal imperfections. Kumbyechants billets ranked second (50% recovery), followed by Why Not billets (45%). The Windemere billets had the lowest net recovery (42%), demonstrating that although the internal billet imperfections were relatively low, it could not offset the negative impacts that resulted from the billet geometry.

The recovery values achieved are similar to the rotary veneer recovery analysis reported by McGavin *et al.* (2014a) for six different hardwood plantation species (*Eucalyptus* and *Corymbia* species) using similar processing methods.

Table 6.5. Veneer recoveries

	Dry recovery (% of log volume)	Gross recovery (% of log volume)	Gross recovery (% of dry veneer volume)	Net recovery (% of log volume)
Why Not, Douglas Daly, NT	73	52	71	45
Kumbyechants, Douglas Daly, NT	68	57	84	50
Windemere, Bowen, Qld	56	48	87	42
Elderslie, Cooktown, QLD	68	63	93	55

According to the Engineered Wood Products Association of Australasia (EWPAA, www.ewp.asn.au), the Australian rotary veneer industry requires approximately 30 to 40% of their veneer production to be C-grade or better to enable saleable product manufacture. The grade recovery analysis showed that the Windermere billets achieved this target with 37% of the net recovered veneers being C-grade or higher (24% C-grade and 13% B-grade). While the dry, gross and net recoveries for this site were the lowest, having the potential to achieve higher grade qualities could be critically important to secure markets. At the remaining three sites the majority of recovered veneers failed to make a grade higher than D-grade, the lowest grade quality in accordance with *AS/NZS2269.0:2012* (Table 6.6). No veneers meet the requirements of A-grade. While D-grade is the lowest visual grade quality for structural veneer, the veneers are suitable for face veneers on non-appearance structural panels as well as the core veneers for most appearance and non-appearance structural panels. The higher recovery of higher grade veneers (C-grade and better which are suitable for face veneers) from the older site at Windermere, may allow the commercial production of a standard mix of appearance veneer-based products from a thinning resource of this quality.

Table 6.6. Graded veneer recoveries

	A-grade recovery (% of log volume)	B-grade recovery (% of log volume)	C-grade recovery (% of log volume)	D-grade recovery (% of log volume)	B-grade recovery (% of net veneer volume)	C-grade recovery (% of net veneer volume)	D-grade recovery (% of net veneer volume)
Why Not, Douglas Daly, NT	0	1	6	38	*2*	*13*	*85*
Kumbyechants, Douglas Daly, NT	0	3	7	40	*6*	*14*	*80*
Windermere, Bowen, Qld	0	6	10	26	*13*	*24*	*63*
Elderslie, Cooktown, QLD	0	3	3	49	*5*	*6*	*89*

Table 6.7 details the top 5 ranked defects that prevented veneer sheets from achieving a grade higher than D-grade. Note that some veneers may be grade limited due to more than one defect. As expected, there are similarities across all sites. Internal log natural defects such as knots etc., were not the main influence in reducing grade, rather veneer defects that result from the interaction between the resource and the conversion process feature most.

Table 6.7. Top 5 ranked defects preventing graded veneers from attaining assigned grades higher than D-grade

	Rank				
	1	2	3	4	5
Why Not	Roughness (53%)	Compression (38%)	Grain breakout (32%)	Splits (31%)	Cumulative defects (20%)
Kumbyechants	Compression (55%)	Grain breakout (33 %)	Roughness (31%)	Cumulative defects (20%)	Wane (10%)
Windermere	Roughness (33%)	Unsound knots –fractured (23%)	Unsound knots –bark encased (22%)	Compression (21%)	Wane (17%)
Elderslie	Roughness (77%)	Compression (47%)	Grain Breakout (34%)	Unsound Knots – fractured (22%)	Cumulative defects (18%)

Veneer surface roughness was the highest ranked defect for three sites and ranked third for the fourth site. Many factors can influence the severity of veneer surface roughness including resource orientated factors such as grain angle, log taper, growth stresses, reaction wood etc., as well as process orientated factors such as lathe setup, billet pre-treatment method and temperature, target veneer thickness, knife sharpness etc. Given the range of factors that potentially influence this defect, there may be opportunities to improve the veneer roughness through intervention, especially through process modification. Grain breakout also featured in three of the four sites. Grain breakout is similar to roughness in appearance, although is often more concentrated in small zones and the resulting undulations can be much deeper, and the causes are very similar to veneer roughness.

Knot type defects featured within the top five defects which limited veneers from Windermere and Elderslie plantations to D-grade. The Windermere veneers were most affected with 23% and 22% of veneers being limited to D-grade due to unsound fractured knots and unsound bark-encased knots respectively. With all sampled plantations receiving similar pruning treatments, it is not clear why Windermere in particular was most affected by knot type defects, especially given this plantation was harvested at an older age by comparison to the other sites, which should have resulted in greater proportion of post-pruning growth. Further investigation into the pruning methodology adopted at Windermere may assist in understanding the lower effectiveness that the pruning treatments had in producing knot and knot associated defect free wood.

The presence of wane was ranked fifth for the Kumbyechants and Windermere veneers. Wane is the natural absence of wood in the product section. This defect can be prevented by undertaking additional round-up prior to peeling, however, it is generally preferred to manage a small percentage of the natural tree edge on the billet during peeling rather than risk the loss of log volume during round up that may have produced usable veneer (Figures 6.10 and 6.11). Billets with smaller diameter and non-uniform shape (taper, sweep, ovality and fluting) can increase the occurrence of wane in recovered veneer sheets.

Cumulative defects are described as an area within the veneer sheet that contains more than one defect in close proximity to others which if assessed individually, would not limit the veneer grade, but when measured cumulatively in accordance with *AS/NZS 2269.0.2012*, either limits grade potential or results in the veneer sheet being rejected. This defect category prevented around 20% of the veneers from Why Not, Kumbyechants and Elderslie and 9% of Windermere veneers achieving a grade higher than D-grade. Indeed, cumulative defects were the main cause of veneers from all sites failing to achieve D-grade (i.e. reject grade).

Figure 6.10. Billets after round-up will often still contain patches of bark or natural log surface

Figure 6.11. Veneer with wane resulting from areas of natural log surface remaining after round-up

A significant amount of compression was observed in the recovered veneer sheets and this is supported by this defect ranking in the top 4 defects preventing veneers from achieving grades higher than D-grade across all sites. Veneer compression is evidenced by the lack of sheet flatness and a wavy undulating surface. Veneer sheets containing a high level of compression and waviness can be difficult to dry (e.g. can jam drier systems) and are difficult to store in stable packs. Affected veneer may be unable to be passed through conventional adhesive application equipment or if they are able to be passed through, the adhesive is spread in a very uneven manner leading to poor bonding in the manufactured product. Veneers containing compression also tend to split when the sheets are forced flat during pressing for product manufacture resulting in downgraded and poor quality product.

While the market acceptance of compression affected mahogany veneer is untested, it may be a reasonable assumption that D1-grade and better veneers may have some likelihood of being marketable quality veneer. Adopting this assumption would further reduce the recovery values reported above, as no veneers were failed due to compression in the grade quality analysis. Kumbyechants veneers would be most affected with 31% of veneers graded between D2-grade and D4 grade for compression. Why Not and Elderslie veneers had similar proportions of veneer graded between D2-grade and D4-grade for compression (18% and 21% respectively). Windermere had the least amount of veneer graded between D2-grade and D4 grade for compression at 2%.

Figure 6.12 illustrates the distribution of veneer compression grading for the four sites. The distribution of compression grades are similar for three of the sites, however Windermere veneers did show less severe compression, with most veneers (98%) graded as D1-grade or better. With a variety of factors potentially influencing the presence of veneer compression, it is not possible to explain the result accurately, however, the older age and smaller log size may have proved advantageous in limiting the impact of this defect.

The proportion of veneers downgraded due to the presence of compression wood decreased as age increased (Figures 6.13a, and 6.13b). When the data for the four sites used in this Grade

Recovery analysis were included the relationship between age and compression defects had a regression coefficient of $R^2 = 0.85$ and P value of 0.077 (Figure 6.13a). By including data from the thinning by fertilizer factorial (T x F) trial at Stray Creek, Wallaroo1 (from Section 7, Table 7.7) in the Douglas Daly the $R^2 = 0.68$ with a P value of 0.045 (Figure 6.13b). It is possible that the lower influence of compression in older material may be influenced by smaller log size and hence slower growth in the older material particularly from the Windemere site. However in 9.5 year old material from the Wallaroo 1 T x F trial, there was no difference between the incidence of compression between fast and slow grown trees (Figure 6.13b). This comparison was between material from slow grown trees (unfertilized at 800 sph) and fast grown trees (fertilized at 300 sph). With a variety of factors potentially influencing the presence of veneer compression, it is not possible to explain the result accurately. However, a probable contributor of the compression severity could be the log form (especially taper and sweep) which results in the veneer being recovered that contained a range of wood age (cambial age) resulting from the peeling process cutting parallel to the geometrical center of the tree, not parallel with the log surface (Figure 6.14).

Further studies are critical to understand this phenomenon and to allow potential management strategies to be developed. It could be possible that the mechanism causing veneer compression may also influence the level of distortion (twist, spring and bow) in sawn boards.

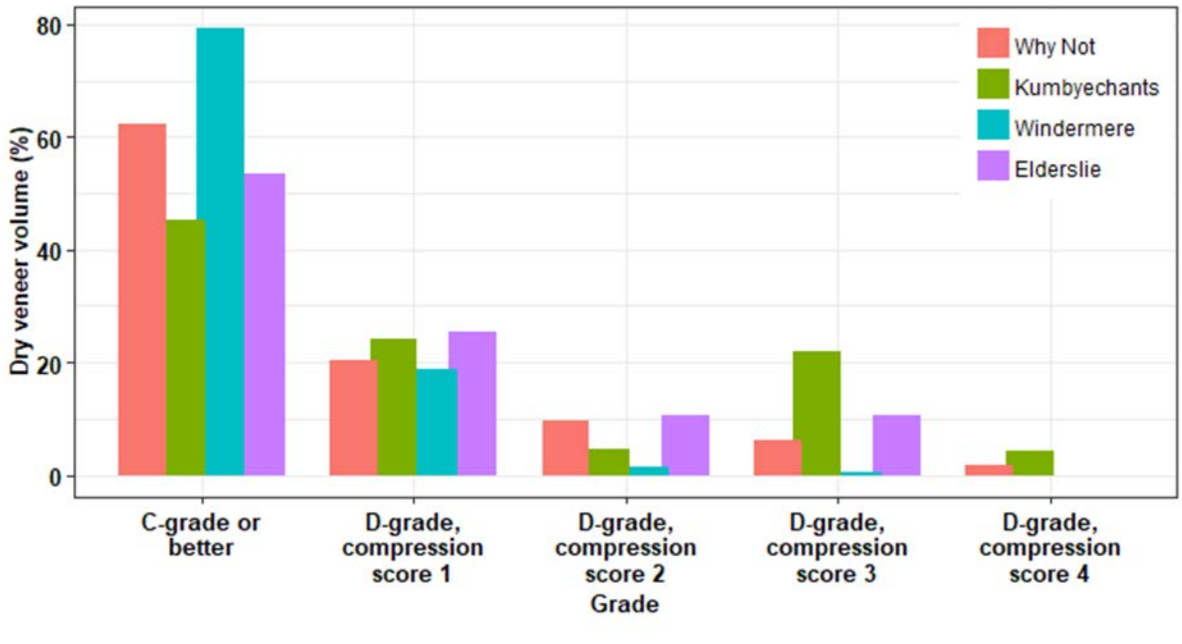

Figure 6.12. Dry veneer volume recovery assessed on the basis of veneer compression severity (ignoring all other defects in the veneer sheets)

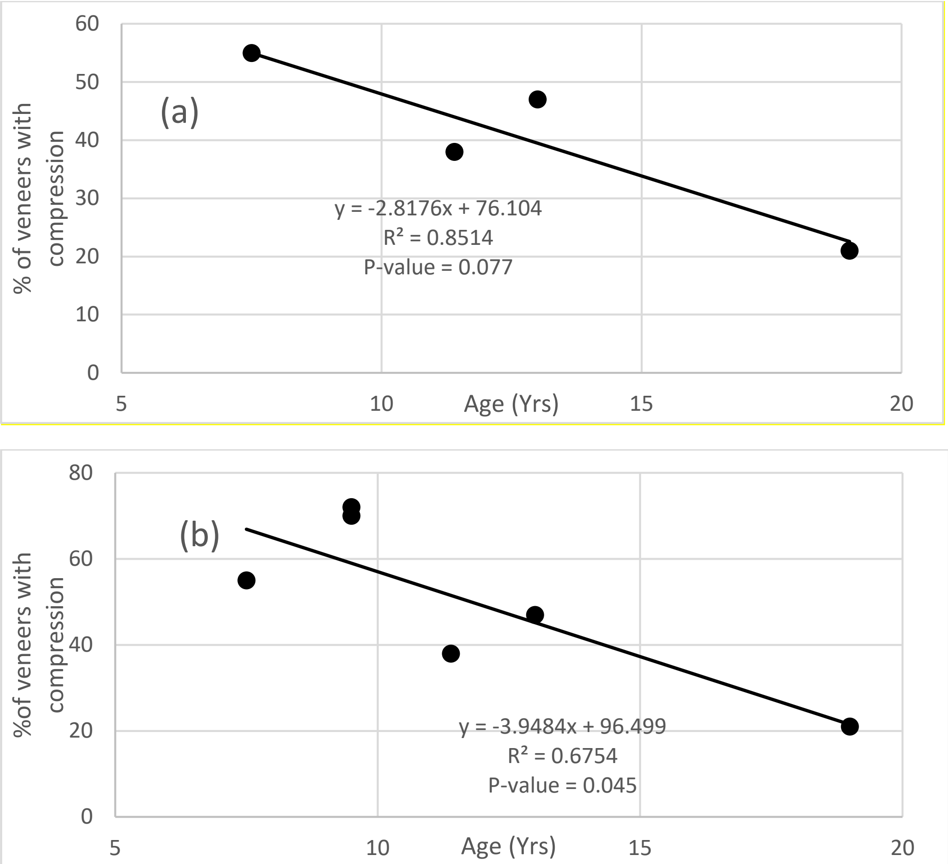

Figure 6.13. Relationship between age (years) and the proportion of veneer downgraded due to compression for (a) the four sites sampled for grade recovery assessment and (b) with the data from the additional silviculture impacts study added (See Section 7).

Figure 6.14. Veneer containing variable wood resulting from processing logs with non-uniformity (especially taper and sweep)

Sawmilling

Table 6.8 provides details of the various recovery analyses undertaken. The sawn recovery focuses on the volume of square dimension boards recovered from the sawmilling process. Similar to dry veneer recovery, internal log defects aren't considered at this point, therefore log geometry (diameter and log form) has a large influence on recovery. In addition, the potential recovery from sawing processes are more sensitive to changes in log diameters, especially as diameters decrease below 30 cm.

Similar to the veneer processing results, the logs sampled from Why Not plantation provided the highest recovery (49%), benefiting from better log form. The lower than expected sawn recovery from the larger diameter Elderslie logs can be attributed to both an influence of log form, but also as a result of a higher proportion of 150 mm boards recovered from these larger logs compared to predominately 100 mm wide boards recovered from the smaller logs from the other three sites. While the wider board width was compatible with the log diameter, the log form (particularly taper) resulted in many boards containing wane on the board ends which negatively influenced the sawn recovery. The benefits however are more visible post-grading where 67% of the sawn recovery was recovered in graded boards, 10% more than the second ranked site (Why Not). Windermere provided a low sawn recovery, again as a direct result of small-diameter logs and the negative impact of log form.

While the sawn recoveries appear to be in line with traditional sawmilling production rates, the low (<20%) recovery of sawn-dried-dressed boards highlights the well-recognised challenge of sawing relatively small diameter, young plantation hardwood logs (e.g. Leggate *et al.* 2000, Northway and Blakemore 1997, Waugh and Yang 1994).

Table 6.8. Sawn timber recoveries

	Sawn recovery (% of log volume)	Sawn graded recovery (% of log volume)	Sawn graded recovery percentage of dry recovery (% of dry sawn volume)	Sawn-dried-dressed recovery (% of log volume)
Why Not, Douglas Daly, NT	49	30	57	20
Kumbyechants, Douglas Daly, NT	44	22	50	15
Windermere, Bowen, Qld	35	16	45	10
Elderslie, Cooktown, QLD	40	26	67	19

The Australian Standard *AS 2796.2:2006 Timber-Hardwood-Sawn and milled products, Part 2: Grade description* provides grade criteria for three grades – select grade, medium feature grade and high feature grade. Interestingly the grade analysis resulted in identical grade recoveries when the sawn boards were graded independently to these three grades. That is, the sawn graded recovery and the sawn-dried-dressed recovery values reflect the grade recovery for either select, medium feature or high feature grade. Normally it would be expected that the recovered volume would decrease as the grade criteria increases (e.g. more high feature grade would be recovered compared to select grade). There are various reasons for these results. As the log selection and merchandising strategy targeted superior trees and the log was selected avoiding branches and other defects, the log was relatively free of defects such as knots.

Secondly, the defects present in the boards were those that have identical permissible limits across all three grades (e.g. wane, heart shakes etc.).

Table 6.9 outlines the top 5 ranked defects that contributed to boards being rejected in accordance with *AS 2796.2:2006*. Of the rejected board volume, the presence of wane accounted for the largest volume rejected across all four sites (Figure 6.15). The presence of wane in sawn boards is very common and difficult to avoid when sawing small diameter logs. The occurrence of wane also increases significantly as log form declines with taper, sweep, and fluting. Heart shakes and pith also contributed to downgrading of boards across all four sites (Figures 6.16 and 6.17). These defects originate from the centre of the log (i.e. pith) or surrounding wood being included in sawn boards. The wood surrounding the pith (nominally within 50 mm radius of the pith) is often prone to splitting (called heart shakes) during drying. Again, these defects are common, especially when the log size is small as the proportion of wood affected by the pith and surrounding heart shake prone wood increases. Wandering pith, a characteristic of plantation grown African mahogany that utilises unimproved raw genetic stock, also increases the impact of these defects.

Table 6.9. Top 5 ranked defects resulting in boards being rejected

	Rank				
	1	2	3	4	5
Why Not	Wane (65%)	Heart shake (26%)	Pith (8%)	Want (1%)	End-Split (<1%)
Kumbyechants	Wane (69%)	Heart Shake (30%)	Pith (<1%)	End-Split (<1%)	-
Windermere	Wane (42%)	Heart Shake (39%)	Pith (12%)	Want (4%)	Decay Knot (4%)
Elderslie	Wane (37%)	Heart Shake (35%)	Decay Knot (19%)	Fractured Knot (6%)	End-Split (2%)

Figure 6.15. Example of a wane on a board edge

Figure 6.16. Example of a heart shake

Figure 6.17. Example of pith in a sawn board

As explained earlier, board distortion (twist, spring and bow) was undertaken independent to the grade analysis. The main reason for this, was the boards were phantom docked as part of the grading process, therefore the board distortion could not be measured on the shortened ‘in-grade’ board length that would result after defect docking. Figures 6.18 to 6.20 illustrate the board distortion (twist, spring and bow respectively) when measured on the original board.

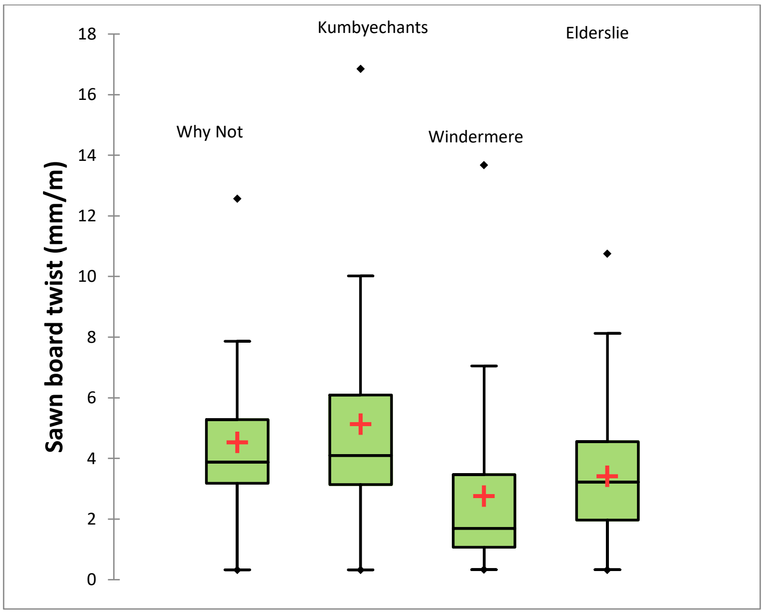

Figure 6.18. Sawn board twist

Notes: Why Not *n*=55, Kumbyechants *n*=57, Windermere *n*=36, Elderslie *n*=69

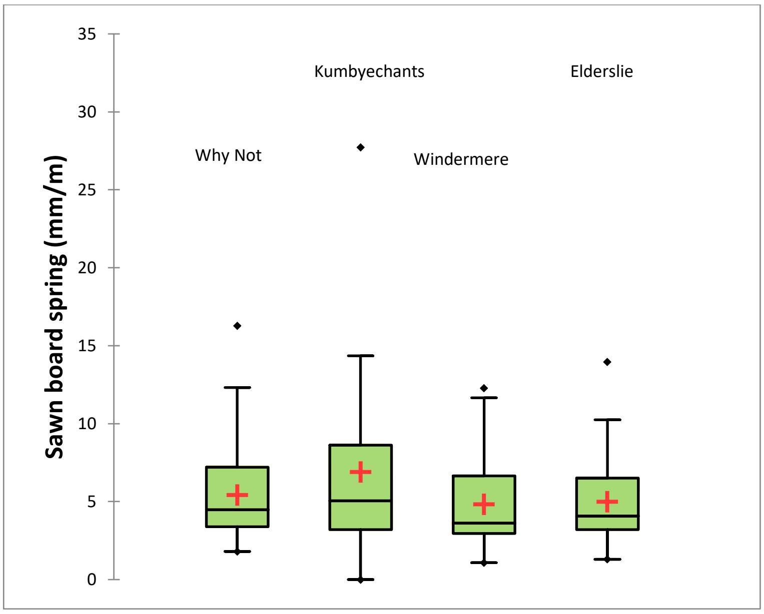

Figure 6.19. Sawn board spring

Notes: Why Not *n*=55, Kumbyechants *n*=57, Windermere *n*=36, Elderslie *n*=69

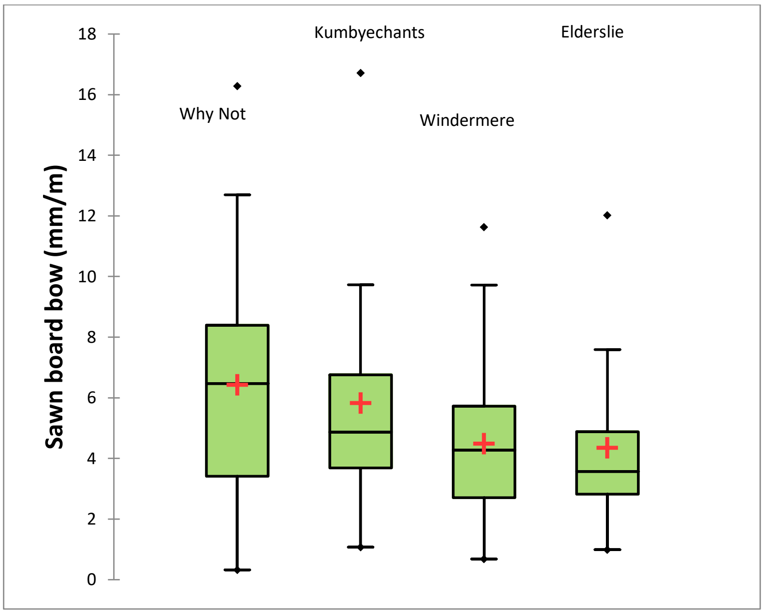

Figure 6.20. Sawn board bow

Notes: Why Not *n*=55, Kumbyechants *n*=57, Windermere *n*=36, Elderslie *n*=69

Australian Standard *AS2796.1:1999 Timber-Hardwood-Sawn and milled products, Part 1: Product specification* outlines the sawn board distortion limits for several product groups. Table 6.10 outlines the impact of the distortion limits when applied to the sawn boards recovered from each of the four sites. All sites demonstrate the high presence of board distortion which negatively impacts the efficiency during processing along with product recovery. Table 6.10 includes a product example which African mahogany may target (strip flooring) and the analyses shows that less than 50% of the recovered boards would meet the distortion requirements of this product group. The Elderslie boards had only 10% of the recovered boards meeting the strip flooring distortion criteria. This potentially reflects the negative impact that high growth rate and relatively young harvest age can have on product quality. This is also supported by the highest performing site being Windermere with 47% of boards meeting the strip flooring distortion criteria. The trees from this site were the oldest and also the slowest growing. Further studies are critical to understand this phenomenon and to allow potential management strategies to be developed. It could be possible that the mechanism influencing board distortion (twist, spring and bow) in sawn boards may also be influencing the severity of compression in veneer.

Table 6.10. Board distortion

	Why Not, Douglas Daly, NT	Kumbyechants, Douglas Daly, NT	Windermere, Bowen, Qld	Elderslie, Cooktown, QLD
	% of boards that pass the AS2796.1:1999 distortion allowance			
Twist	40	33	72	64
Spring – joinery, dressed boards	0	11	81	1
Spring – light decking, lining boards, etc.	51	50	67	17
Spring – strip flooring, mouldings	80	73	81	83
Bow – joinery, dressed boards	2	7	0	3
Bow – strip flooring, light decking, lining etc.	80	84	89	93
Example: Strip flooring (combines twist, spring and bow)	15	23	47	10

Conclusions

1. The four plantation sites sampled for process performance and product recovery assessment displayed very different growth rates, reflected in wide variation in log diameters. The variation in growth performance aligned well with the site's annual rainfall and also influenced by silviculture management. Increasing log taper, log sweep and ovality all negatively affected, the potential product recovery that can be achieved from a thinning resource of this age and size. The variation in log form characteristics was much wider within sites than the variation in mean values between sites. There may be opportunities to reduce this wide variation through future selection and tree breeding programs that target more desirable tree form and properties; recognising that these plantations are a relatively unselected first-generation population.

2. Dry veneer recovery varied between sites and ranged between 56% and 73%. The variation can be generally explained by the variation in log diameter and log form characteristics (e.g. taper, sweep and ovality). The Elderslie plantation logs yielded the highest gross recovery (63% of log volume) attributed to the larger diameter and lower presence of internal log defects. The proportion of down grade due to compression effects was lowest for the logs from Elderslie which were the oldest trees sampled. Net veneer recoveries ranged between 42% and 55% reflecting the proportion of log volume that could be potentially marketed as veneer.

3. According to the Engineered Wood Products Association of Australasia (EWPAA, www.ewp.asn.au), the Australian rotary veneer industry requires approximately 30 to 40% of their veneer production to be C-grade or better to enable saleable product manufacture. The grade recovery analysis showed that the Windermere billets achieved this target with 37% of the net recovered veneers being C-grade or higher (24% C-grade and 13% B-grade). While the dry, gross and net recoveries for this site were the lowest, having the potential to achieve higher grade qualities could be critically important to secure markets. At the remaining three sites the majority of recovered veneers failed to make a grade higher than D-grade, the lowest grade quality in accordance with *AS/NZS2269.0:2012* (Table 6.6). No veneers meet the requirements of A-grade. While D-grade is the lowest visual grade quality for structural veneer, the veneers are suitable for face veneers on non-appearance structural panels as well as the core veneers for most appearance and non-appearance structural panels. The higher recovery of higher-grade veneers (C-grade and better which are suitable for face veneers) from the older site at Windermere, would allow the commercial production of a standard mix of appearance veneer-based products from a resource of this quality.

4. The sawn recovery was in line with that expected with 35% to 49% of log volume being achieved. However, the sawn graded recovery was low with less than 30% of the log volume achieving a market grade quality (high feature, medium feature or select grade in accordance with *AS 2796.2:2006)* and less than 20% of the log volume recovered as boards which meet final market grade quality in a final product dimension. Defects such as wane, heart shake and pith dominated the reason for boards not reaching grade. These defects are expected given the log form characteristics (e.g. large taper and sweep) and the high recovery of boards from the log central zone (nominally 50 mm radius of the pith) which is prone to checking or splitting during drying.

The board distortion analysis highlighted the negative impact that twist, spring and bow could result on the marketability of African mahogany sawn boards, depending on the target product specifications. The deviation in board straightness can cause problems during processing, during drying, during storage, during machining to the final product dimension and during final use. The causes of board distortion may be linked to the phenomenon causing veneer compression and waviness.

The phenomenon causing the compression in the veneer and distortion in the sawn boards is not well understood and may be influenced by genetics, growth cycles, log form characteristics (resulting in veneers or boards containing zones of different wood ages), wood structure (reaction wood) or by processing protocols (e.g. lathe setup, pre-treatment conditions etc.), or most likely, a combination of factors. A focused study to further investigate this phenomenon is critical to develop possible management strategies. Failure to address this problem before the plantation resource is marketed to the processing sector may result in a negative long-term reputation attached to the resource potentially limiting the available markets and reducing the resource value.

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Section 7: Silviculture impacts on veneer grade recovery

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Summary

An industrial African mahogany plantation estate of approximately 15 000 hectares exists in northern Australia. With most of these plantations now requiring thinning to ensure sustainable growth (see Section 2), , there was increased interest in identifying suitable processing systems and target markets for material resulting from thinnings. In addition to the exploration of processing opportunities for the current plantation mid-rotation resource, there is strong industry interest in understanding how the early age plantation resource and new plantings can be manipulated to further improve the potential recoverable volume and/or improve the grade quality of the recovered product through the implementation of different silvicultural treatments.

Thirty-six trees were harvested from a dedicated silviculture trial located in the Douglas Daly area of the Northern Territory (T x F trial in Wallaroo plantation - Section 2). The harvested trees were 9-years-old and represented a low stocking, high fertiliser treatment and a high stocking, low fertiliser treatment. The harvested trees yielded 51 logs which were able to be separated into three log types: low stocking butt logs, high stocking butt logs and low stocking top logs. These logs were processed into rotary veneer using spindleless lathe technology. The logs were relatively small in diameter and displayed high levels of taper, sweep and ovality.

Dry veneer recoveries between 44% and 65% of log volume where achieved with the low stocking butt logs achieving the highest recovery, followed by the low stocking top logs and then the high stocking butt logs. The fastest growing trees produced the highest veneer recovery. The variation in dry veneer recovery is mostly explained by log diameter and form. More variation between the logs types was evident with the gross (20% to 58%) and net recovery analysis as a result of the impact of internal log characteristics on the resulting veneer grade.

As previously identified (Section 6 this report) the veneer grade recovery from young mahogany showed that the majority of veneer from across the three log types failed to make a grade higher than D-grade. Thus, thinnings from young mahogany would likely be confined to producing structural grade material.

Veneer compression, surface roughness, grain breakout and unsound knots all featured prominently and with similar severity across all log types as defects that limited veneer grade potential. In contrast, defects such as unsound kino-encased knots, knot holes, bark pockets, kino veins, insect tracks, etc. had little or no impact on reducing the grade quality of the recovered veneers.

Introduction

African mahogany (*Khaya senegalensis*) is an internationally important, high-value, forest tree species and early trials in northern Australia have demonstrated significant potential for the plantation species. Commercial plantation establishment commenced in the Northern Territory in 2006 with a current commercial estate at around 14 000 hectares. A smaller plantation estate of around 1 000 hectares exists in north Queensland. These plantations have been established primarily to grow sawlogs from which high-quality and high-value sawn timber is expected.

While numerous research projects have existed to support the African mahogany industry in Australia, the majority of the research effort has focused on plantation establishment and management. Research on wood properties, processing systems and target products has been limited and restricted to activities such as those reported by Zbonak *et al.* (2010) and Armstrong *et al.* (2007). Both Zbonak *et al.* (2010) and Armstrong *et al.* (2007) reported valuable base line information on wood properties, sawn timber qualities and sawn recoveries of Australian-grown African mahogany. In addition, Zbonak *et al.* (2010) reported limited rotary veneer grade and recovery information. However, both of these studies were conducted on a limited number of logs, included a range of plantation ages and were sourced from plantations that potentially don't represent the growth and form expected from a larger 'commercial' plantation resource.

With many of the plantation areas now considered to be post mid- rotation, there is increasing interest in identifying suitable processing systems and target markets for material resulting from both thinnings and final rotation harvesting. While the African mahogany plantations were predominately established for the production of sawlogs, with an expectation that these would be used to pursue high-value sawn timber markets, the large proportion of relatively short bole trees (<3 m) and a wide range of tree diameters (including predominately smaller diameter trees <30 cm) may restrict the efficiency of this processing approach. Rotary veneer, using spindleless lathe technology, may provide an alternative and more efficient processing method assuming a viable market exists for the resultant veneer.

In addition to the exploration of processing opportunities for the current plantation resource which is post mid-rotation, there is strong industry interest in expanding the understanding of how the early age plantation resource and new plantings are able to be manipulated to further improve the potential recoverable volume and/or improve the grade quality of the recovered product through the implementation of different silvicultural treatments. While there are several silviculture focused trials underway which mainly focus on tree growth effects, there is a lack of information and understanding on how these different silvicultural management strategies influence the potential recoverable volume and/or impact the grade quality of the recovered product.

This study investigates the difference in volume and grade of veneer recovered from African mahogany logs harvested from an established silviculture trial and processed into rotary veneer using a spindleless veneering system. The study compares the veneer recovered from trees grown in high stocking plots which received a low fertiliser application and veneer recovered from trees grown in a low stocking plots which received a high fertiliser application. Where relevant, reference is made to outcomes and findings from earlier components of work undertaken within the same overarching project. This earlier of work included veneer recovery and grade quality assessments for four African mahogany plantations sourced across Queensland and the Northern Territory.

Research method

Plantation resource

Trees for the study were selected from the thinning and fertilizer trial in Stray Creek Station compartment, Wallaroo 1, located approximately 200 km south of Darwin. The area of African mahogany in the Douglas Daly region is approximately 14 000 hectares with Stray

Creek estate containing approximately 2,700 hectares. The site was originally occupied by open forest dominated by *Eucalyptus miniata* and *E. tetradonta*, along with tropical pasture grasses and legumes. The compartment was planted in January 2008. The African mahogany plantations in the Douglas Daly have been established from seed collected from wild trees across the Sahel, with most seed originating from Mali. Little is known about the relative performance of the different provenances and very wide variation in growth and form was expected and has been observed. The Wallaroo planting targeted 1 029 stems per hectare (s/ha) with a nominal spacing of 3.6 m x 2.7 m. Table 7.1 provides additional site details.

Table 7.1. Site details

Location	Stray Creek Station Compartment: Wallaroo 1
Plantation establishment	January 2008
Soil Type	Tippera
Aspect	Westerly, 1% slope
Original Vegetation	Tropical pasture grasses and legumes. Originally open forest dominated by *E. miniata* and *E. tetradonta*
Elevation	129 m.a.s.l
Latitude/longitude	14.00’ 38.88”S 131.20’ 46.14”E at start point
Rainfall	Mean annual rainfall: ≈1200 mm/year (based on the 40 year record at Douglas River ~ 30km north)

In May 2012 (age 4), a stocking (thinning) and fertiliser trial was established. This site was selected for the trial as it was considered to have good form and was uniform across the site. Due to post planting mortality, the stocking at the trial establishment was 810 s/ha. Table 7.2 provides details of the stocking treatments included in the trial.

Table 7.2. Thinning treatments

Treatment Number	Nominal initial stocking at age 4 (s/ha)	Stocking after T1 (2012) (s/ha)	Stocking after T2 (2017) (s/ha)
1 & 11	800	800	800
2 & 12	800	800	400
3 & 13	800	600	600
4 & 14	800	600	300
5 & 15	800	500	500
6 & 16	800	500	250
7 & 17	800	400	400
8 & 18	800	400	200
9 & 19	800	300	300
10 & 20	800	300	150

Fertilizer application

Treatments 1-10 received a low fertilizer application and treatments 11-20 received a high fertilizer application. There was no control (nil fertilizer) as the site was judged to be highly nutrient deficient and without a small application of fertilizer, it was thought that the plantation would fail.

The low fertilizer plots received 400 kg/ha of Rustica and the high application received 2 x 400 kg/ha of Rustica. Rustica contains 12% N, 5% P, 14% K and 10% S, therefore:

- 400 kg of fertilizer provided: 48 kg N, 20 kg P, 56 kg K and 40 kg S, and
- 800 kg of fertilizer provided: 96 kg N, 40 kg P, 112 kg K and 80 kg S.

Pruning

During the dry season which followed the stocking and fertiliser trial establishment, the whole stand was 'form pruned'. The objective of the pruning operation was to produce a single stem (singling) with limited or no branches. Thus all large ramicorns or branches were removed up to a height of approximately 2 m.

Tree selection, harvesting and log merchandising

Tree selection was undertaken during the planning of the second thinning activity and prioritised selection from the high stocking 800 s/ha low fertiliser treatment (treatment number 20) and the low stocking 300 s/ha high fertiliser treatment (treatment number 2) plots. These treatments were selected in order to represent the extreme silviculture treatments which were expected to produce the largest difference of tree growth and recoverable wood properties. Trees selected from within these plots targeted tree diameters at breast height over bark (DBHOB) close to the plot DBHOB mean. Trees were selected across several plots within each treatment type such that there was no more than four trees per plot represented in the trial.

Trees were harvested (thinned) with a mechanical harvester in July 2017 (age 9 years). Harvested logs were merchandised to length in the field targeting a 1.5 m butt log from the two target treatments and a 1.5 m top log from the 300 s/ha high fertiliser treatment (treatment number 2). The top logs targeted the upper part of the stem. Any log section between the top of the butt log and the bottom of the top log was discarded. The ends of the billets were sealed and the logs bundled together and covered in hessian which was watered frequently to minimise the drying of the logs during transport (Figure 7.1). Logs were transported via Darwin to Queensland Department of Agriculture and Fisheries (DAF), Salisbury Research Facility in Brisbane, Queensland. The time between harvesting and delivery to the Salisbury Research Facility was minimised to limit log degrade.

After delivery to the Salisbury Research Facility, the following parameters were then measured on each peeler billet (Figure 7.2):

- Large-end diameter under bark or *LEDUB* (m) – measured from the circumference with a diameter tape;
- Small-end diameter under bark or *SEDUB* (m) – measured from the circumference with a diameter tape;
- Log length or *L* (m) – measured using a length tape;
- Log sweep deviation or *a* (mm) – measured as the maximum distance on the curved side of a log when a line is extended between the log ends and specifically used to calculate log sweep (see Equation 4.2 below);
- Shortest small-end diameter or *SD* (m) – the shortest small-end diameter measured using a steel rule;
- Longest small-end diameter or *LD* (m) – the longest small-end diameter measured using a steel rule.

From the measured data, the following characteristics were measured:

Log volume, V (m^3) was derived for each log and was calculated as follows:

$$V = \left(\frac{SEDUB + LEDUB}{2}\right)^2 \times \pi \times L \qquad \text{[eq. 4.1]}$$

where V is the individual green log volume (m^3);

π is 3.141593; and

All other variables are previously defined.

Log sweep, S (mm/m) was calculated as the rate of deviation per lineal meter of log length and was calculated as follows:

$$S = \frac{a}{L} \qquad \text{[eq. 4.2]}$$

Log ovality, O (%) was calculated as the difference between longest small-end diameter (LD) and the shortest small-end diameter (SD) as a proportion of the longest small-end diameter (LD), expressed as a percentage and was calculated as follows:

$$O = \frac{LD - SD}{LD} \times 100 \qquad \text{[eq. 4.3]}$$

Log taper, T (mm/m) was calculated as the change in diameter per lineal meter of log length and was calculated as follows:

$$T = \left(\frac{LEDUB - SEDUB}{L}\right) \qquad \text{[eq. 4.4]}$$

Figure 7.1. Logs were end-sealed and wrapped in wet hessian to minimise degrade during transportation

Figure 7.2. Trial logs waiting to be measured

Rotary veneer processing

Log conversion

The peeler billets were processed using a semi-industrial scale spindleless veneer lathe (Figure 7.3). The lathe is capable of processing billets up to 1300 mm in length and 500 mm in diameter. The minimum peeler core size is 40 mm. For the study, a nominal dried veneer thickness of 2.5 mm was selected. The peeler billets were pre-heated prior to peeling using saturated steam until the billet cores reached approximately 50^0C. Immediately after being pre-heated, billets were docked to 1300 mm billet lengths, debarked and rounded in a dedicated rounding lathe before being peeled into veneer (Figure 7.4).

Figure 7.3. African mahogany veneer produced from a semi-industrial scale spindleless veneer lathe

Figure 7.4. Debarked and rounded billets ready for veneer processing

Veneer management

The resulting veneer ribbon was sequentially clipped to sheets with a 1 350 mm maximum width. Veneer sheets were labelled with a unique identifier and seasoned with a commercial veneer jet-box drier using the factory's standard practices with a target moisture content of 8%.

The following parameters were measured on the veneer sheets:

- Dried veneer thickness (*DT*)—the mean thickness of each dried veneer sheet, measured using a dial thickness gauge at four locations along the sheet length; and
- Dried veneer width (*DW*)—the width (perpendicular to grain) of each dried veneer sheet.

Veneer grading

Veneer quality was assessed by visual grading in accordance with Australian and New Zealand Standard *AS/NZS 2269.0:2012* (Standards Australia 2012). This standard is widely adopted across the Australian veneer industry and follows the same principles as other international veneer visual grading classification systems. The standard separates structural veneer into four veneer surface qualities (A, B, C and D-grade) and a reject grade according to severity and concentration of imperfections and defects. The grades are summarised as follows:

- A-grade veneer is a high-quality appearance grade veneer suitable for a clear finish.
- B-grade veneer is an appearance grade veneer suitable for high-quality painted finish.
- C-grade veneer is defined as a non-appearance grade veneer with a solid surface.
- D-grade veneer is defined as a non-appearance grade veneer with permitted open imperfections where decorative appearance is not a requirement.

The grading process was undertaken by a minimum of two experienced graders to minimise variation with defect definition and measurement, and to ensure consistent assessment.

Veneer recovery

Four recovery calculation methods were used: dry veneer recovery, gross veneer recovery, net veneer recovery, and graded veneer recovery.

Dry veneer recovery provides a useful measure of the maximum recovery, taking into account log geometry (e.g. sweep, taper, circularity), lathe limitations (e.g., peeler core size) and the drying process (e.g. veneer shrinkage, etc.). Dry veneer recovery disregards internal log quality. Dry veneer recovery (*DR* as %) was calculated as follows:

$$DR = \frac{L \times \sum_{veneer}(DT \times DW)}{\sum_{billet} V} \times 100 \qquad \text{[eq. 4.5]}$$

where *DT* is the average dry veneer thickness of each veneer (m);

DW is the dry veneer width (m, perpendicular to grain); and

All other variables are previously described.

Gross veneer recovery provides a useful measure of the maximum recovery of dried veneer that meets the quality specifications of *AS/NZS 2269.0:2012* (A-grade to D-grade). This recovery includes the losses accounted for in dry veneer recovery but also includes additional losses from visual grading (*i.e.,* veneer which failed to meet grade). Gross veneer recovery (*GSR* as %) was calculated as follows:

$$GSR = \frac{L \times \sum_{veneer}(DT \times GRW)}{\sum_{billet} V} \times 100 \qquad \text{[eq. 5.6]}$$

where *GRW* is the width (m, perpendicular to grain) of dried veneer that meets the grade requirements of A, B, C, and D grades in accordance with *AS/NZS 2269.0:2012*; and

All other variables are previously described

Net veneer recovery provides a useful measure of process efficiency, as it identifies the saleable product, taking into account the product manufacturing limitations. Net veneer recovery includes the losses accounted for in gross veneer recovery and also includes the additional losses due to the trimming of veneer before, during, and after product manufacture. The loss incurred when veneer sheets are reduced in width to the final product size is known as a trimming factor. In this study the trimming factor was 0.94. This corresponds to reducing the veneer sheet width perpendicular to the grain from 1 275 mm to 1 200 mm. The veneer sheet parallel to the grain was systematically reduced from 1 300 mm to 1 200 mm. Net veneer recovery (*NR* as %) was calculated as follows:

$$NR = GSR \times 0.94 \times \frac{1200}{1300} \qquad \text{[eq. 4.7]}$$

Thus,

$$NR = GSR \times 0.869$$

Graded veneer recovery is the net veneer recovery for each grade as defined by *AS/NZS2269.0:2012* (*i.e.,* A, B, C, or D grades). Graded veneer recovery was calculated for each grade quality and is defined as NR_A, NR_B, NR_C, and NR_D.

Results and discussion

Resource

Thirty-two trees were harvested for the study. The plots which provided the low stocking trees (treatment number 2, 300 s/ha) and the high stocking trees (treatment number 20, 800s/ha), had a mean DBHOB prior to harvesting of 22 cm and 16 cm respectively. Sixteen trees were harvesting from high stocking plots and from low stocking plots, each with a mean DBHOB of 21.7 cm and 15.9 cm respectively (Figure 7.5). Table 7.3 provides comparative details of the mean DBHOB values for the selected trees and the mean DBHOB prior to harvesting for each of the sampled plots.

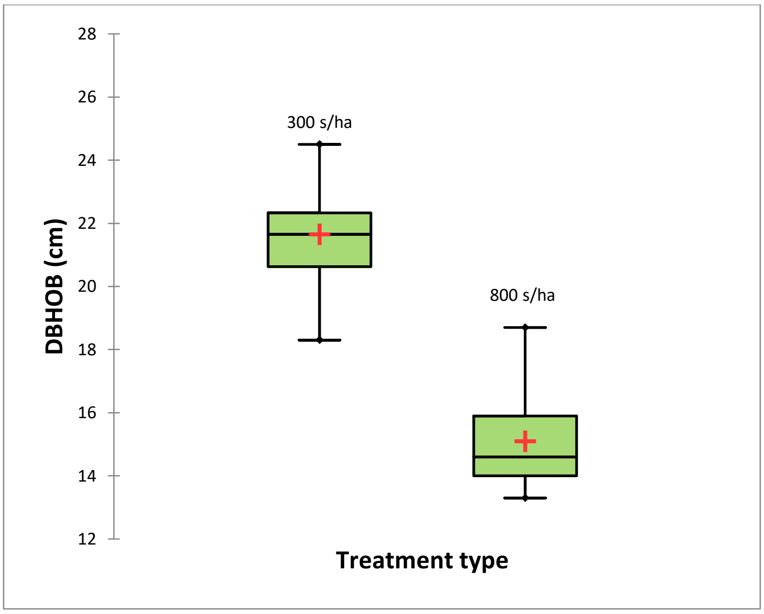

Figure 7.5. Diameter at breast height over bark of trees harvested

Notes: 300 s/ha *n*=16, 800 s/ha *n*=16

Table 7.3. Sampled tree characteristics relative to surrounding trees

Plot number	Treatment number	Plot mean DBHOB (cm)	Selected trees mean DBHOB (cm)
3	2	22	23
34	2	21	22
60	2	22	22
66	2	22	20
20	20	15	15
35	20	15	14
45	20	16	15
64	20	17	16

From the harvested trees, 51 logs (1.36 m^3) resulted after final merchandising. For analysis purposes, the logs were separated according to the silvicultural treatment (low stocking and high stocking) and butt or top logs. Butt logs were all recovered within the bottom 1.6 m of the trees, while the top logs (which were only recovered from the lower stocking treatment number 2 trees) were recovered between 1.3 m and 6.4 m up the tree. Table 7.4 provides further details of the log groupings. As illustrated in Table 7.4 and Figure 7.6, the butt logs originating from the lower stocking treatment yielded larger diameter logs (mean SEDUB of

19 cm) while the butt logs from the higher stocking treatment had the smallest mean SEDUB (13 cm). The top logs from the lower stocking treatment provided a mean SEDUB marginally higher but similar to the high stocking treatment butt logs.

Table 7.4. Log characteristics

Log type	Treatment number	Stocking at time of harvest (s/ha)	Number of logs after final merchandising	Mean SEDUB (cm)	Total log volume (m^3)
Butt log	2	300	15	19	0.611
Butt log	20	800	16	13	0.304
Top log	2	300	20	15	0.449
Total					**1.36**

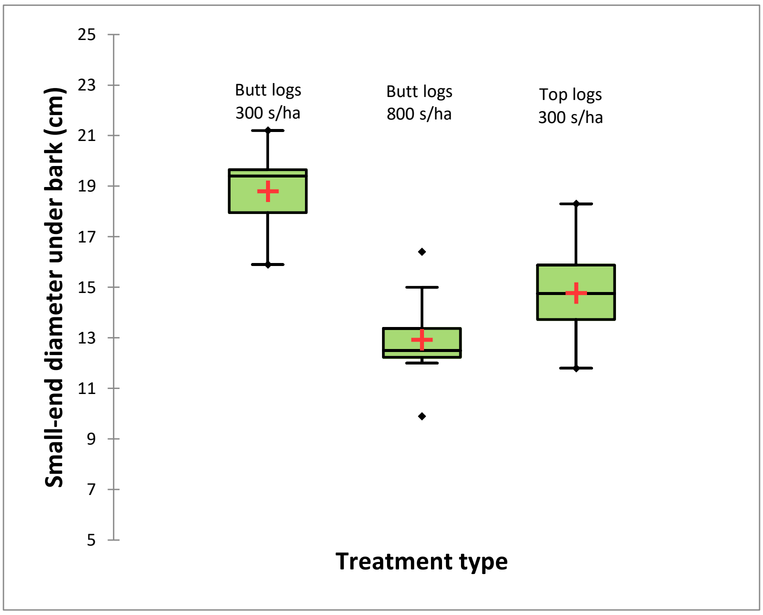

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Figure 7.6. Merchandised log small-end diameters
Notes: 300 s/ha butt logs *n*=15, 800 s/ha butt logs *n*=16, 300 s/ha top logs *n*=20

Figures 7.7 to 7.9 illustrate the variation in log taper, log sweep and log small-end ovality for the three different log types. The butt logs from the low stocking treatment type had the highest log taper (mean of 40.5 mm/m), followed by the butt logs from the high stocking treatment type (mean of 32 mm/m) (Figure 7.7). The top logs from the low stocking treatment type had the least taper with a mean taper value of 17.5 mm/m. The results are similar to those reported previously in Section 6 and provide further evidence that plantation African mahogany logs have relatively large log taper (relative to log diameter) compared to other plantation hardwood resources established in Australia.

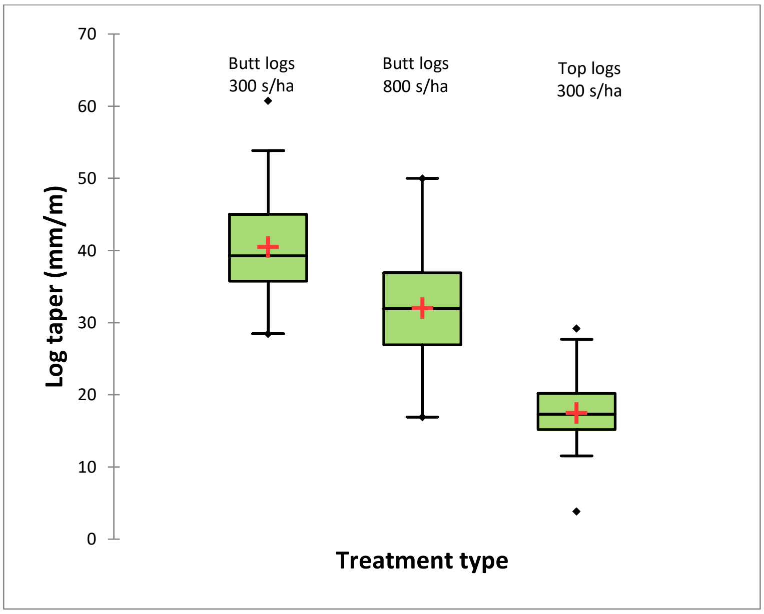

Figure 7.7. Log taper
Notes: 300 s/ha butt logs *n*=15, 800 s/ha butt logs *n*=16, 300 s/ha top logs *n*=20

The butt logs from the higher stocking treatment type had a higher mean log sweep (21 mm/m), while the butt and top logs from the lower stocking treatment had a lower and similar presence of sweep (16 mm/m) (Figure 7.8). The lower levels of sweep in the lower stocking treatment type may be a result of improved log quality connected to the improved growth rate (due to less within-stand competition) or possibly the logs with more severe sweep were removed as part of the first thinning (at age 4), whereas the higher stocking treatment type had not been previously thinned and therefore may contain more variation in log sweep.

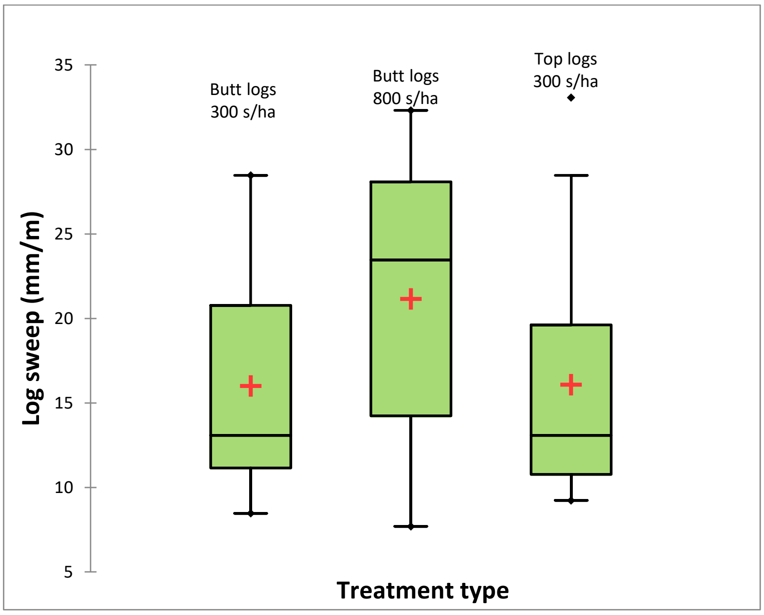

Figure 7.8. Log sweep
Notes: 300 s/ha butt logs *n*=15, 800 s/ha butt logs *n*=16, 300 s/ha top logs *n*=20

The presence of log ovality in the three log groupings showed mean ovality values between 3% and 7% (Figure 7.9). The top logs from the lower stocking treatment type contained the highest levels of log ovality and the butt logs from the high stocking treatment type contained the least amount of ovality.

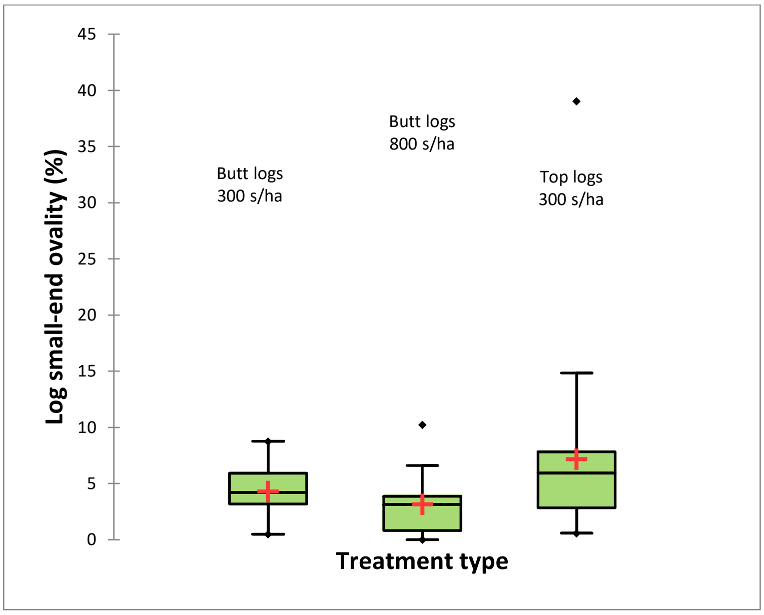

Figure 7.9. Log small-end ovality

Notes: 300 s/ha butt logs *n*=15, 800 s/ha butt logs *n*=16, 300 s/ha top logs *n*=20

As reported in Section 5 especially as log diameter decreases, increasing log taper, log sweep and ovality all negatively affects, not only the potential product recovery that can be achieved from a resource, but also has significant impacts on the financial viability of a commercial operation (e.g. reduces the log price that processors are able to pay, increases cost of production etc.).

Comparison to earlier studies

By comparison to the African mahogany logs processed during the earlier project trial (refer to Section 6), the logs processed in this study were smaller (Figure 7.10). The butt logs from the lower stocking treatment were similar to the peeling billets sourced from Windermere plantation at Bowen, Qld (19 cm versus 21 cm mean SED), although the Windermere plantation was 4-years older but with a similar stocking. The Why Not and Kumbyechants plantations from the Douglas Daly that were processed in the earlier trial were close to the age of the trees included in this study (Why Not –age 11, Kumbyechants – age 7.5 and Wallaroo – age 9) however the mean peeler billet SEDUBs where higher (23 cm and 21 cm respectively). The sampling strategy for the earlier trial did however favour the higher performing ‘superior’ trees while the sampling for this trial focused on logs closer to the mean DBHOB for the relevant treatment type. The high stocking butt logs and the low stocking top logs had a much smaller SEDUB compared to the previously processed logs.

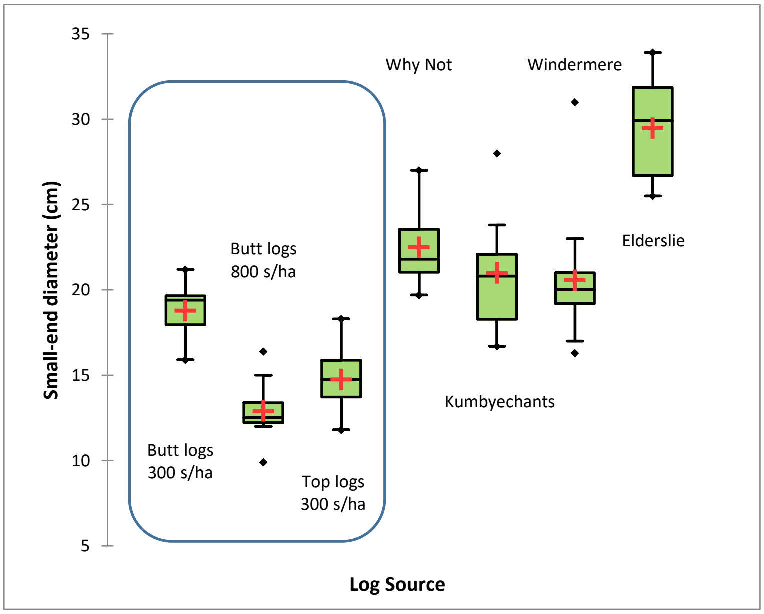

Figure 7.10. Small-end diameter log comparison

Notes: 300 s/ha butt logs *n*=15, 800 s/ha butt logs *n*=16, 300 s/ha top logs *n*=20, Why Not n=13, Kumbyechants n=13, Elderslie n=18, Windermere n=12

The log taper present in the logs from the current study compare similarly with the logs processed during the recent study (refer to Section 6) except for the top logs of the low stocking treatment type which showed a lower level of taper (Figure 7.11). When the previous trial log taper data is reviewed to separate the butt and top logs, the top logs had a mean log taper value of 21 mm/m and the butt logs had a mean log taper value of 38 mm/m (four sites combined). This result is similar to the current trial when the top and bottom logs from the low stocking treatment type are compared suggesting log taper improves as the log height is increased.

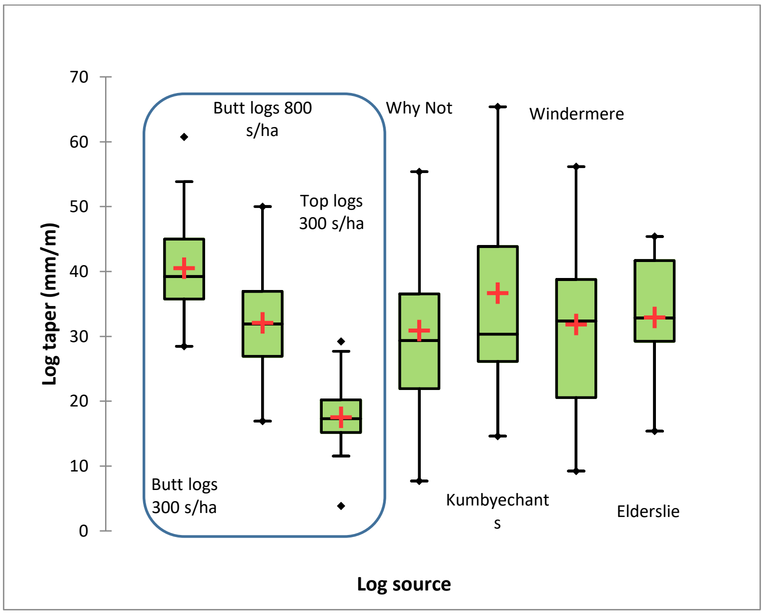

Figure 7.11. Log taper comparison

Notes: 300 s/ha butt logs *n*=15, 800 s/ha butt logs *n*=16, 300 s/ha top logs *n*=20, Why Not n=13, Kumbyechants n=13, Elderslie n=18, Windermere n=12

The presence of sweep in the logs of the current study are consistently higher than the logs provided from the four sites for the previous study (Figure 7.12). As a comparison to other plantation resources, McGavin *et al.* (2014) reported mean sweep values from nearly 1 000 1.3 m long plantation hardwood (*Eucalyptus* and *Corymbia* spp.) logs of between 8 and 12 mm (therefore around 6 to 9 mm/m).

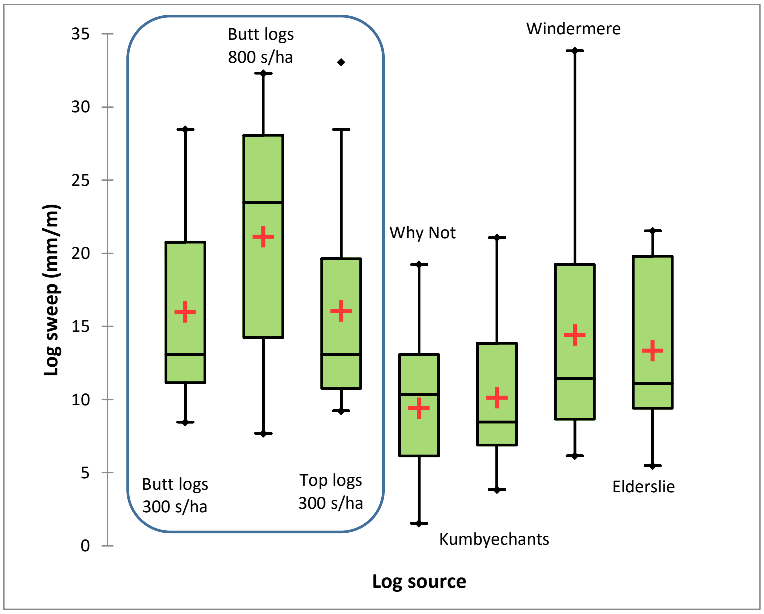

Figure 7.12. Log sweep comparison

Notes: 300 s/ha butt logs *n*=15, 800 s/ha butt logs *n*=16, 300 s/ha top logs *n*=20, Why Not n=13, Kumbyechants n=13, Elderslie n=18, Windermere n=12

The log small-end ovality is similar across all the logs resources (Figure 7.13).

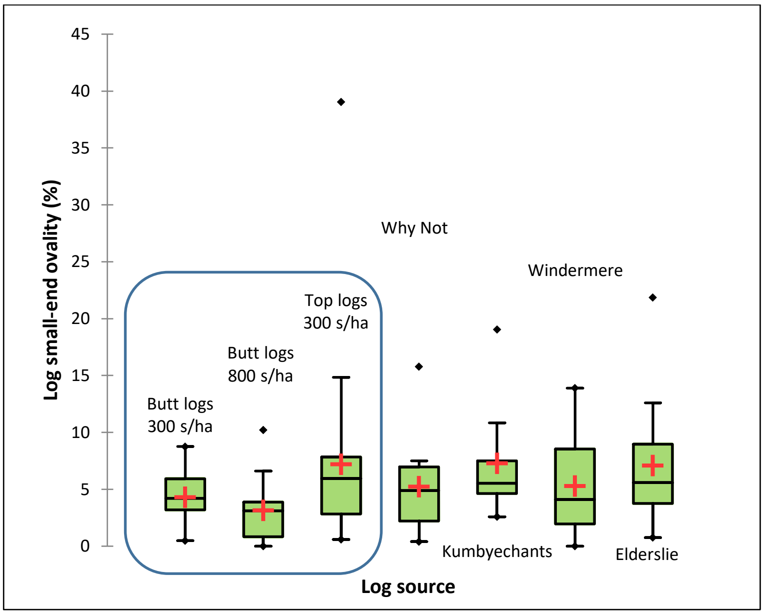

Figure 7.13. Log small-end ovality comparison

Notes: 300 s/ha butt logs *n*=15, 800 s/ha butt logs *n*=16, 300 s/ha top logs *n*=20, Why Not n=13, Kumbyechants n=13, Elderslie n=18, Windermere n=12

Rotary veneer processing and veneer recovery

Table 7.5 presents the dry veneer recovery, gross veneer recovery and net recovery. In order to separate the internal billet imperfections from the billet geometry, the gross recovery is also presented as the percentage of dry veneer volume (rather than log volume).

Table 7.5. Veneer recoveries

Treatment Type	Dry recovery (% of log volume)	Gross recovery (% of log volume)	Gross recovery (% of dry veneer volume)	Net recovery (% of log volume)
300 s/ha butt logs	64.3	57.1	88.7	50.9
800 s/ha butt logs	43.8	32.0	72.9	30.3
300 s/ha top logs	57.6	21.3	37.0	20.4

In addition to Table 7.5, Figure 7.14 shows the recovery of dry veneer and also included is the dry veneer recovery results from the African mahogany logs processed during the earlier project trial (refer to Section 6). As the calculation method for dry veneer recovery doesn't include grading for internal log defects, most of the variation in recovery between the log groups can be explained by the log geometry (diameter and form deviation from a cylindrical column) rather than other factors such as tree age, wood quality or impacts of silviculture (McGavin *et al.* 2014, Section 5).

The billets sourced from the low stocking butt logs provided the highest dry veneer recovery (mean value of 64%) and these logs also provided the least variation. The high stocking butt logs achieved the lowest dry veneer recovery (mean value of 44%) with wide variation. The low stocking top logs had a dry veneer recovery in between the other two groups but had the widest variation. These results can be explained by the interaction between log diameter and sweep, taper and ovality. For example, the top log which recorded the lowest dry veneer recovery (25%) was characterised by high sweep (25 mm/m), high ovality (9%) and moderate taper (21 mm/m). While each of these log characteristics has a negative impact on veneer recovery, the impact is compounded if multiple characteristics are present, especially if the log diameters are small. Other log form factors that can influence dry veneer recovery are stem fluting, hollows etc.

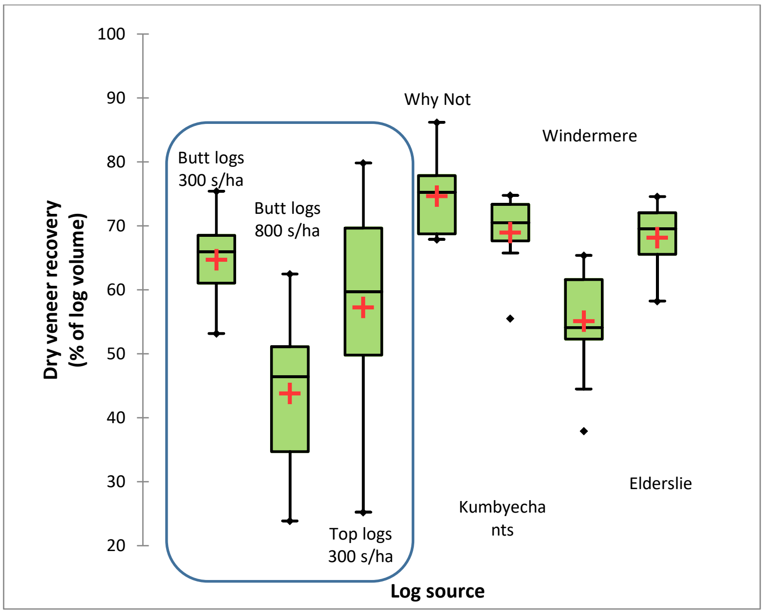

Figure 7.14. Dry veneer recovery

Notes: 300 s/ha butt logs *n*=15, 800 s/ha butt logs *n*=16, 300 s/ha top logs *n*=20, Why Not n=7, Kumbyechants n=7, Elderslie n=6, Windermere n=12)

In addition to Table 7.5, Figure 7.15 shows the of gross veneer recovery and also included is the dry veneer recovery results from the African mahogany logs processed during the earlier project trial (refer to Section 6). The low stocking butt logs yielded a gross veneer recovery of 57% (of log volume) meaning that 89% of the dry veneer volume recovered from this log type achieved D-grade or better. This performance was in line with the results from the earlier project processing trial.

The high stocking butt logs achieved a gross veneer recovery of 32% (of log volume) meaning that 73% of the dry veneer volume recovered from this log type achieved D-grade or better.

While the low stocking top logs achieved a dry veneer recovery of 58%, which was higher than the high stocking butt logs and within range of the low stocking butt logs, all advantage was lost with only 21% of log volume recovered as gross veneer. This represents only 37% of the dry veneer volume achieving D-grade or better confirming that by comparison to the butt logs (both low stocking and high stocking), much of the recovered veneer contained internal log defects that prevented it from meeting the minimum quality necessary to at least meet the D-grade specification.

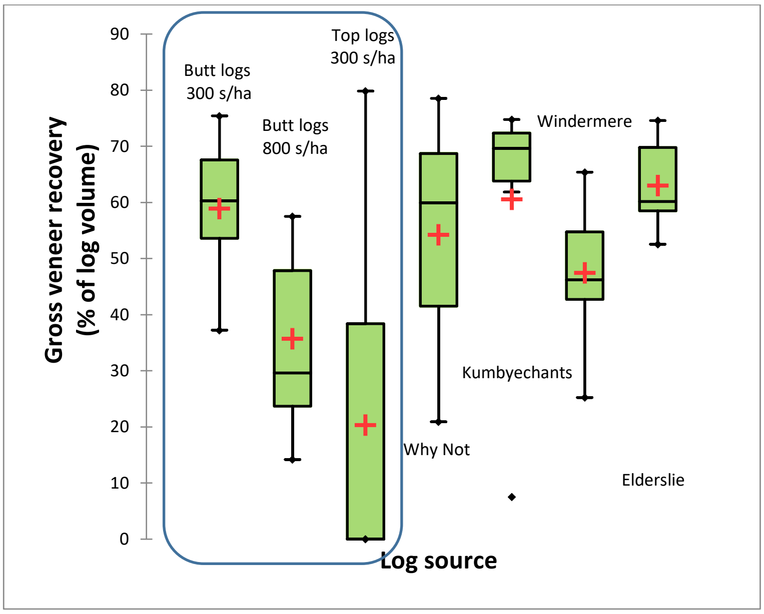

Figure 7.15. Gross veneer recovery

Notes: 300 s/ha butt logs *n*=15, 800 s/ha butt logs *n*=16, 300 s/ha top logs *n*=20, Why Not n=7, Kumbyechants n=7, Elderslie n=6, Windermere n=12)

The net recovery (Table 7.5) presents the percentage of the billet volume which is marketable (veneer which is dried, graded and trimmed to a nominal final product dimension). The low stocking butt logs achieved the highest net recovery of 51% (of log volume), followed by the high stocking butt logs at 30% and the low stocking top logs achieved 20%.

While a detailed analysis would consider many more factors, a simple comparison can be made between the impact of the low stocking and high stocking treatments using the net veneer recovery data. For example, assuming only the butt log (1.3 m) is considered, the mean SEDUB for each treatment type (18.8 cm and 12.9 cm), the theoretical stocking (300 s/ha and 800 s/ha) and the butt log net recovery figures (51% and 30%), the low stocking plantation would yield around 35% more marketable veneer per hectare. This is despite the high stocking treatment producing a higher log volume per hectare. Under this scenario, the higher log volume per hectare advantage is not able to be capitalised on due to the low net veneer recovery by comparison.

If it was assumed that the low stocking planting was also able to yield a top log (mean SEDUB of 14.8 cm) due to the larger diameter trees, while the high stocking plantation could only yield a butt log, the benefit in the low stocking treatment increases to 68% more marketable veneer per hectare.

Further advantage also exists with the low stocking treatment with the higher saleable veneer volume being recovered from a lower number of logs which also decreases processing costs. A more thorough analysis that better considers the merchantability up the tree, includes the compounded cost of conducting the thinning and fertilising treatments etc. would provide a more accurate assessment.

Grade recovery and defect analysis

The grade recovery analysis showed that almost all of recovered veneers failed to make a grade higher than D-grade, the lowest grade quality in accordance with *AS/NZS2269.0:2012* (Table 7.6). No veneers meet the requirements of A-grade and only a very low proportion meet the requirements of B- or C-grade. While D-grade is the lowest visual grade quality for structural veneer, the veneers are suitable for face veneers on non-appearance structural panels as well as the core veneers for most appearance and non-appearance structural panels. The low recovery of higher grade veneers (C-grade and better), which are more suitable for face veneers, would make the commercial production of a standard mix of appearance veneer-based products challenging when only using material from young mahogany thinnings. According to the Engineered Wood Products Association of Australasia (EWPAA, www.ewp.asn.au), the Australian rotary veneer industry requires approximately 30 to 40% of their veneer production to be C-grade or better to enable saleable product manufacture.

Table 7.6. Graded veneer recoveries

	A-grade recovery (% of log volume)	B-grade recovery (% of log volume)	C-grade recovery (% of log volume)	D-grade recovery (% of log volume)	*B-grade recovery (% of net veneer volume)*	*C-grade recovery (% of net veneer volume)*	*D-grade recovery (% of net veneer volume)*
300 s/ha butt logs	-	<1%	<1%	49.6	*1.2*	*1.3*	*97.4*
800 s/ha butt logs	-	-	2.5	27.8	-	*8.5*	*91.5*
300 s/ha top logs	-	<1%	<1%	18.6	*4.5*	*4.4*	*91.1*

Table 7.7 displays the top 5 ranked defects that prevented veneer sheets from achieving a grade higher than D-grade. Veneer compression, surface roughness, grain breakout and unsound knots all featured prominently across all log types. Similarly, Figure 7.16 displays the proportion of veneer that achieved (or was limited to) D-grade when assessed against all individual defects. Note that for this analysis, the grade influence of each defect was undertaken independent of other defects. For example, just over 50% of the gross veneer volume recovered from the low stocking top logs was limited to D-grade due to unsound bark-encased knots and nearly 70% of the same veneer is limited to D-grade due to unsound fractured knots. Some of the veneer contained both defects (and potentially other grade limiting defect types) and for this reason, the information displayed cannot be combined across defects. Doing so will be misleading and may incorrectly result in proportion of volumes greater than 100%.

Table 7.7. Top 5 ranked defects preventing graded veneers from attaining assigned grades higher than D-grade

	Rank				
	1	2	3	4	5
300 s/ha butt logs	Compression (72%)	Roughness (62%)	Grain breakout (44%)	Cumulative defects (25%)	Unsound knots –fractured (25%)
800 s/ha butt logs	Compression (70%)	Roughness (52%)	Unsound knots –fractured (47%)	Grain breakout (43%)	Unsound knots –bark encased (35%)
300 s/ha top logs	Roughness (75%)	Grain breakout (70%)	Unsound knots –fractured (67%)	Compression (62%)	Unsound knots –bark encased (50%)

Notes: Some veneers may be grade limited due to more than one defect.

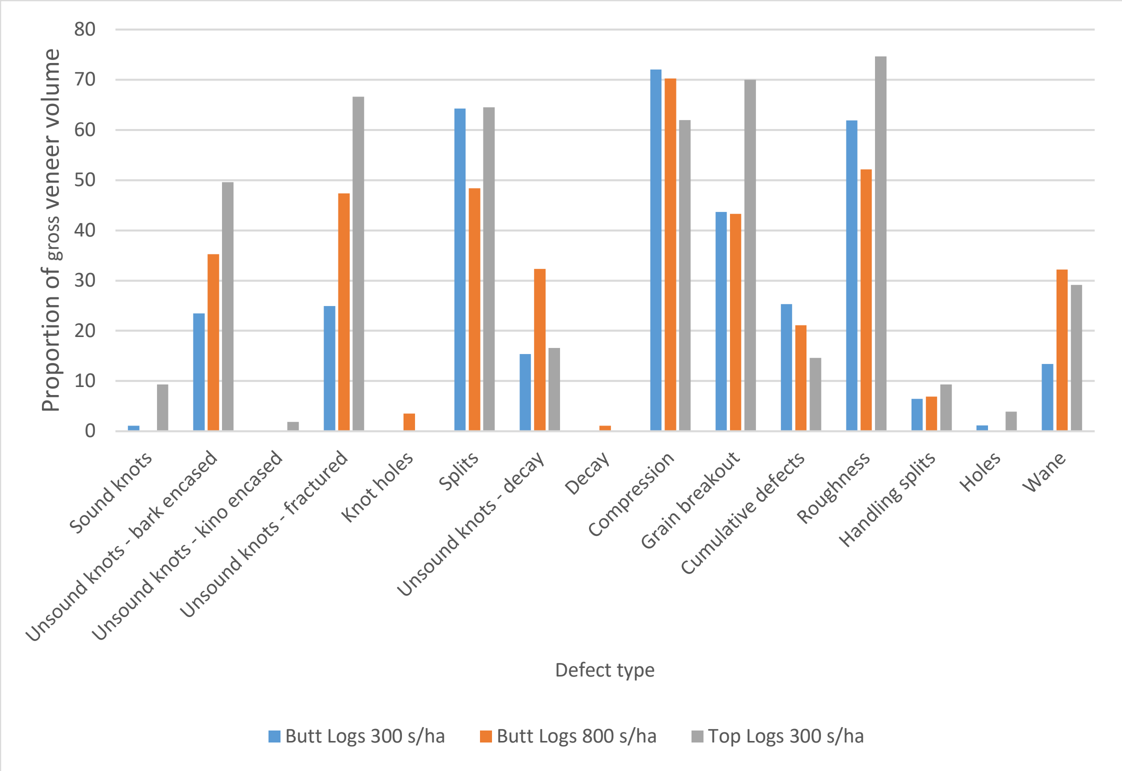

Figure 7.16. The proportion of veneer that achieved D-grade when assessed against individual defects

Notes: Some veneers may be grade limited due to more than one defect.

Veneer compression, as identified in the project's earlier processing study (Section 6), was one of the dominant defects that prevented the majority of veneers from all log types from achieving a veneer grade higher than D-grade. Both low and high stocking butt logs recorded similar results with over 70% of the recovered veneer being limited to D-grade due to veneer compression. The low stocking top logs were slightly less affected however still recorded a very high occurrence of veneer compression (62%).

Veneer compression is evidenced by the lack of sheet flatness and a wavy undulating surface. Veneer sheets containing a high level of compression and waviness can be difficult to dry (e.g. can jam drier systems) and are difficult to store in stable packs. Affected veneer may be unable to be passed through conventional adhesive application equipment or if they are able to be passed through, the adhesive is spread in a very uneven manner leading to poor bonding in the manufactured product. Veneers containing compression also tend to split when the sheets are forced flat during pressing for product manufacture resulting in downgraded and poor quality product. As explained in the previous processing trial report (Section 6), although the veneer may have achieved D-grade, the usability and therefore value of the veneer may be severely compromised by the severity of the compression which is present. The phenomenon causing the compression in the veneer is not well understood and may be influenced by a combination of factors such as genetics, growth cycles, log form, wood structure and processing protocols (e.g. lathe setup, pre-treatment conditions etc.). A focused study to investigate this phenomenon is critical to develop possible management strategies. Addressing this problem before the plantation resource is marketed to the processing sector will optimise the value of the resource.

Just under 10% of the gross veneer volume recovered from the low stocking top logs was limited to D-grade due to the presence of sound knots, compared to very minimal veneer from the butt logs from both the low stocking and high stocking treatments. This result is expected with the top logs being sourced from the part of the tree where branching is common. While the study trees were pruned, some logs were merchandised from above the pruning height and therefore probably contained living branches at the time of harvest. In addition, the four year period between pruning and harvesting would be insufficient to facilitate effective knot occlusion and allow any reasonable volume of knot free wood to be produced. The small amount of knot free wood that may have been produced would probably be lost in the log rounding phase with limited (if any) being recovered into veneer.

Other knot related defects including unsound bark-encased knots and unsound fractured knots showed a similar trend with veneer from low stocking top logs showing a higher presence of these defect types compared to the butt logs from both treatment types. The reasoning for this is the same as described above for sound knots.

Unlike the top logs, the zone of the trees where the butt logs were sourced spent more growing time with fewer or no significant branches and therefore knot-type defects are less than for the top logs. There is the small inner core which has some knot-type defects resulting from branches present in the first 12 months or so of tree growth but these are generally removed early in the growth cycle. Any branches that did not self-prune very early in the growth cycle, would have been removed during the pruning treatment at age 4. The increased growth rate of the low stocking treatment illustrates the benefit of maximising the growth after pruning (self-pruning or pruning treatment) to not only benefit the log diameter which increases recovery potential (see Section 5) but also increases the proportion of veneer that is recovered with minimal knot-type defects.

The veneer recovered from the high stocking butt logs displayed a higher presence of unsound decayed knots compared to the other log types. These trees may not have self-pruned as effectively by comparison to the low stocking trees or possibly the limited growth post-pruning has delayed the opportunity to achieve effective branch occlusion, essentially leaving an open wound exposed and allowing moisture to enter and decay to become established in the branch stub.

Grain breakout and veneer roughness are additional defect types where the proportion of gross veneer volume recovered from the low stocking top logs is more negatively affected than the veneer from the butt logs (70% of veneer limited to D-grade for the top logs versus ~44% for the butt logs). Many factors can influence the severity of veneer surface roughness and grain breakout including resource orientated factors such as grain angle (often associated around knots), log taper, growth stresses, reaction wood etc., as well as process-orientated factors such as lathe setup, billet pre-treatment method and temperature, target veneer thickness, knife sharpness etc. Given the range of factors that potentially influence this defect, there may be opportunities to improve the veneer roughness through intervention, especially through process modification.

There was noticeable variation between the three log groupings with the presence of wane. Thirteen percent of the recovered veneer from the low stocking butt logs was reduced to D-grade due to wane, whereas the veneer from the high stocking butt logs and the low stocking top logs recorded levels around 30%. The variation is directly linked to log diameter with the latter log groupings having similar smaller diameters and similar log characteristics.

Figure 7.12 displays the proportion of veneer that achieved A-grade when assessed against individual defects. Note that for this analysis, the effect of each defect was undertaken independent of other defects. Unlike Figure 7.11 where a high representation of a defect type indicated a barrier to veneer achieving higher grades, a high representation in Figure 7.17 indicates limited negative affect. For example, 100% of the recovered veneer across all the three log types achieved A-grade when assessed for bark pockets, essentially meaning bark pockets didn't result in any veneer being downgraded for this defect type. The analysis shows that defects such as unsound kino-encased knots, knot holes, bark pockets, kino veins, insect tracks, etc. had little or no impact on reducing the grade quality of the recovered veneers.

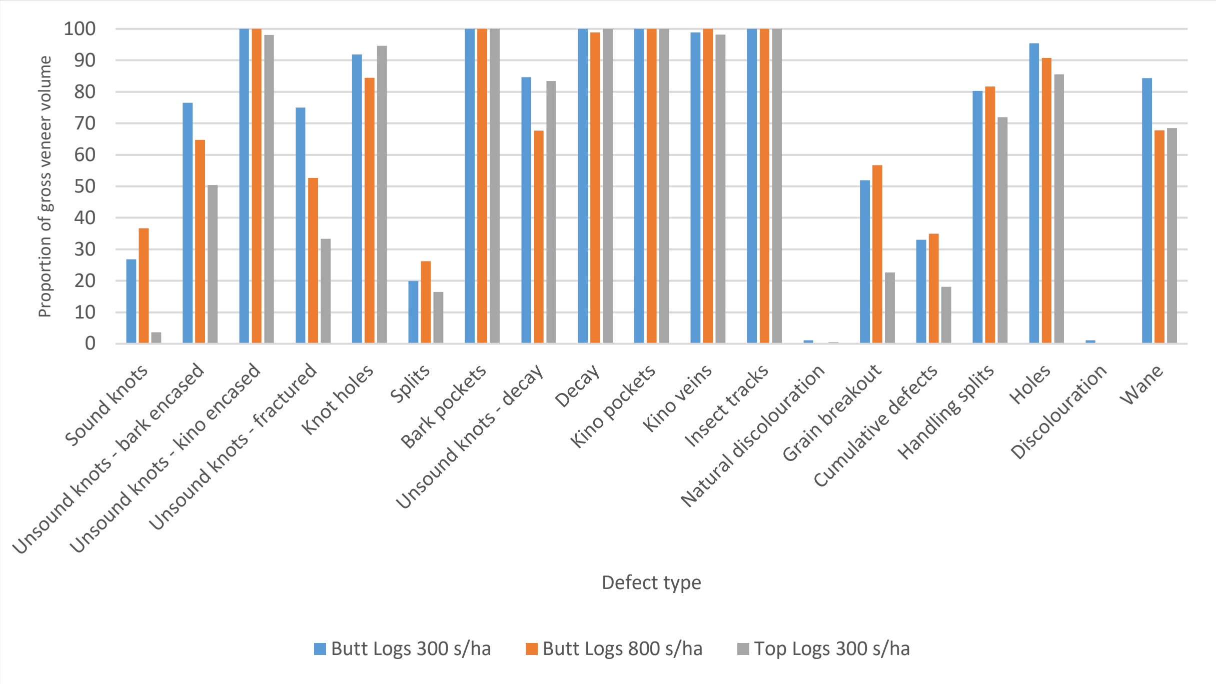

Figure 7.17. The proportion of veneer that achieved A-grade when assessed against individual defects

Notes: Some veneers may be grade limited due to more than one defect.

Conclusions

1. The African mahogany logs used in the study were sourced from a dedicated silviculture trial located in the Douglas Daly, Northern Territory. The silviculture trial was established when the plantation was 4-years-old and included different thinning regimes and fertiliser treatments. The study logs were harvested at age 9 and included representation from plots which were maintained at 800 s/ha and had received a low fertiliser treatment as well as plots which were thinned to 300 s/ha at age 4 and received a high fertiliser treatment. Butt logs were provided from both treatments and top logs were included from the low stocking, high fertiliser treatment. The harvested logs contained log form characteristics such as taper, sweep and ovality at levels above what would be expected from other plantation resources. Increasing log taper, log sweep and ovality all negatively affects, not only the potential product recovery that can be achieved from a resource, but also has significant implications for the financial viability of a commercial operation (e.g. reduces the log price that processors are able to pay, increases cost of production etc.).
2. The low stocking treatment yielded larger diameter butt logs compared with the butt logs from high stocking treatment demonstrating the individual tree growth benefits gained from the reduced between-tree competition. The low stocking butt logs were similar in size to the logs processed during earlier project processing trials which were sourced from several different plantations across Queensland and the Northern Territory.
3. There was a notable difference in log taper between the three log types included in the study with the low stocking butt logs displaying the most log taper compared to the low stocking top logs which contained the least amount of log taper.
4. Log sweep was highest in the high stocking butt logs compared to the low stocking logs (both butt and top logs). It is unclear whether this difference is directly connected to the improved growth as a result of the thinning treatment, or the mean sweep of the plots were improved as a result of the thinning operation (i.e. the thinning operation removed the lower quality, including bendy trees). The mean sweep values for the three logs types was higher than values recorded from the early project trial, however the difference in tree selection strategy may explain this variation.
5. Dry veneer recovery was variable with the low stocking butt logs achieving 64%, high stocking butt logs 44% and low stocking top logs 58%. The latter two log types were also widely variable. These results can be explained by the interaction between log diameter and sweep, taper and ovality.
6. The low stocking butt logs yielded a gross veneer recovery of 57% (of log volume) meaning that 89% of the dry veneer volume recovered from this log type achieved D-grade or better. This performance was in line with the results from the earlier project processing trial. In contrast, the low stocking top logs achieved a dry veneer recovery of 58%, however only 21% of log volume could be recovered as gross veneer. This represents only 37% of the dry veneer volume achieving D-grade or better confirming that by comparison to the butt logs (both low stocking and high stocking), much of the recovered veneer contained internal log defects that prevented it from meeting the minimum quality necessary to at least meet the D-grade specification.
7. A simplistic analysis demonstrated the impact of the low stocking and high stocking treatments using the net veneer recovery data and showed that the low stocking plantation would yield significantly more marketable veneer per hectare, despite the high stocking treatment probably producing a higher log volume per hectare. A more detailed analysis is required to fully quantify the benefits and advantages of targeting larger diameter logs.

8. The veneer grade recovery analysis showed that the majority of the recovered veneer from across the three log types failed to make a grade higher than D-grade, the lowest grade quality in accordance with *AS/NZS 2269.0:2012*. The low recovery of higher grade veneers (C-grade and better), which are more suitable for face veneers, would make the commercial production of a standard mix of appearance veneer-based products challenging when only using young mahogany thinnings. According to the Engineered Wood Products Association of Australasia (EWPAA, www.ewp.asn.au), the Australian rotary veneer industry requires approximately 30 to 40% of their veneer production to be C-grade or better to enable saleable product manufacture.
9. Veneer compression, surface roughness, grain breakout and unsound knots all featured prominently and with similar severity across all log types as defects that limited veneer grade potential. In contrast, defects such as unsound kino-encased knots, knot holes, bark pockets, kino veins, insect tracks, etc. had little or no impact on reducing the grade quality of the recovered veneers. Further studies are critical to understand the veneer compression phenomenon and to allow potential management strategies to be developed.
10. In general, this study provided similar veneer recovery and grade analysis results when compared to the previous processing study reported in Section 6 which included tree sampling from four different African mahogany plantations from across the Northern Territory and north Queensland estate.

Acknowledgements

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The industry research group supported the study through the identification of suitable trees, harvesting and transport of the logs to the DAF Salisbury Research Facility along with providing the plantation history and silvicultural details for the sample sites. This input was provided in the NT by Adeline Armougom, Frank Miller and Chris Oliver from AMA and Rob Tap (Forest Farmer PL).

The DAF research team at the Salisbury Research Facility and in particular Chris Fitzgerald, Xavier Murray, Eric Littee, Rica Minnet and Daniel Field are acknowledged for their contribution to the log, process and grade quality components of the project. The support provided by DAF through the provision of the unique facilitates located at the Salisbury Research Facility is acknowledged as critical to facilitate processing and product studies of this nature.

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Additional publications

Venn, T. J.,McGavin, R. L., Ergashev, A. (2020) Accommodating log dimensions and geometry in log procurement decisions for spinldeless rotary veneer production. BioResources 15(2): 2385-2411,

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Appendix 1. Market scoping of domestic and international face and feature grade hardwoods

Final Report

AFRICAN MAHOGANY AUSTRALIA

MARKET SCOPING OF DOMESTIC AND INTERNATIONAL FACE AND FEATURE GRADE HARDWOODS

AUX000292 – 22-June-2020

MARGULES GROOME

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ABBREVIATIONS LIST

-	Minus
%	Percent
&	and
$	dollar
%/a	Percent per annum
'000	thousand
/a	Per annum
AC	Age class
APAC	Asia-Pacific
CAGR	Compound Annual Growth Rate
CHP	Combined Heat and Power
CIF	Cost, insurance and freight (to destination port)
cm	Centimetre
dbh	Diameter at Breast Height
E. , euca	Eucalyptus
EU	European Union
EWP	Engineered Wood Products
EXP	Export
FAO	Food & Agriculture Organization of the United Nations
fc	Forecast
FDT	Forest Development Trust
FTE	Full time equivalent
GDP	Gross Domestic Product
GIS	Geographic information system
Ha	Hectares
HWD	Hardwood
IT	Information Technology
IHS GTA	HIS Markit Global Trade Atlas
IMP	Imports
JV	Joint Venture
k	Thousand
km	Kilometre
m	Metres
m^3	Cubic metres
m^3/a	Cubic metres per annum
m^3/ha	Cubic metres per hectare
MGC	Margules Groome Consulting
mm	Millimetres
NF	Natural Forest
No.	Number
PLY	Plywood
spp.	Species
SWD	Softwood
Timber	Sawnwood
UN Comtrade	United Nations COMTRADE
US	United States of America
USD	United States dollar
Vs	Versus
WP	Wood products
yr.	Year

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MARKET SCOPING STUDY- PROJECT BACKGROUND

African Mahogany Australia (AMA) believes an improved understanding of the commercialisation potential of the African mahogany resource in Australia and wider APAC region will allow for planning for value optimisation

AMA requested an independent assessment of the Australian high-end value-added wood products market to determine potential opportunities for plantation grown African mahogany wood. Australia and key APAC export markets are of interest. The scope of this study should include:

- Australian high-value hardwood timber products, market review / trends (high value, niche products markets) – to understand market dynamics (current situation and future potential)
- A comparison between the African mahogany logs against the direct competing species
- Potential for local processing of the AMA logs
- *Main hardwood species imported in Australia and their uses / major importers & distributors & prices (where available) / major hardwood value adding processors*
- *Marketing options for the African mahogany timber for high-end value products*

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HWD/TROPICAL HWD LOG PRODUCTION

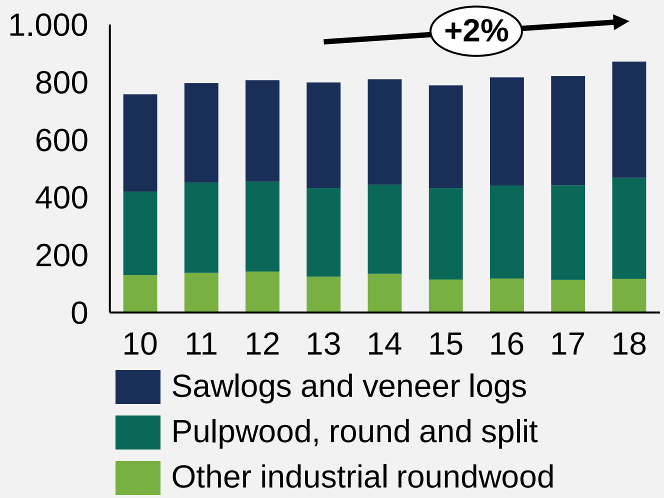
MARGULES GROOME

While the global production of HWD logs is showing only marginal growth, the prospects for tropical logs in specific are worse

HWD Log Production

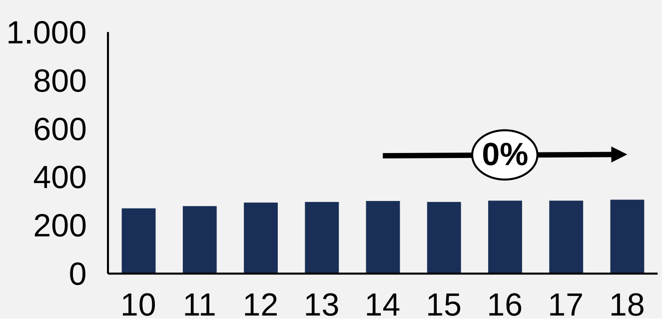
Global HWD Log Production (FAO)

Millions m^3/year



Global HWD Tropical Log Production (ITTO)

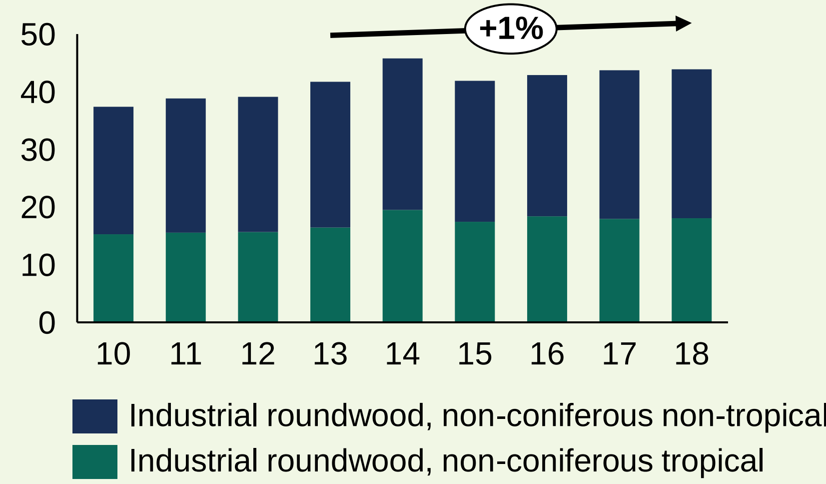
Millions m^3/year



HWD Log Trade

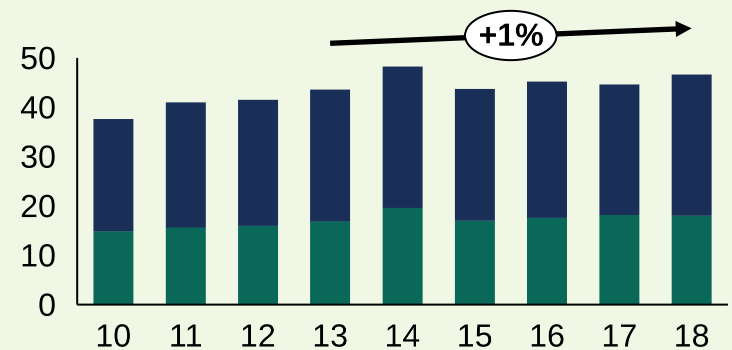
Global HWD Log Exports (FAO)

Millions m^3/year



Global HWD Log Imports (FAO)

Millions m^3/year



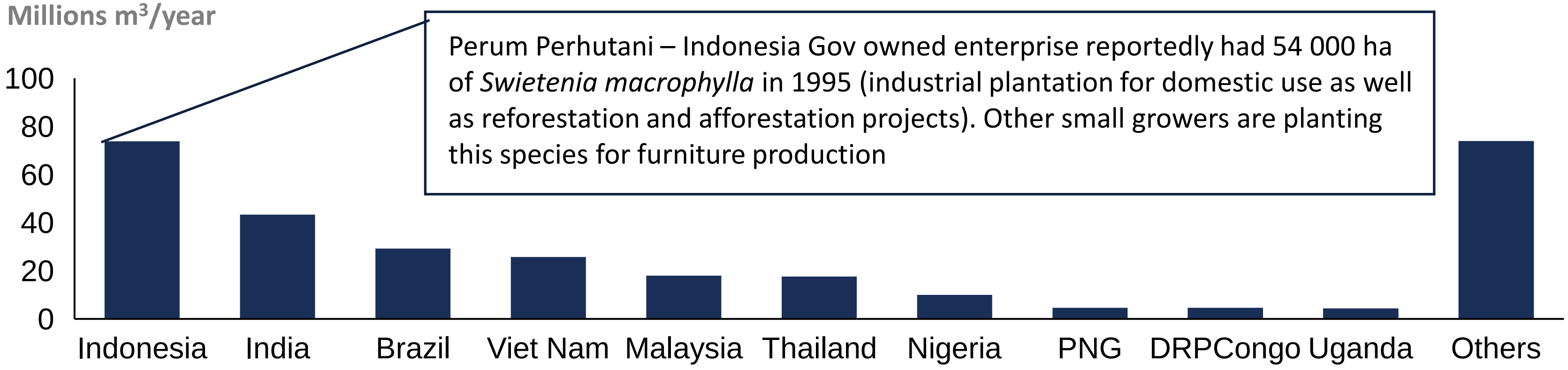
Source: FAO, ITTO, Margules Groome

MAIN TROPICAL LOG PRODUCERS & MARKETS

MARGULES GROOME

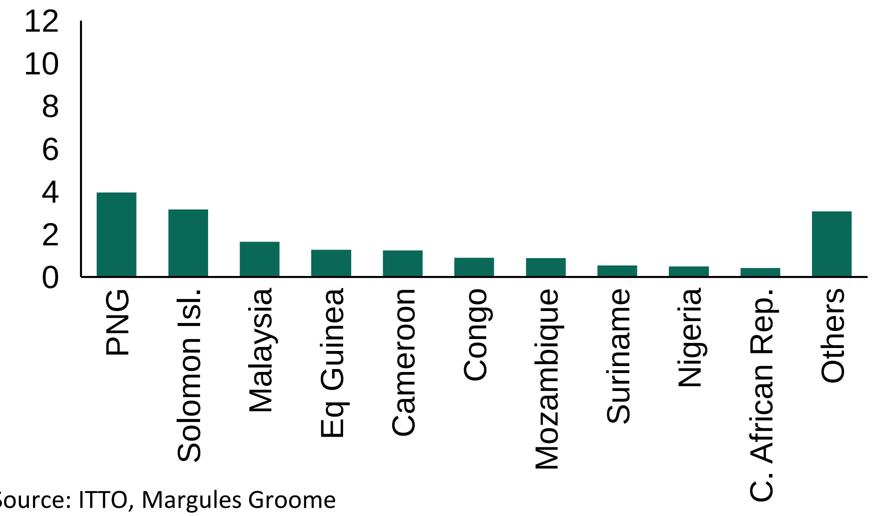
The largest volume HWD producers are focused on the pulp & paper industry, while tropical HWD logs are produced by ~10 countries with questionable future supply availability

Main HWD Logs Producers (ITTO), 2018
Millions m³/year

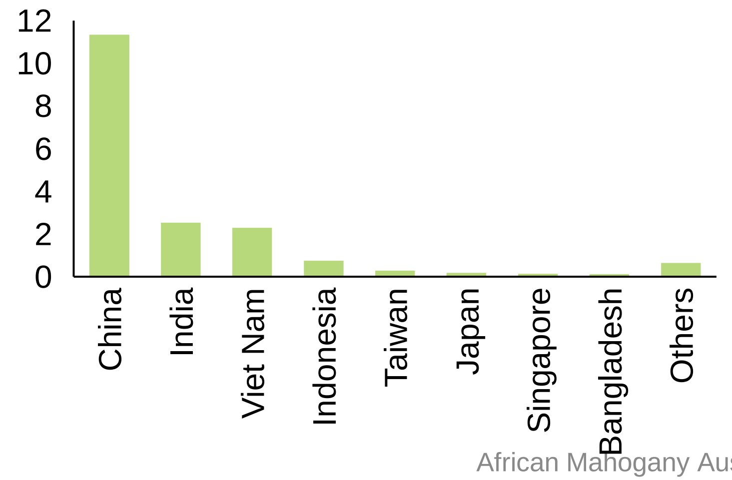


Perum Perhutani – Indonesia Gov owned enterprise reportedly had 54 000 ha of *Swietenia macrophylla* in 1995 (industrial plantation for domestic use as well as reforestation and afforestation projects). Other small growers are planting this species for furniture production

Main HWD Tropical Logs Exporters (ITTO, 2018)
Millions m³/year



Main HWD Tropical Logs Importers (ITTO), 2018
Millions m³/year

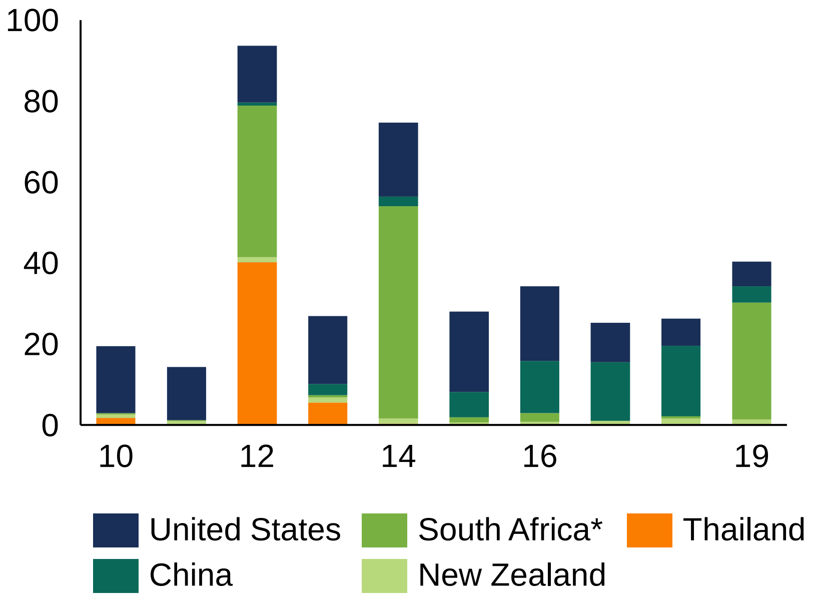


Source: ITTO, Margules Groome

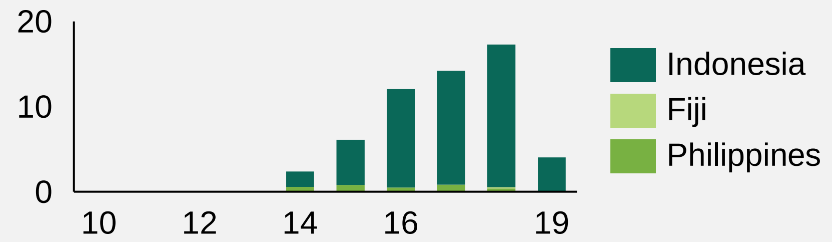
MAHOGANY TIMBER IMPORTS – TARGET COUNTRIES

China and US are the main destination for mahogany logs; Australia imports small volumes of mahogany logs only, with its onerous certification requirements probably being the main reason

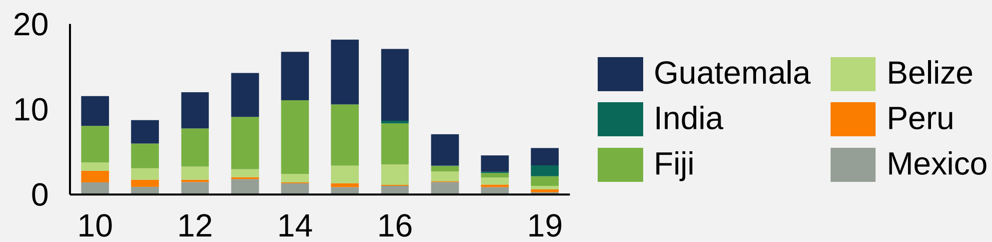
Global Main Mahogany Timber Importers, ‘000 m³/year



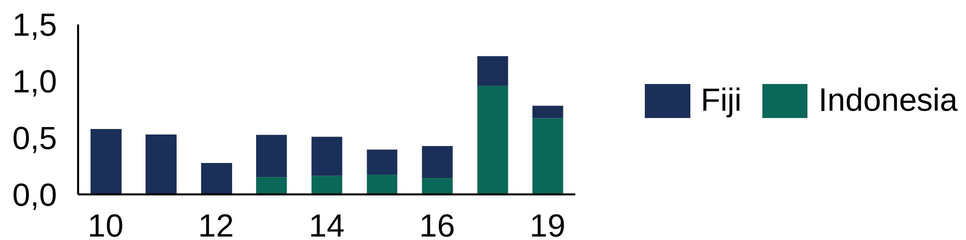
China Mahogany Timber Imports, ‘000 m³/year



US Mahogany Timber Imports, ‘000 m³/year



Australia Mahogany Timber Imports, ‘000 m³/year



Note: Potential South Africa imports reporting issue might exist

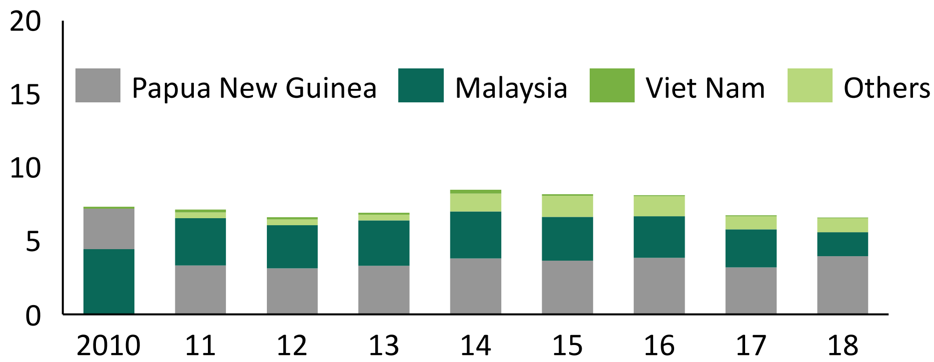
Source: GTA, Margules Groome

APAC REGION TROPICAL HWD LOG TRADE

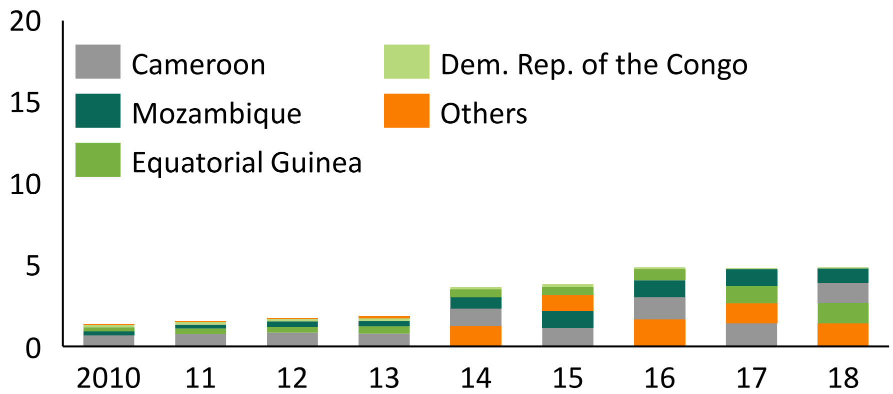
MARGULES GROOME

Growth in APAC wood-based manufacturing will be impeded by limited availability of suitable fibre: declining native tropical HWD and generally low productivity tropical HWD plantations. Demand deficits continues to be met by South American and African exports

APAC Major Tropical HWD Logs Exporters (Millions m³/year)

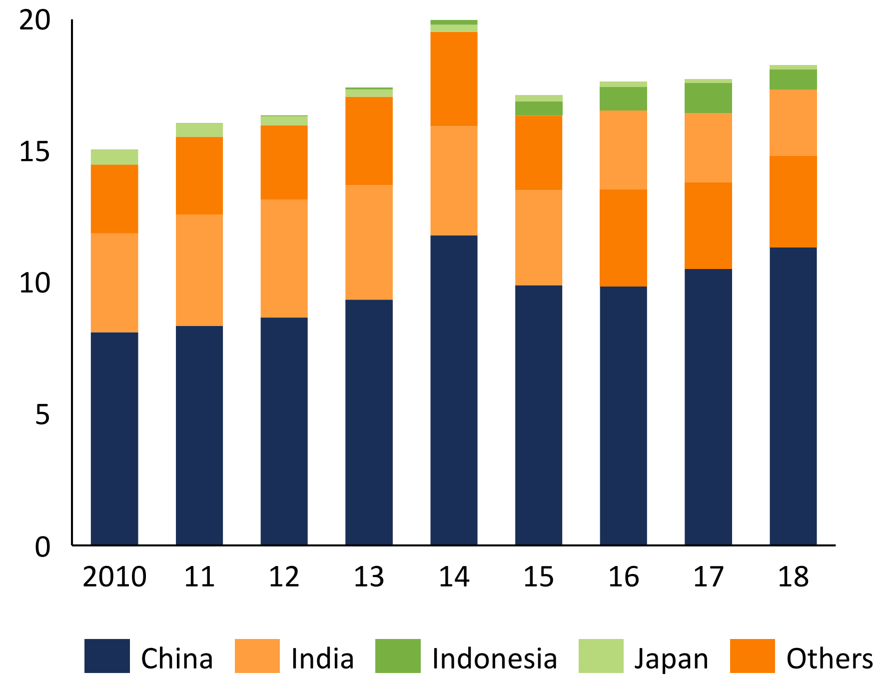


Non-APAC Major Tropical HWD Logs Exporters (Millions m³/year)



Source: ITTO, Margules Groome

APAC Major Tropical HWD Logs Importers (Millions m³/year)

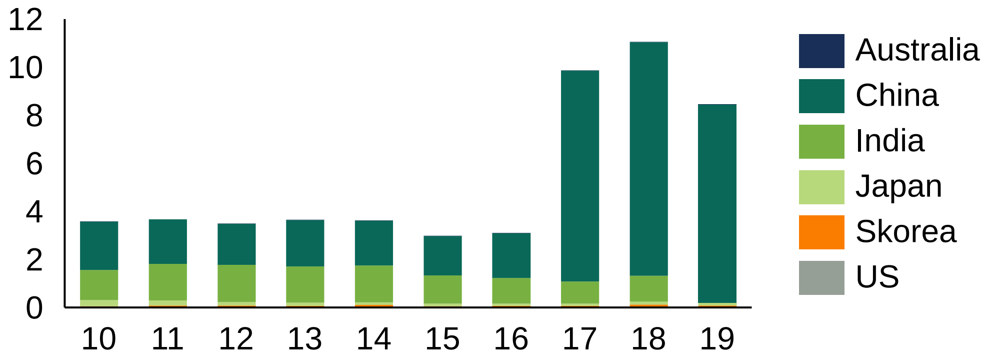


SPECIALITY TROPICAL LOGS TRADE

Beside timber availability, particular timber species trade is driven by certification, political agendas and consumer preference trends

AMA Target Markets "Other Tropical - HS440349" Log Imports

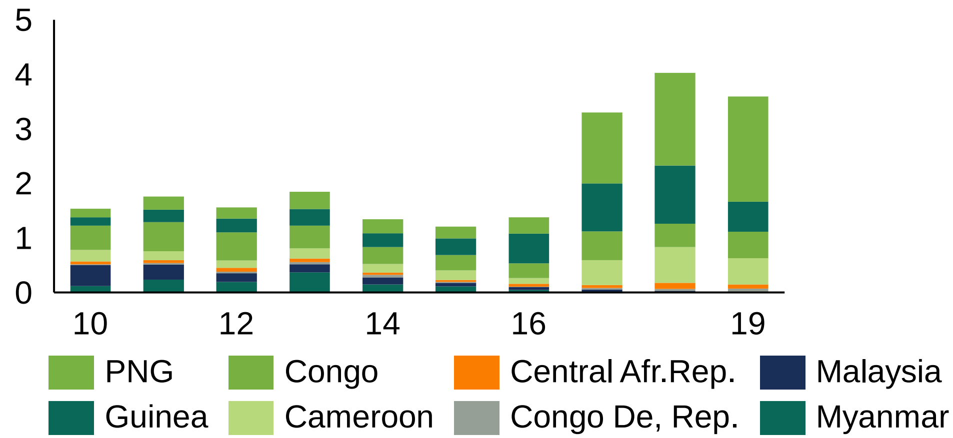
Millions m³/year



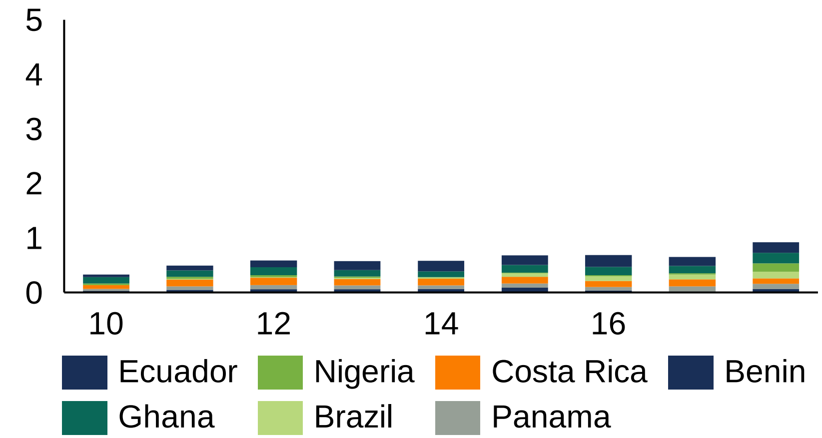
TROPICAL HWD LOGS IMPORTS – TARGET COUNTRIES

Pacific Islands tropical HWD exporters are the main source for the Asian importers, while African and South American exports are reaching India as well

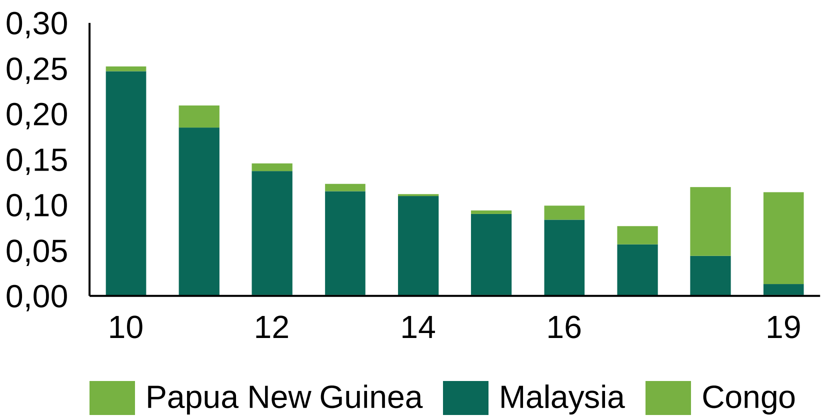
China imports, Millions m³/year



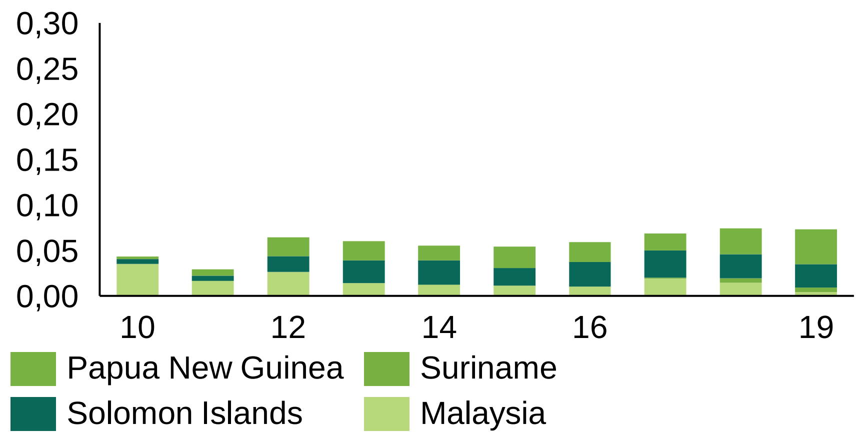
India Imports, Millions m³/year



Japan Imports, Millions m³/year



SKorea Imports, Millions m³/year



Source: GTA, Margules Groome

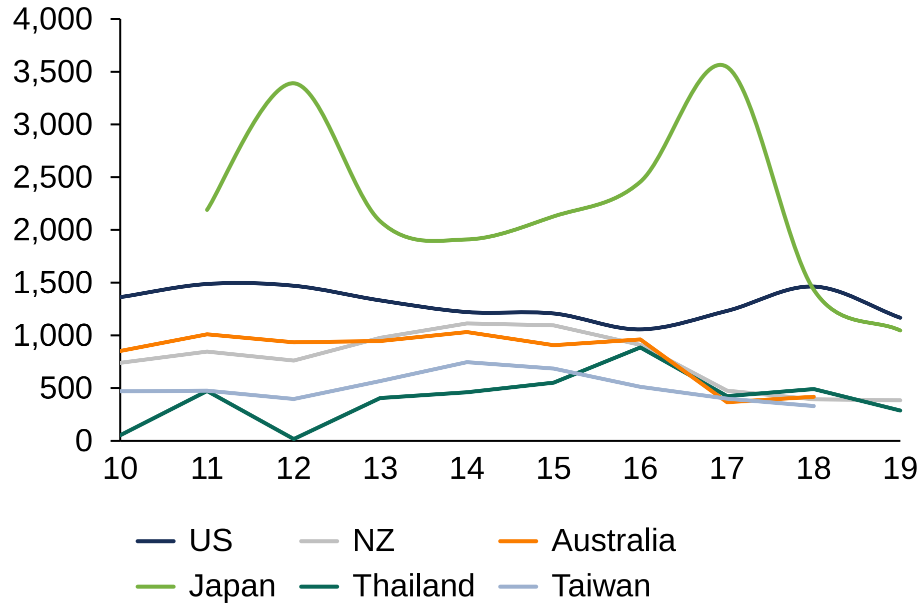
TROPICAL LOG AND WP PRICES HISTORICAL DEVELOPMENTS

- Historical log prices for Central African countries have been reported as relatively stable on the basis of relatively stable demand for high quality HWD furniture in Asia, Europe and N America. Over past ~18 months furniture exports to the US has declined due to the impact of trade sanctions.
- Non-transparent export/import volume and pricing reporting frustrates trade analysis (for example, *Teak is mostly reported as a wide price range – it might have been the case that price fluctuations occurred however they are not easy to detect*)
- In the past 2-3 years forest and/or chain of custody certification requirements have increased as European and N American markets shifted significantly towards sourcing sustainable tropical logs; this development diminished the availability of tropical logs to these markets but prices remained stable; Margules Groome suspects this is due to a shift of exports to the Asian markets were certification requirements are less (*however, this situation appears to be slowly changing in China due to new policies*)
- Illegal timber harvesting remains a problem occurring in various exporting countries – both in Africa and Oceania – resulting in lack of transparency of volume and price
- African Government's ever changing policies and priorities, for example shifts from controlled harvesting to temporarily logging and/or export bans in support of their domestic processing makes the prediction of the availability of tropical logs and prices problematic, still this does not appear to affect prices
- Recent months saw dramatically challenged markets due to the Covid-19 restrictions that affected demand and transportation and resulted in stagnation of major global processing centres/countries – with effects likely to continue for the next 12-24 months. Fordaq reports China Q1 2020 furniture exports dropped by 84% y-o-y.
- Borders closures are now impacting tropical timber movements and exports are on a downward trend – further price movements likely to occur

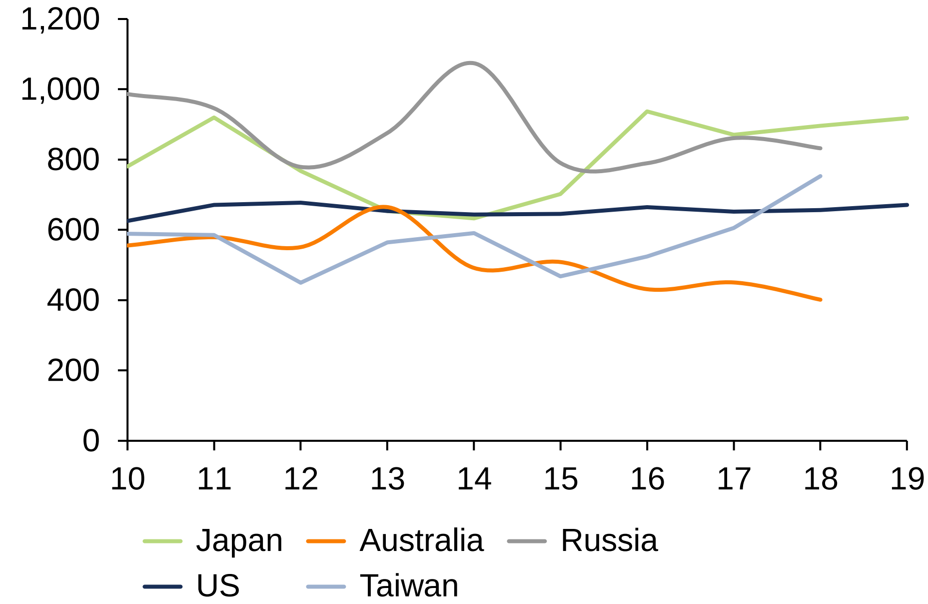
TROPICAL LOG UNIT PRICE (i)

Historically relative flat mahogany log import prices have been on downward trend in 2018-19; Japan as a higher paying country demonstrated a stronger log price decline mostly due to the availability of tightly specified log quality requirements

Mahogany (HS440721) Imports, Unit Value,
USD /m³



Other Tropical (HS440722) Imports, Unit Value,
USD /m³

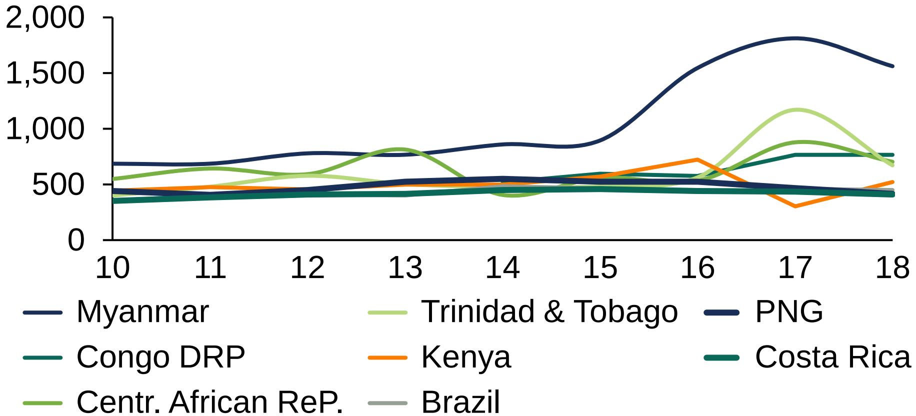


Source: GTA, Margules Groome

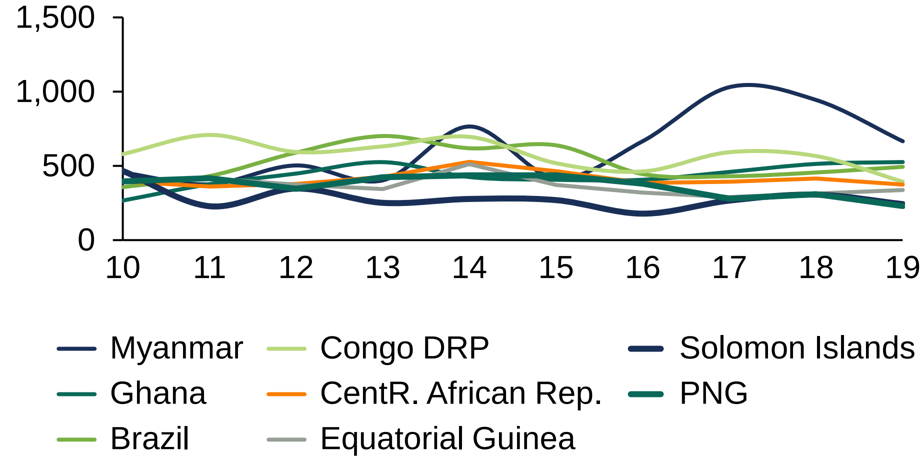
TROPICAL LOG UNIT PRICE (ii)

A similar trend observed across Indian & Japanese markets with relatively flat unit prices reported for Asian and Oceania log exporters and more dynamic price range for African exporters – probably related to log availability and shift in regional forest policies

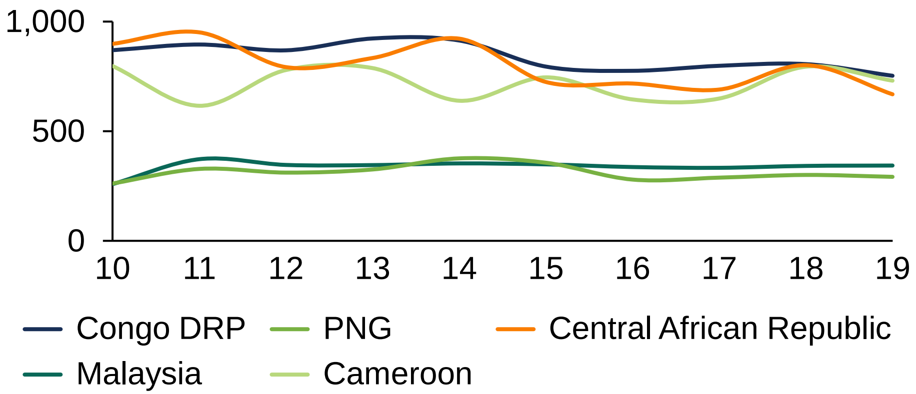
India Other Tropical (HS440349) Imports, Unit Value, USD /m³



China Other Tropical (HS440349) Imports, Unit Value, USD /m³



Japan Other Tropical (HS440349) Imports, Unit Value, USD /m³

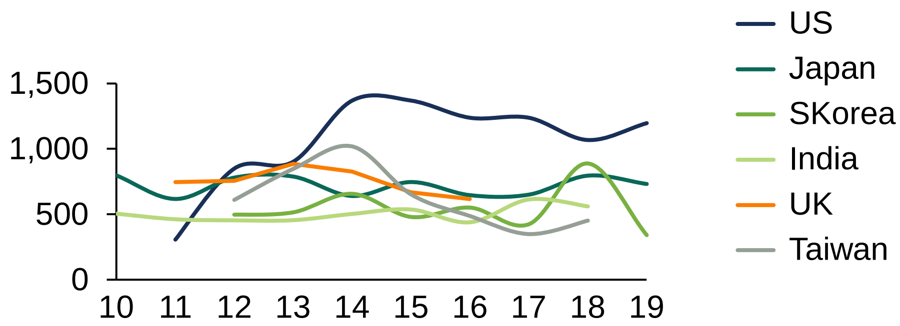


Source: GTA, Margules Groome

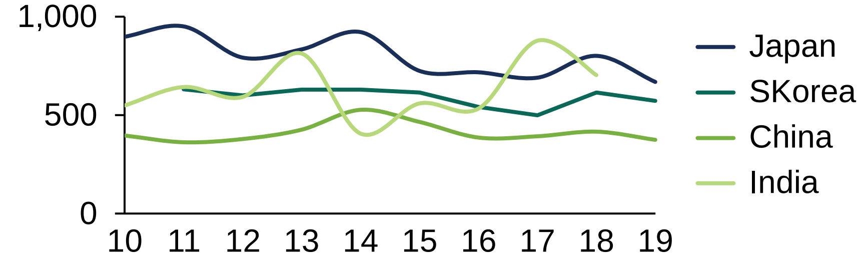
AFRICA TROPICAL LOG EXPORTS UNIT PRICE

An apparent slowing Chinese furniture manufacturing sector demand pushed African log imports and prices to a downward trend in the last ~18 months due the US trade sanctions against China. Some offset through increased European sales but the latter is has a more competitive furniture market

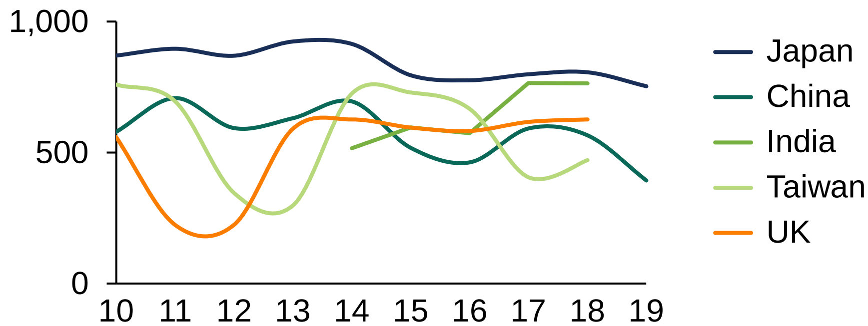
Cameroon Tropical Exports , Unit Value,
USD /m³



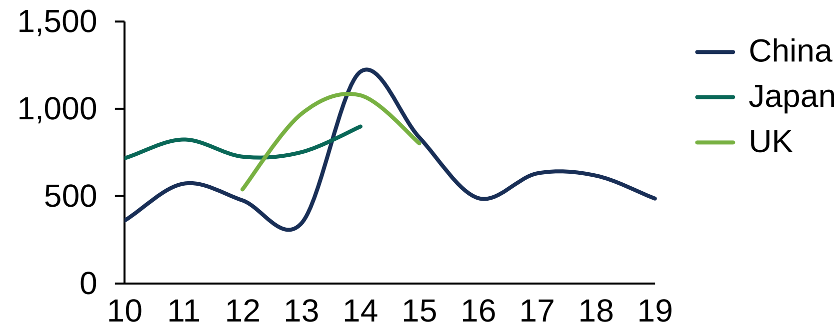
Central African Rep. Tropical Exports , Unit Value,
USD /m³



Congo DRP Tropical Exports , Unit Value,
USD /m³



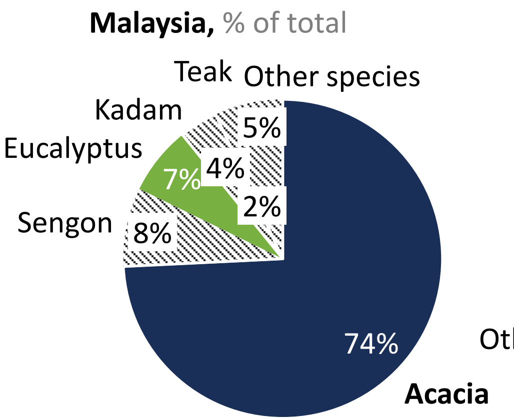
Gabon Tropical Exports , Unit Value, USD
/m³

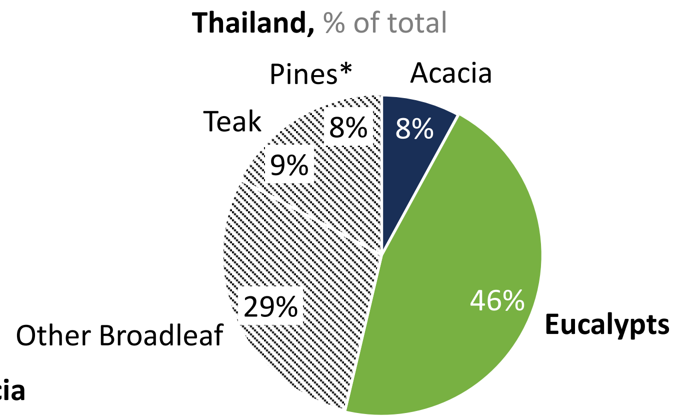


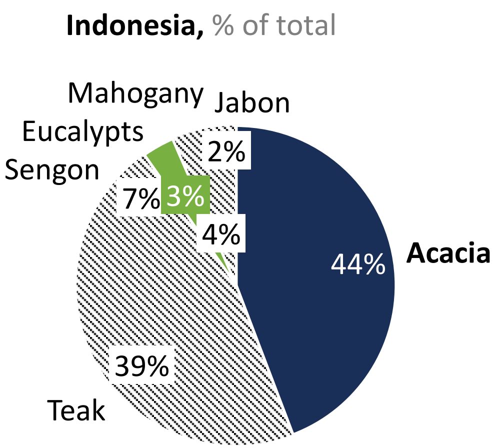
Source: GTA, Margules Groome

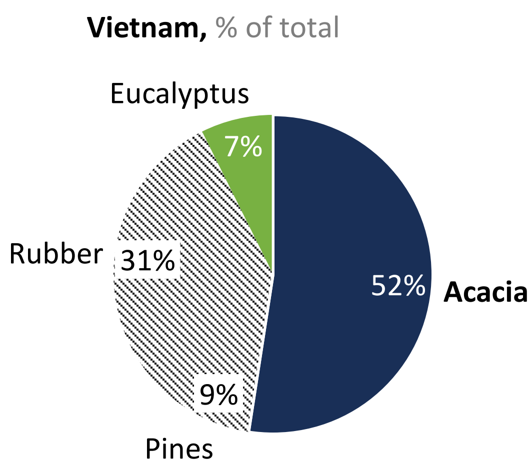
SE ASIA PLANTATION DEVELOPMENT – CASE STUDY

Most HWD plantations in APAC have been established for pulp & paper production and/or woodchips exports; smaller volumes are directed towards veneer, PB/MDF production









Source: FAO, Margules Groome   * in protected forests

Malaysia – 0.48 mil ha

- Acacia & Eucalyptus originally destined mainly for pulp & paper production; 7-8 years rotations
- Largest plantation owner is Sarawak Planted Forests

Thailand – 2.55 mil ha

- Eucalyptus camaldulensis planted mainly for pulp & paper production; 4-6 years rotations

Indonesia – 3.5 mil ha

- Acacia & Eucalyptus spp. destined mainly for pulp & paper production; 5-7 years rotations. Smallholder veneer plantations on Java island

Vietnam – 2.85 mil ha

- *Acacia mangium* is the dominant plantation species mainly destined for woodchips /pellet exports; 5-10 years rotations

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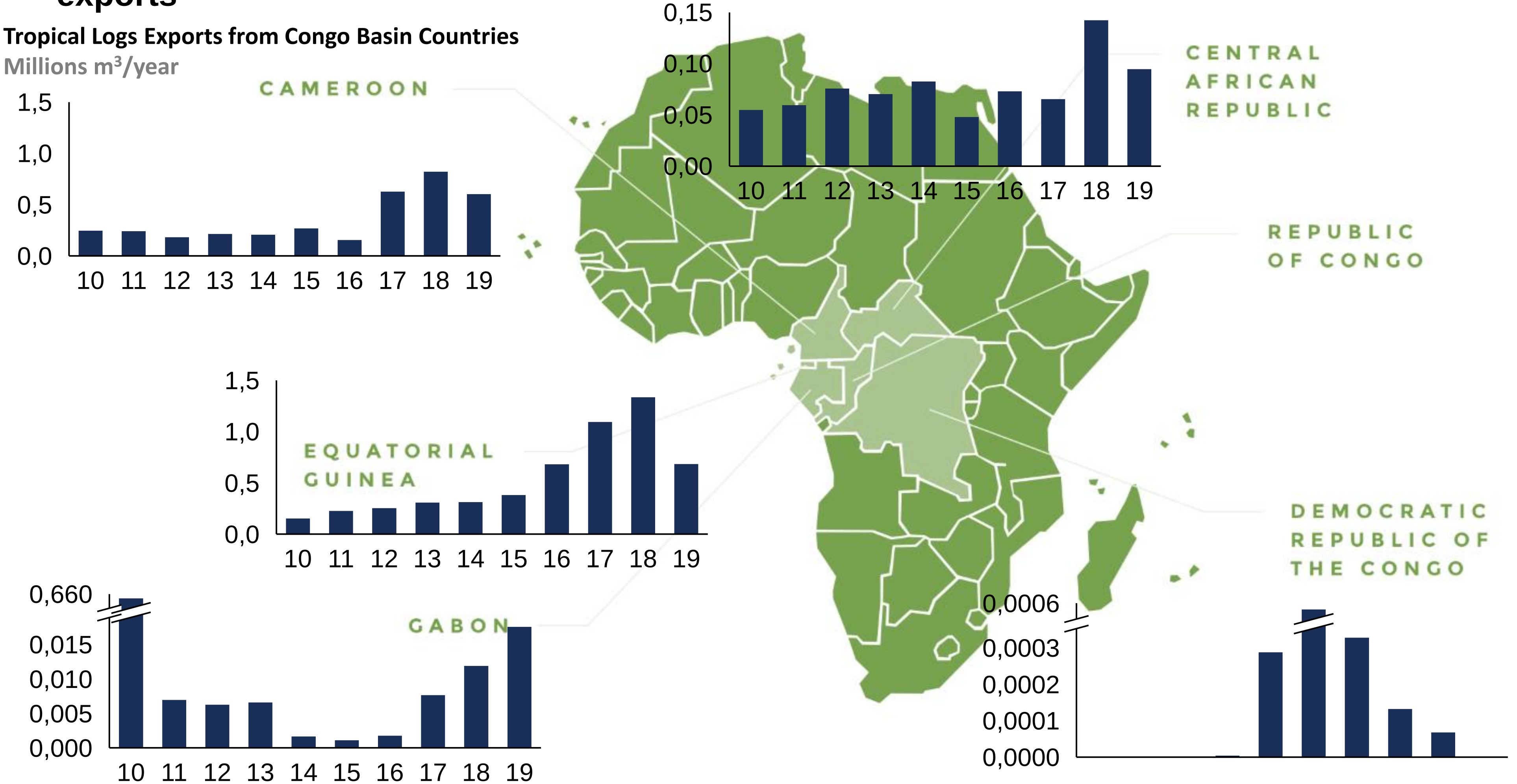
CONGO BASIN COUNTRIES – TROPICAL LOG EXPORTS

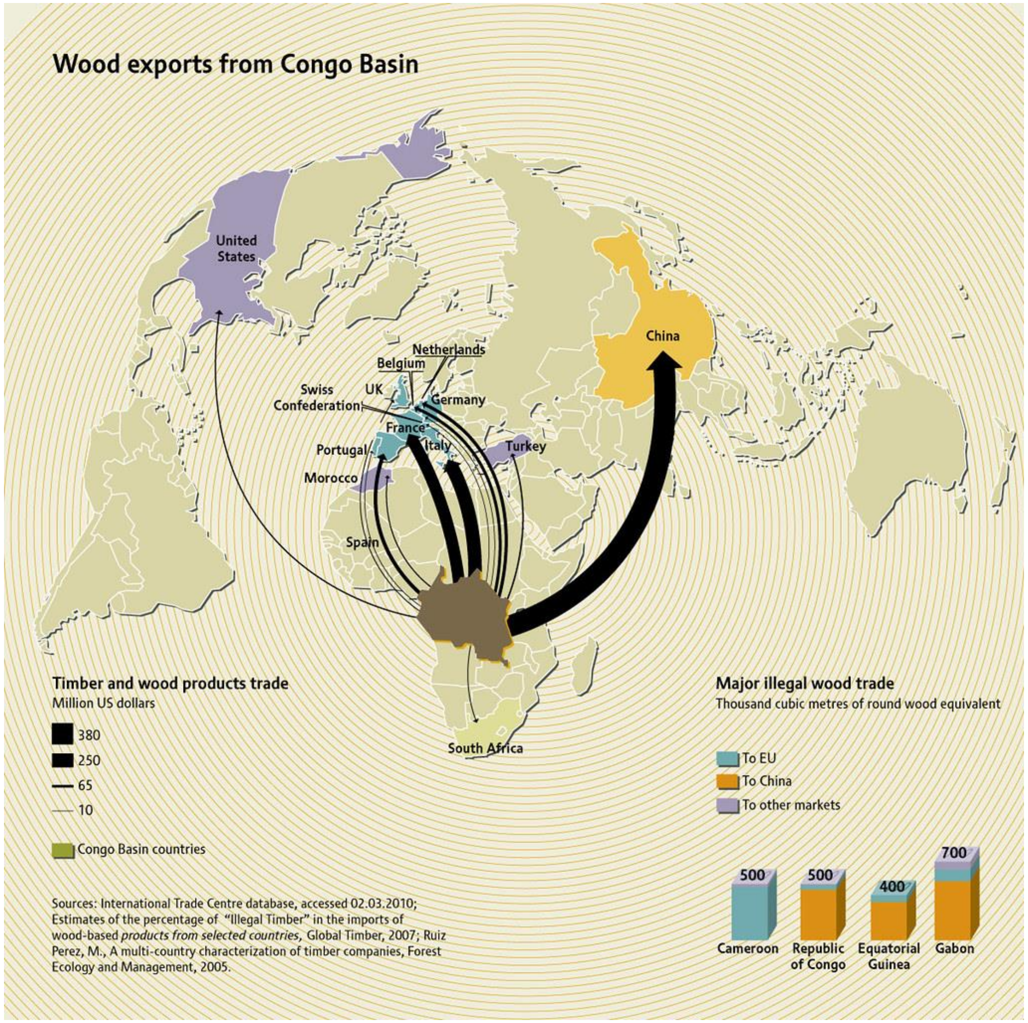
In 2019, more than 1.8 million m³ of tropical logs were exported from the Congo Basin countries to Europe, China and US; recent export restrictions, BREXIT effects, as well as changes on EU consumer preference and illegal logging legislation resulted in decreased exports

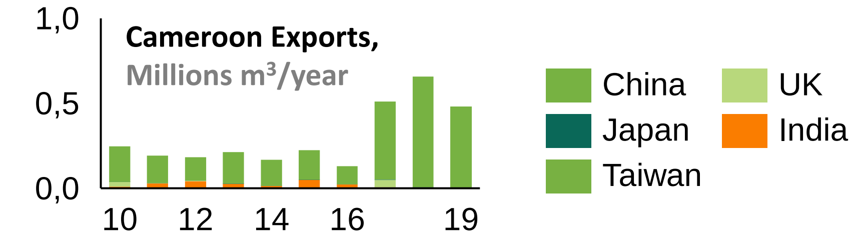


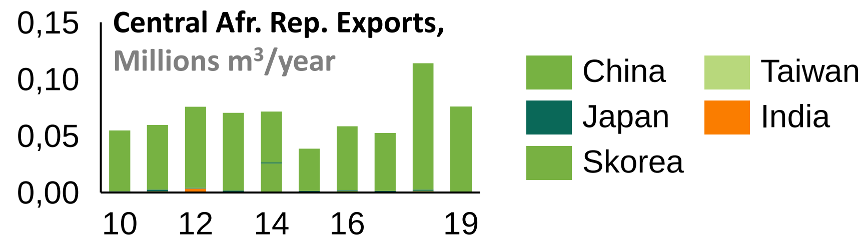
Source: GTA, Margules Groome

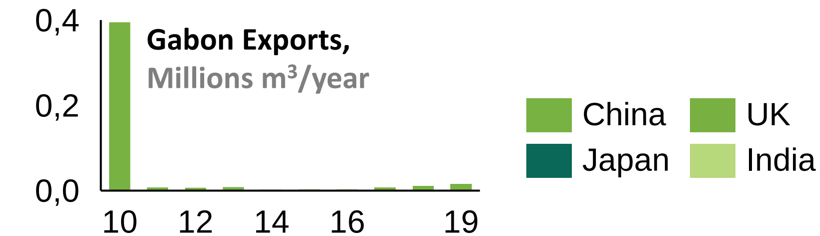
TROPICAL HWD LOGS EXPORTS – CONGO BASIN

China, India and Japan continue to be the main drivers of the HWD logs exports from the Congo basin







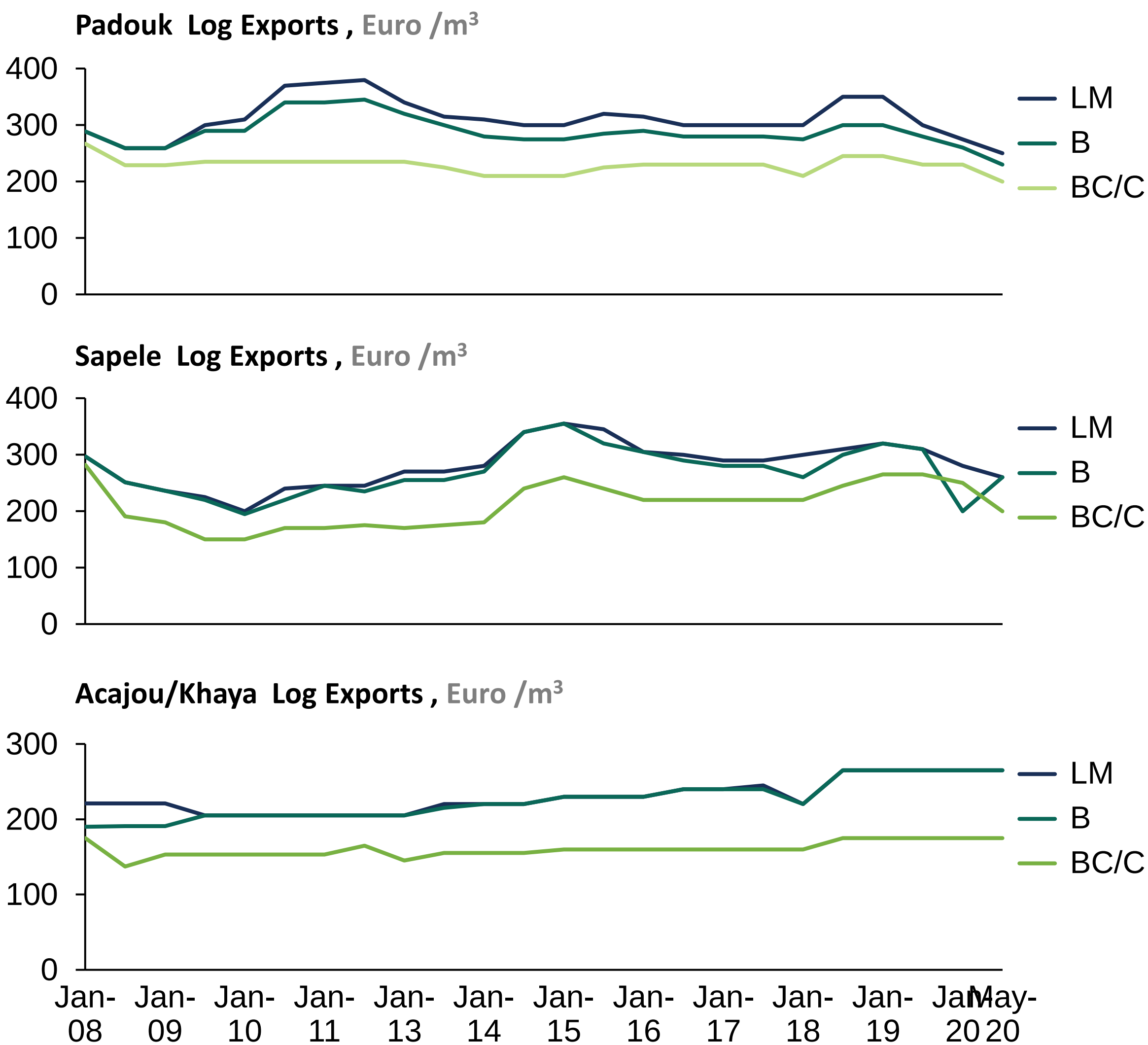


Source: https://www.grida.no/resources/8008, Margules Groome

WEST AFRICAN LOG EXPORT PRICES TO ASIA

MARGULES GROOME

Tropical species identified as potential direct competitors to AMA log resource are reported with relatively flat prices, however on downward trends in the last 18 months



Source: ITTO, Margules Groome

Margules Groome interviewed Chinese trades for their views on **reasons for historical flat prices**:

Demand:
Imported species like Sapelli is used for furniture, interior decorating and flooring. Not considered as expensive or scarce species. Many other species are direct competitors or substitutions. Therefore, the prices are generally steady as consumers can easily switch species if the prices of certain species soar. However, demand for valuable species e.g. Kevazingo, Burma padauk is still growing due to the instability of supply and scarcity.

Supply:
There is no perceived shortage or supply concerns for African logs

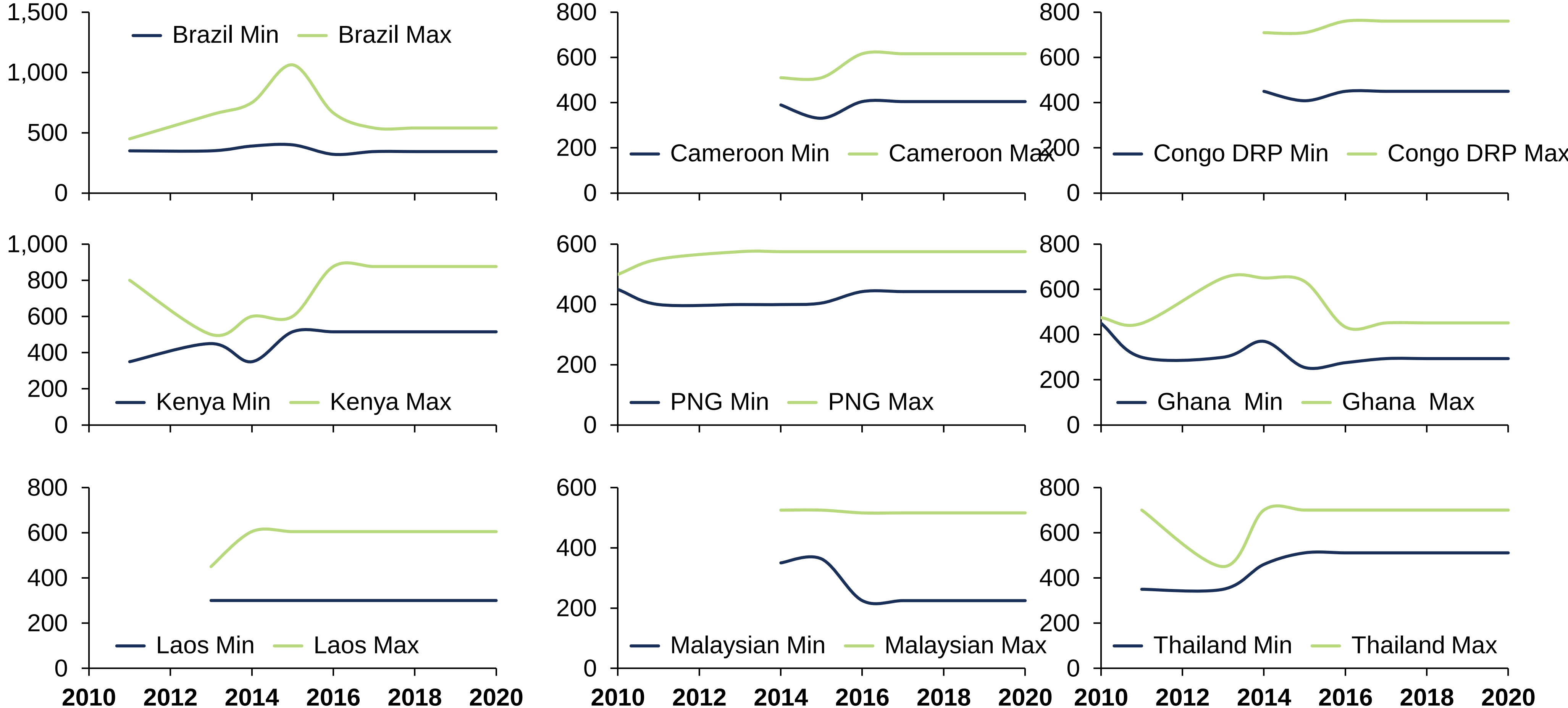
Consumerism:
There are many commercial tropical species on the market from different suppliers including PNG, Africa, South America, Southeast Asia, etc. Compared to the softwood, tropical log species are more complex. Most ordinary consumers are ignorant. Therefore, customer stickiness to these species is exceptionally low. They can easily switch between species. However, the number of people who are capable of distinguishing and appreciating tropical hardwood logs is growing slowly, particularly for those log species of high value. In the long run, the demand will continue to grow.

INDIA TEAK LOG PRICES (RANGE:MIN/MAX)

MARGULES GROOME

Historically, Teak prices fluctuated until 2016; since then less transparent reporting being constant Min and Max values over the last 5 year to May 2020

India Teak Imports USD /m^3, C&F



Source: ITTO, Margules Groome, **Reported in August 2010-2029, May 2020)**

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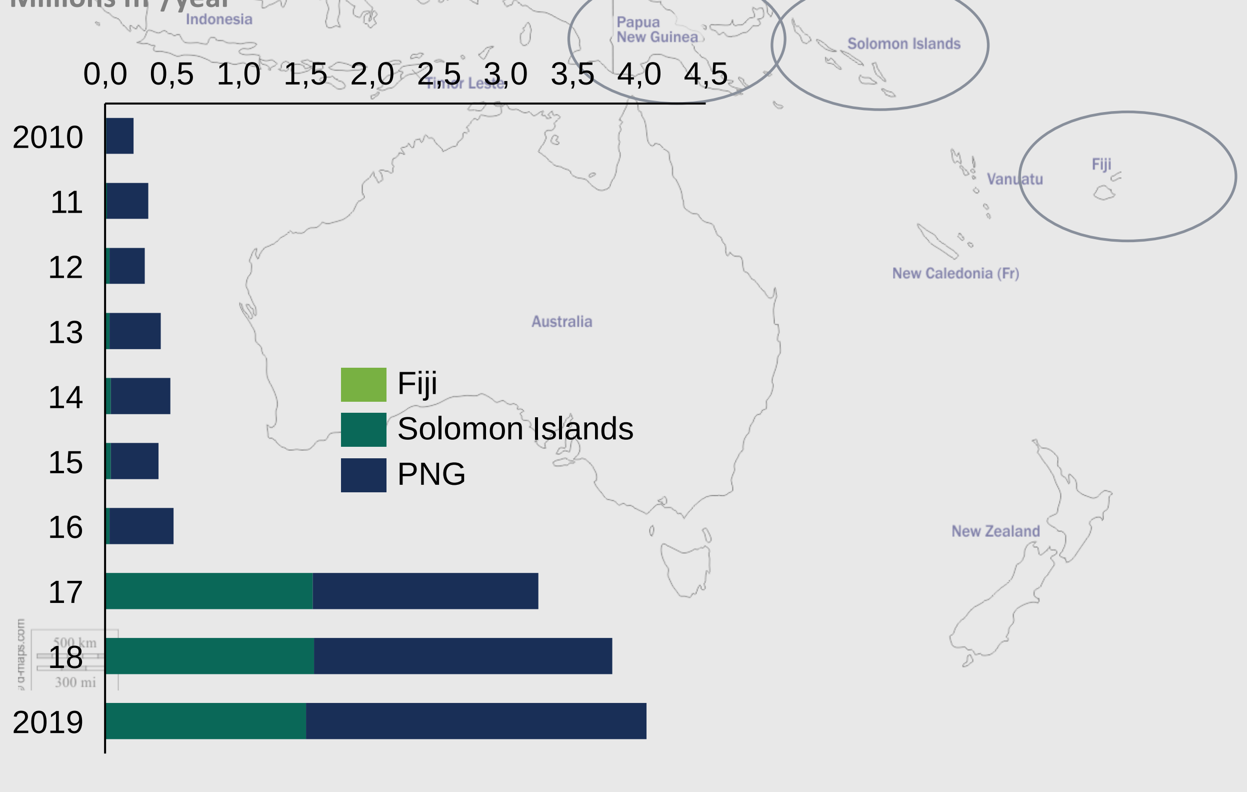
OCEANIA MAIN TROPICAL HWD LOG EXPORTERS

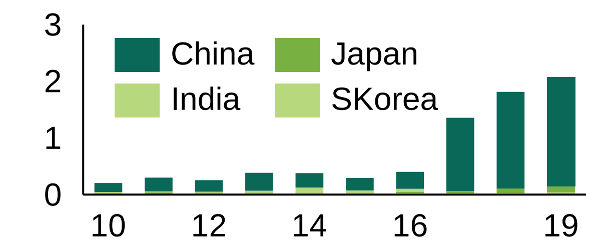
MARGULES GROOME

PNG* continue to be the main tropical HWD logs exporters however its exports continue to be suspected by illegal logging practices

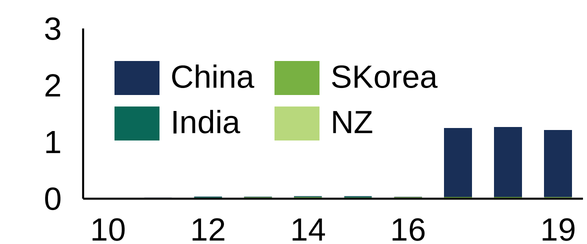
Tropical Logs Exports from Pacific Islands Countries
Millions m³/year



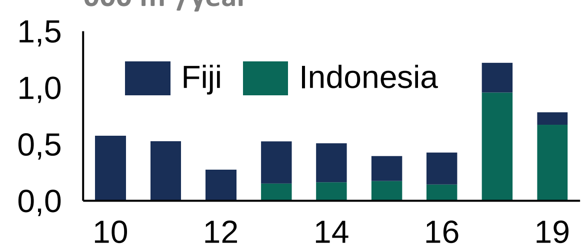
PNG Tropical HWD Log Exports,
Millions m³/year



Solomon Islands Tropical HWD Log Exports,
Millions m³/year



Fiji Tropical HWD Log Exports,
'000 m³/year



Note *: <u>Currently most of the PNG log exports have stopped due to the PNG new Government double-up of the log export royalty and</u> plywood mill closures

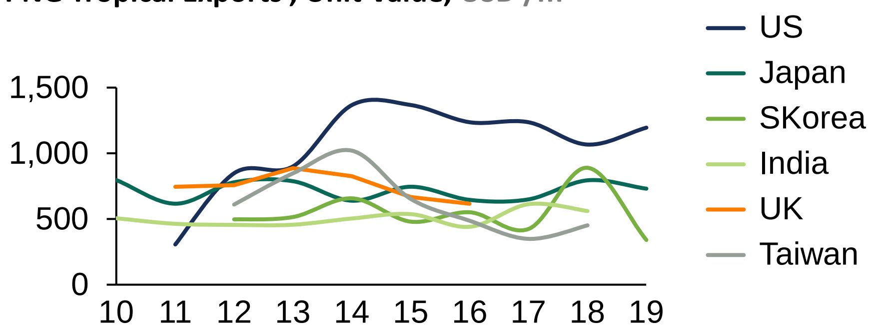
Source: GTA, Margules Groome

OCEANIA TROPICAL LOG EXPORTS UNIT PRICE

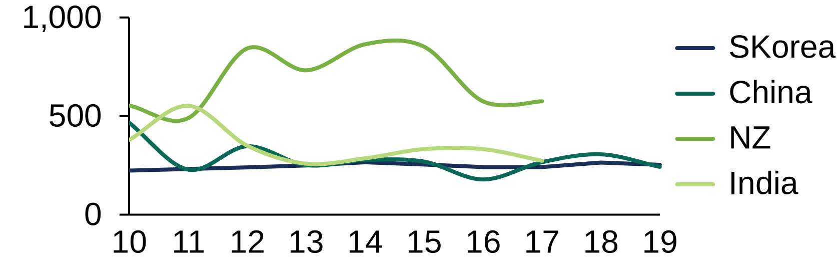
MARGULES GROOME

It remains to be seen if China's increasing presence and influence over Pacific nations will impact future tropical log trade

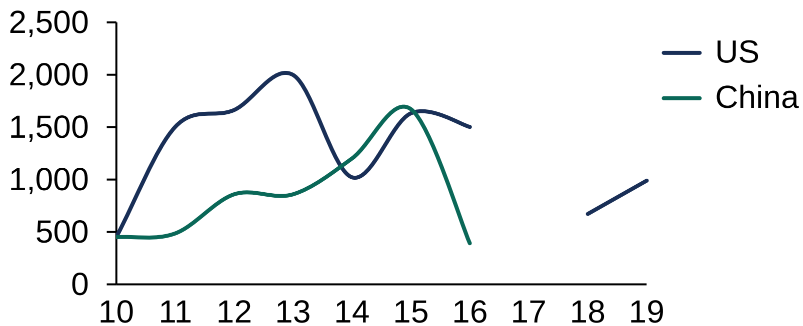
PNG Tropical Exports , Unit Value, USD /m³



Solomon Islands Tropical Exports , Unit Value, USD /m³



Fiji Tropical Exports , Unit Value, USD /m³



Source: GTA, Margules Groome

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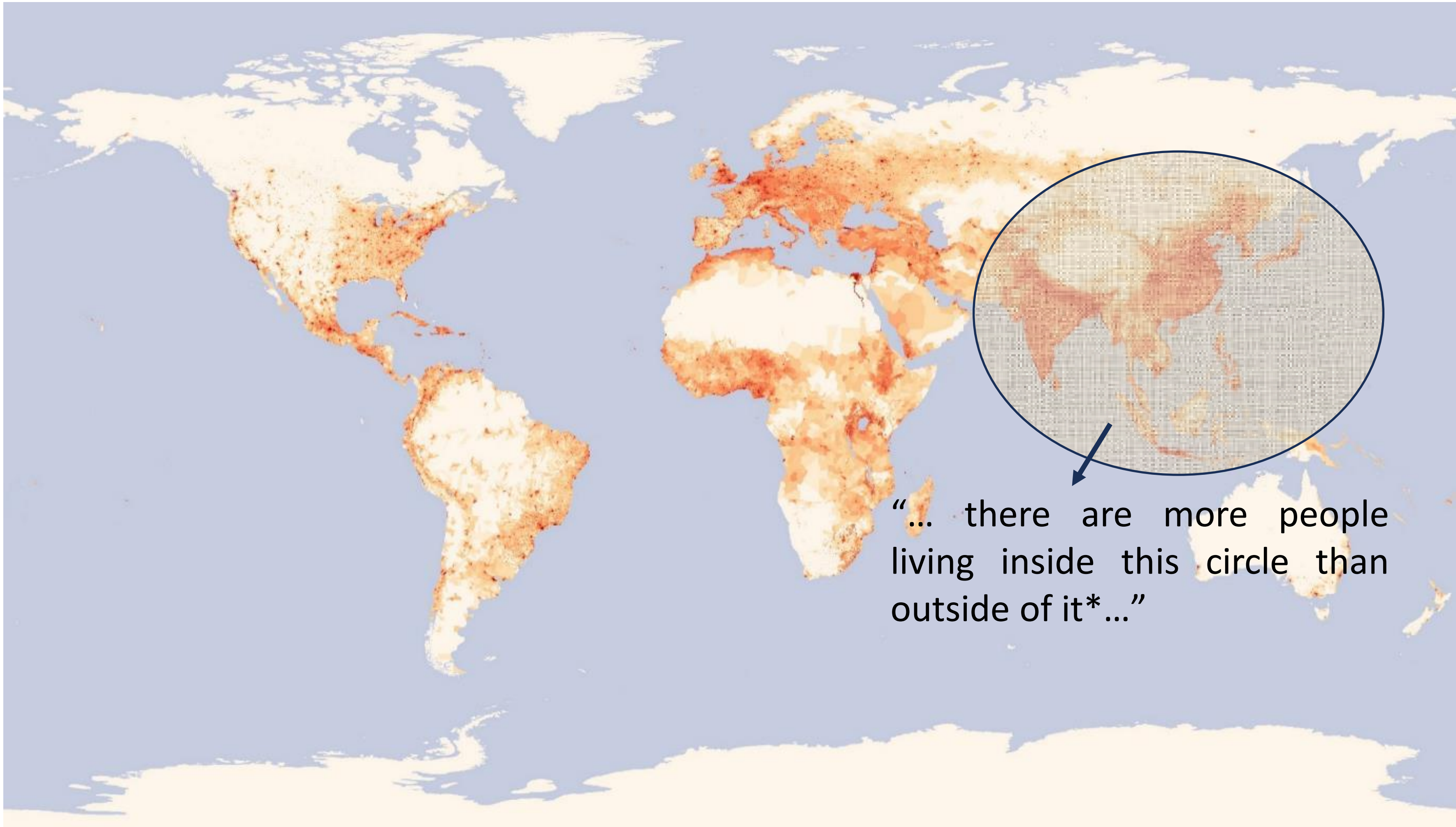
GLOBAL LOGS/WOOD PRODUCTS DEMAND

A significant demand growth opportunity are arising from the region with the largest share of global population

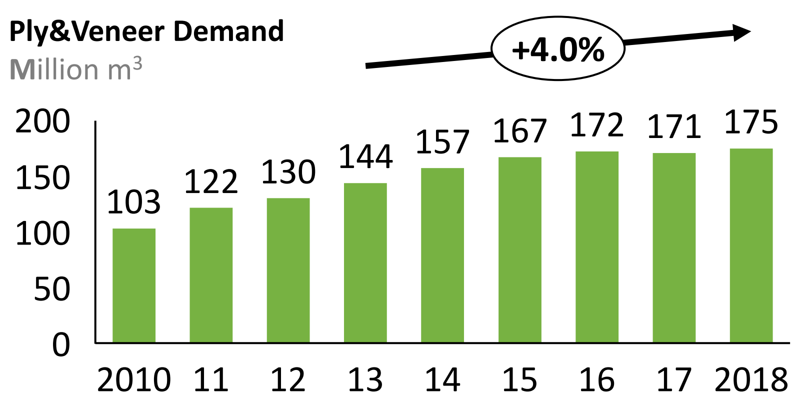


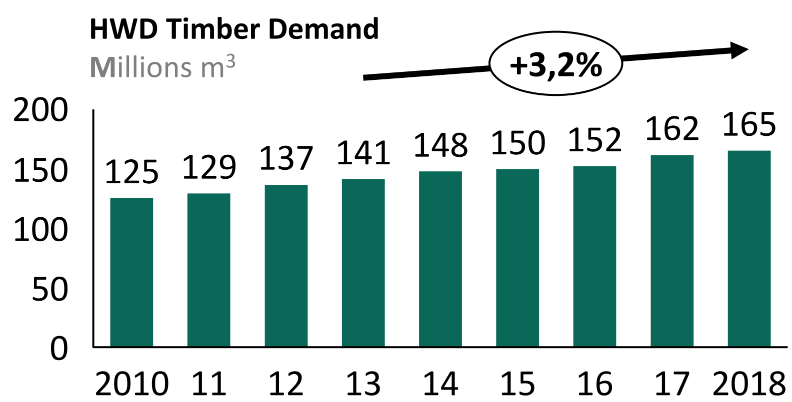
* Stephen Midgley – Partnership for sustainable agro-forestry between Timor-Leste, the EU & Germany

MAIN DEMAND DRIVERS FOR WOOD PRODUCTS

Construction and furniture production are the most important macro-demand drivers for engineered wood products

Product	Main applications	Demand drivers	Macroeconomic Drivers
Timber; Blockboard (value added product)	Structural building components, appearance and visual applications. Raw material for engineered wood products such as glulam and CLT.	Mainly construction / furniture, panelling, components	Population & GDP growth Construction activity Furniture production Substitution rates (i.e. changing consumer trends) Resource availability / regulations / certifications
Veneer & Plywood	Doors, framing, floor, wall and roof siding and cladding and floor underlaying, furniture, joinery products, transportation components	Construction / furniture / transport / shipping	

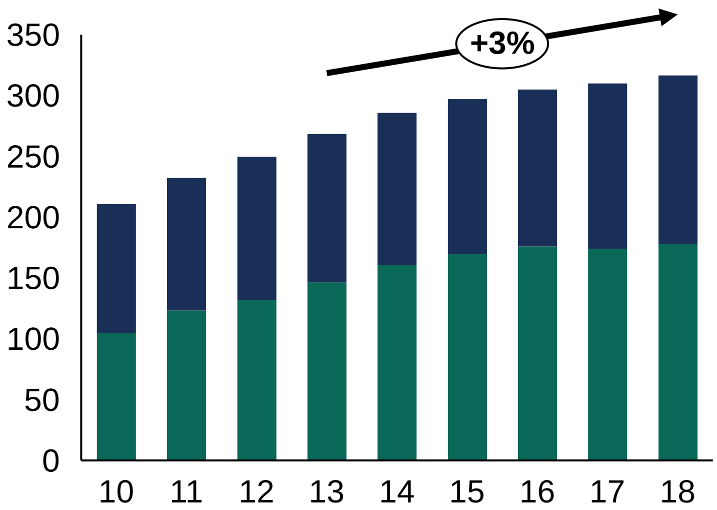




GLOBAL WOOD PRODUCTS CAPACITIES DEVELOPMENT

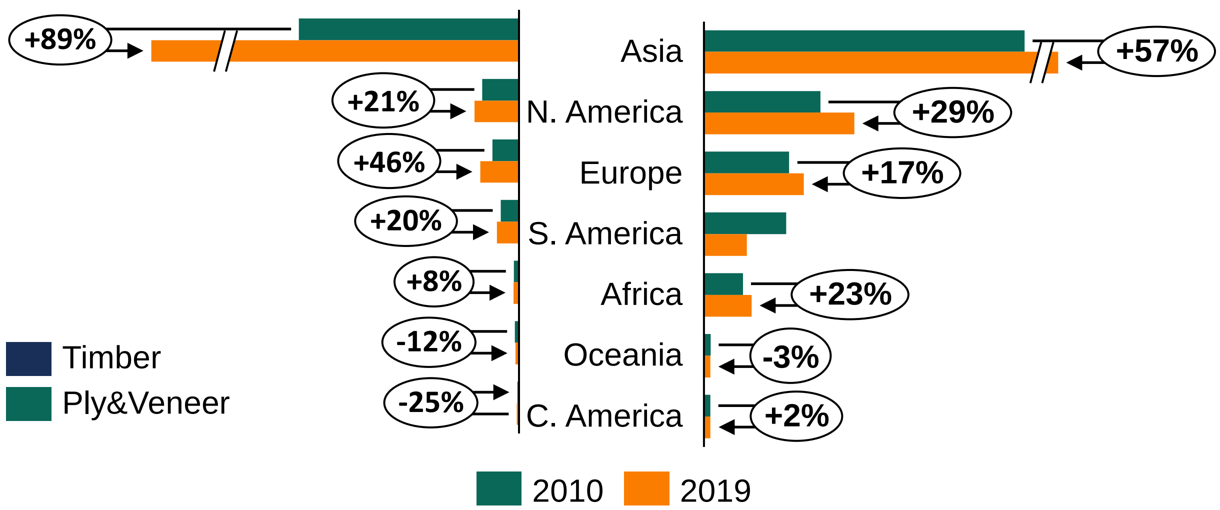
Global timber and EWP production have been growing steadily with ~4%/year in the last 5 years – main driver are construction activity, furniture production in Asia/China

Global HWD Timber and Ply/Veneer Production
Millions m³/year



Global Ply Production Development
% growth, 2010-2019

Global Timber Production
% growth, 2010-2019

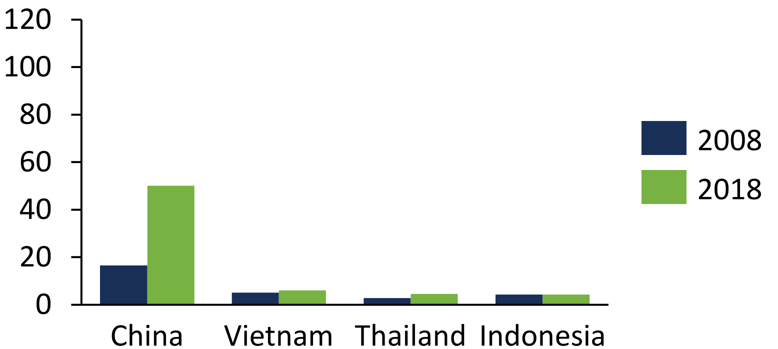


- Globally, timber and plywood continue to be the most important products (as volume traded and used)
- Traditional markets continue to show a positive outlook. African and Middle-Eastern markets are presenting significant growth potential.
- Access to higher value markets must be supported by strong forest plantation development, R&D, investment, certification/legal verification and marketing efforts
- Asia's timber and ply capacity development consolidated its position in the global context. Asia produces ~78% of the global ply and veneer, an increase of 2% global share over the last five years (2013-2018).

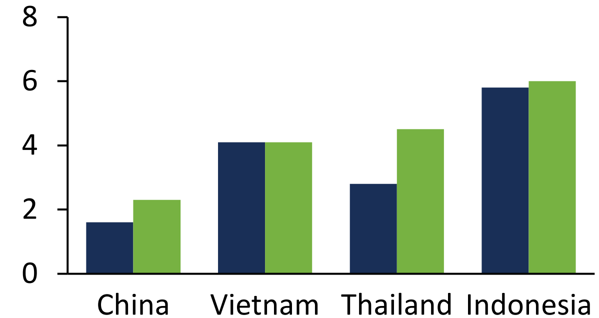
REGIONAL WOOD PRODUCTS CAPACITIES DEVELOPMENT

Asian countries are taking advantage of their low/medium cost human resource and high recovery rates* while increasing the production capacities – mostly using imported logs

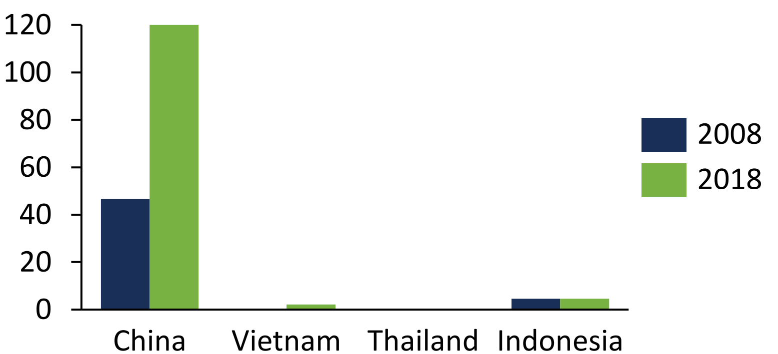
HWD Timber Production
Millions m³/year



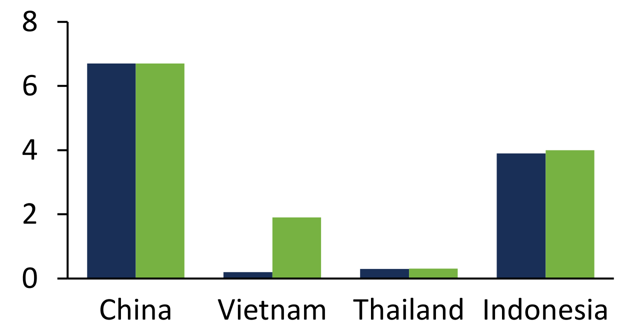
HWD Tropical Timber Production
Millions m³/year



Plywood Production
Millions m³/year



Tropical Plywood Production
Millions m³/year



INSIGHTS:

- Rapid economic growth in China and sustained investment in wood panels capacities over the last decade
- Vietnam and Thailand wood products sectors are growing, based on regional and global demand as well as on strong government programs and economic stimulus

Note: * Small size logs (down to 12-15 cm diameter are often processed using spindleless lathe and even the low quality veneers are reconstituted, patched and used as core veneers in combination with other quality veneers. Intensive manual handling is involved in the plywood production

Sources: European Panel Federation Report 2015, FAO, GTA, Margules Groome databases

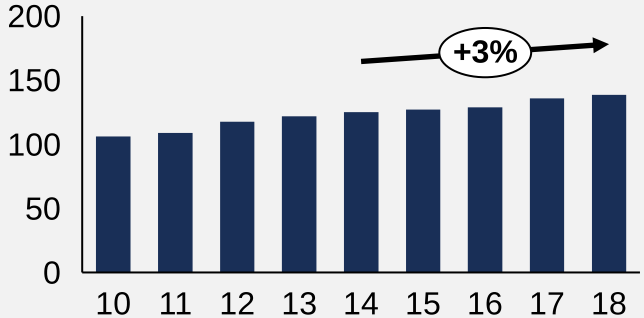
HARDWOOD/TROPICAL WP PRODUCTION

MARGULES GROOME

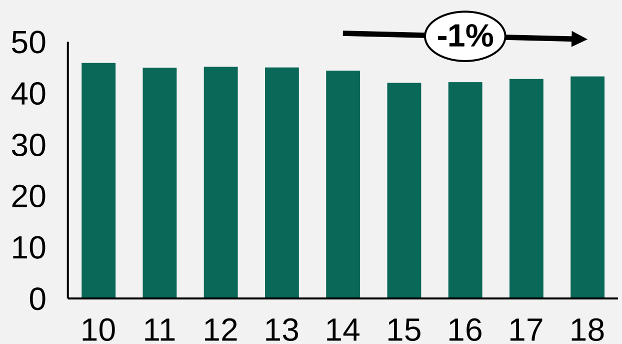
While the global HWD timber and veneer/ply production continue to grow, the tropical products are on a downward trend

Global Timber Production

Global HWD Timber Production (FAO)
Millions m³/year

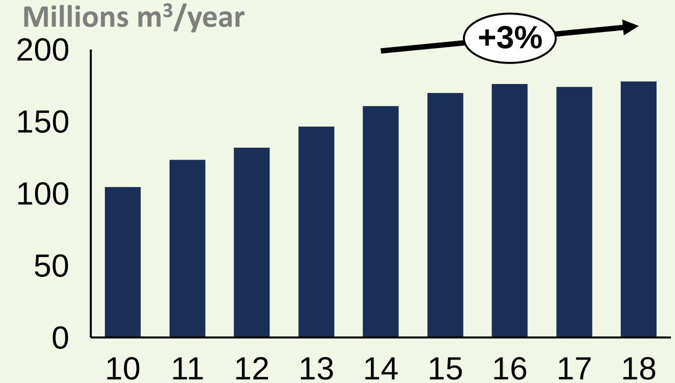


Global HWD Tropical Timber Production (ITTO)
Millions m³/year

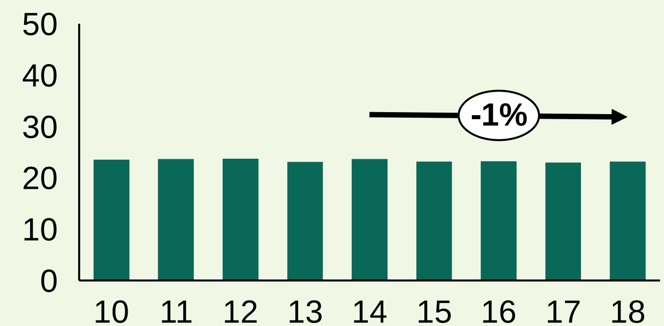


Global Veneer/Ply Production

Global HWD Veneer/Ply Production
Millions m³/year



Global HWD Tropical Veneer/Ply Production
Millions m³/year



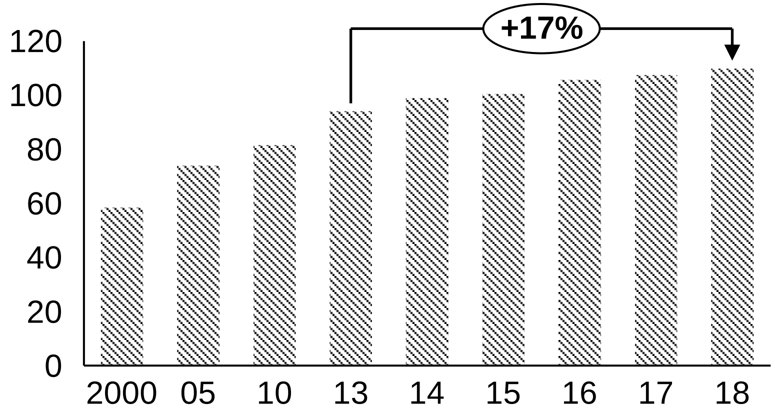
Source: FAO, ITTO, Margules Groome

GLOBAL PLYWOOD (SWD+HWD) MARKET DEVELOPMENT

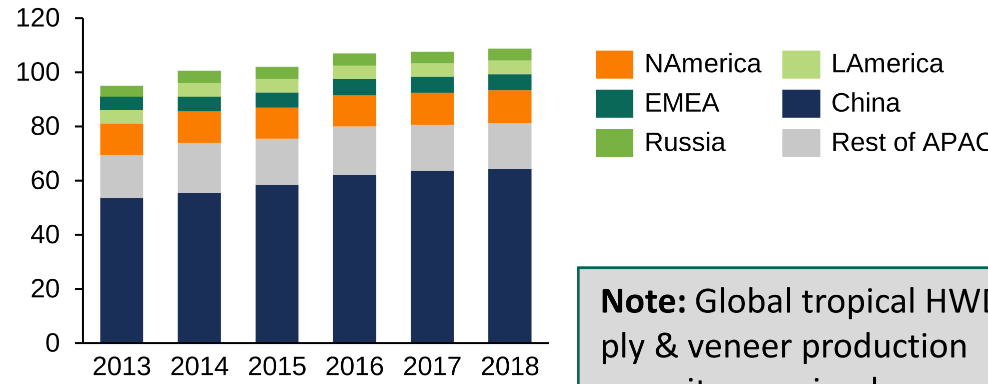
MARGULES GROOME

Production capacities growth is driven by China (<5 000 plants peeling mostly imported logs); “Combi-ply’ manufacturing is growing as importance; Market acceptance of plantation based plywoods is improving

Global Plywood Production
Millions m^3/annum

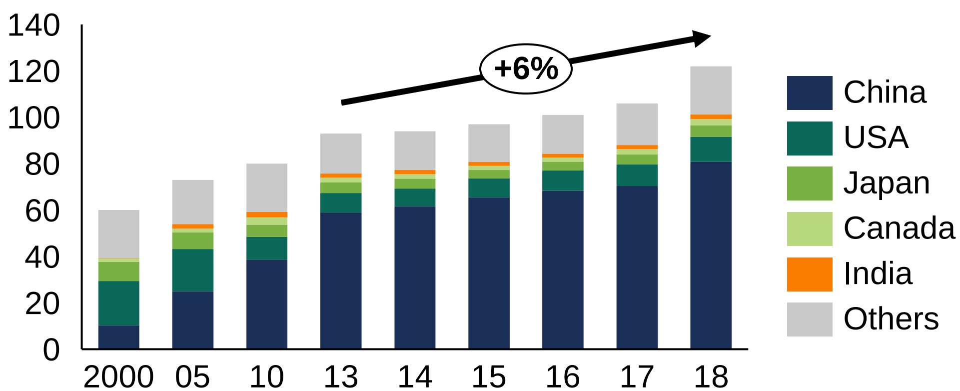


Global Ply Production by market
Millions m^3

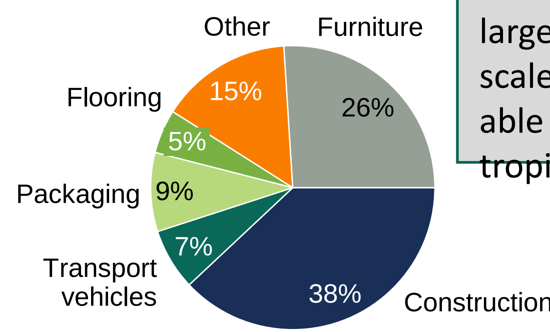


Note: Global tropical HWD ply & veneer production capacity remained relatively constant ~ 23 million m^3 with larger size mills being replaced by a large number of smaller scale more efficient mills able to process smaller size tropical logs

Global Plywood Consumption
Millions m^3/annum



Plywood End-Uses
% of demand

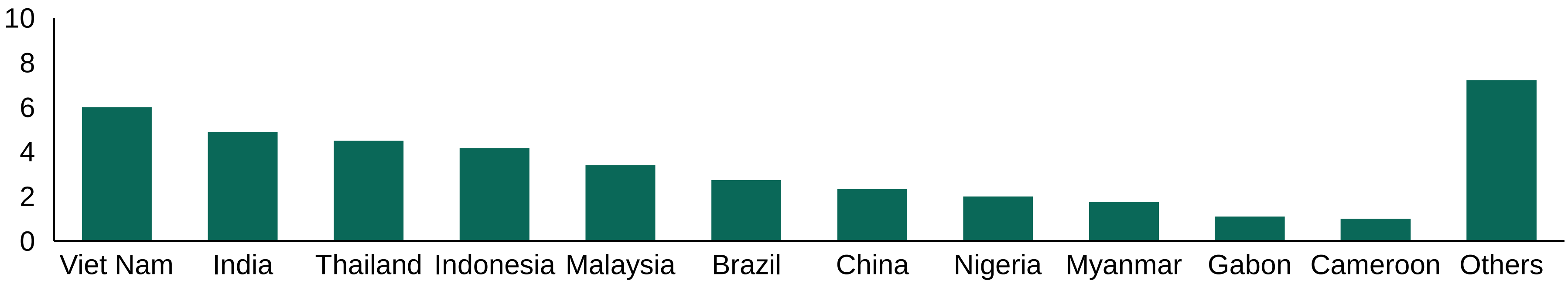


Source: Raute, wbpionline.com

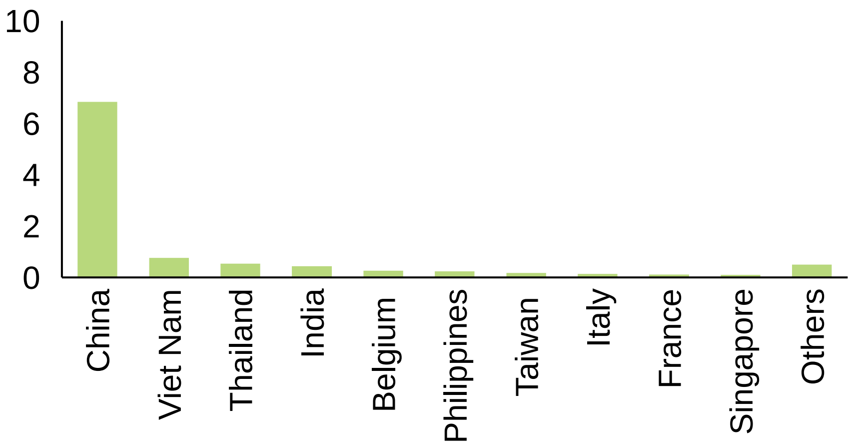
MAIN TROPICAL TIMBER PRODUCERS & MARKETS

A similar trend exists for the tropical HWD timber production with Asian countries maintaining their position as the main producers

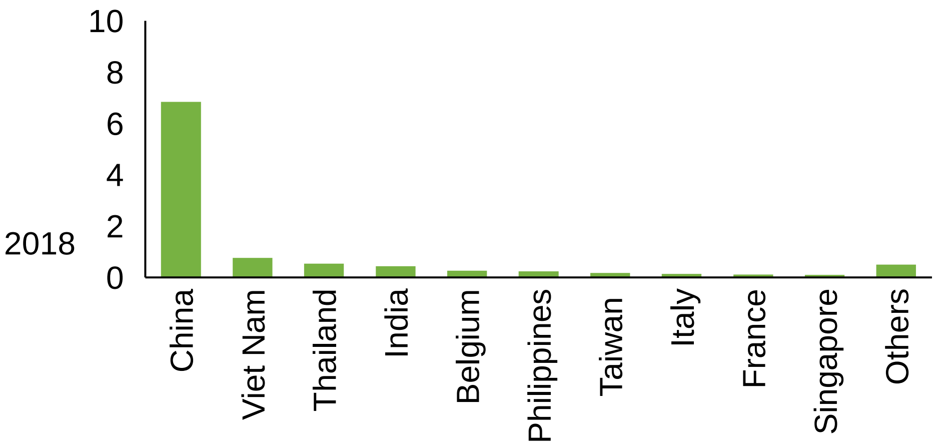
Main HWD Tropical Timber Producers (ITTO), 2018
Millions m³/year



Main HWD Tropical Timber Exporters (ITTO), 2018
Millions m³/year



Main HWD Tropical Timber Importers (ITTO), 2018
Millions m³/year



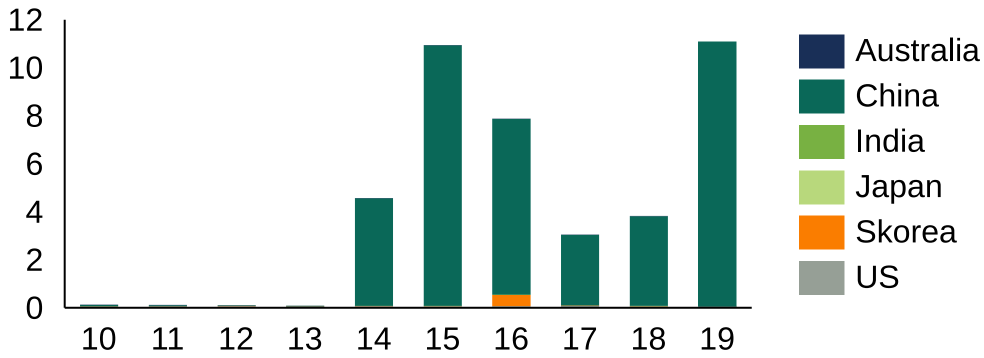
Source: ITTO, Margules Groome

SPECIALITY TROPICAL TIMBER TRADE

Beside timber availability, particular timber species trade is driven by certification, political agendas and consumer preference trends

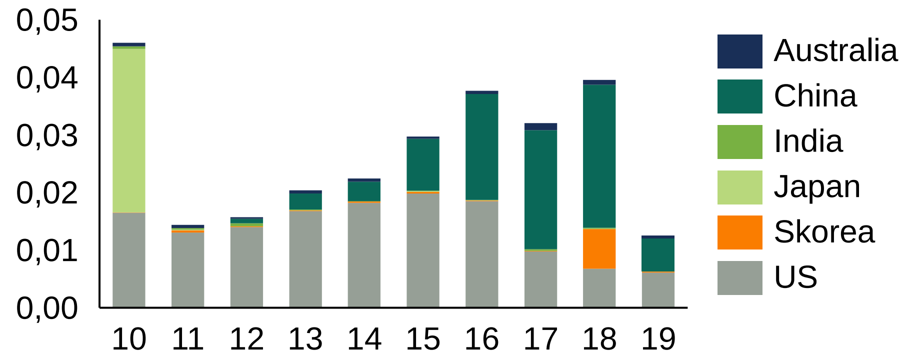
AMA Target Markets "Other Tropical - HS440722" Timber Imports

Millions m³/year



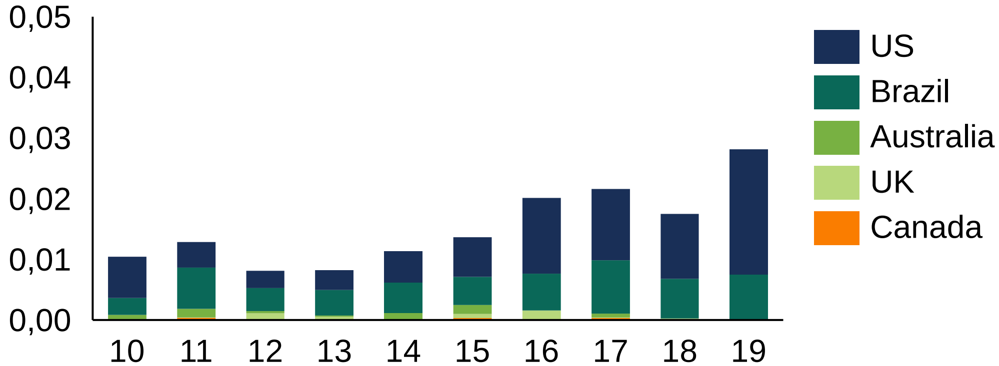
AMA Target Markets Mahogany- HS440721" Timber Imports

Millions m³/year



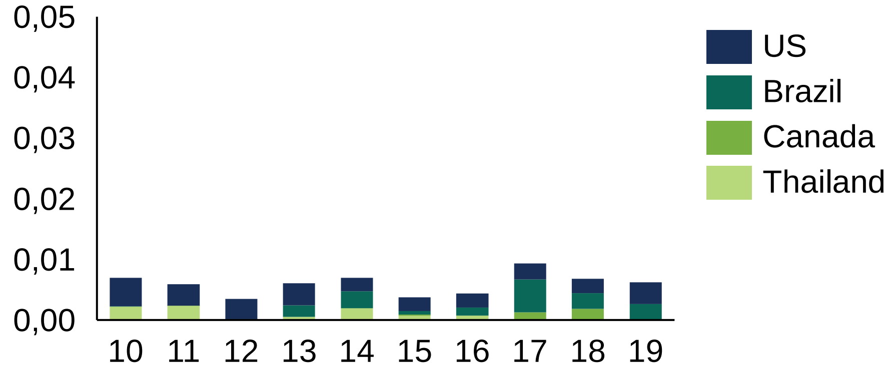
"Other Tropical - HS440722" Main Timber Exporters

Millions m³/year



Mahogany- HS440721" Main Timber Exporters

Millions m³/year



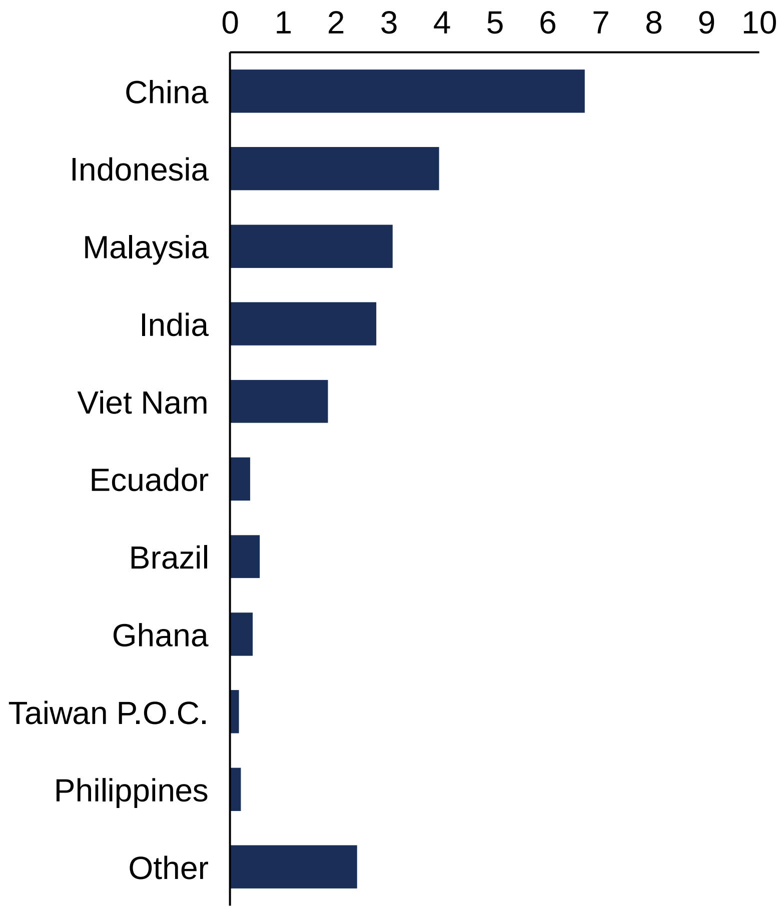
Source: FAO, ITTO, Margules Groome

MAIN TROPICAL PLY/VENEER PRODUCERS & MARKETS

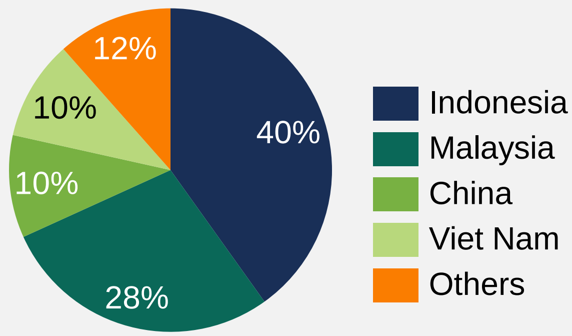
MARGULES GROOME

Ply & veneer production continue to be Asia centric where high recovery rates and low cost workers continue to drive investment in new production capacities

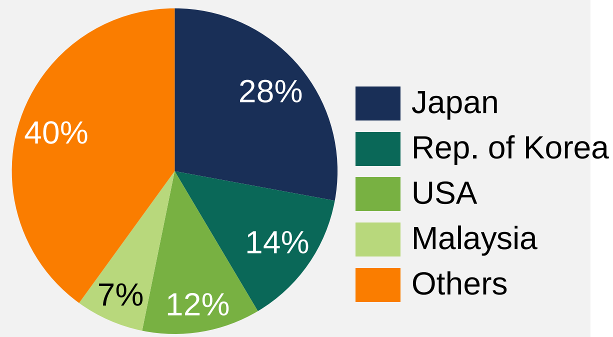
Main HWD Tropical Ply & Veneer Producers (ITTO), 2018
Millions m^3/year



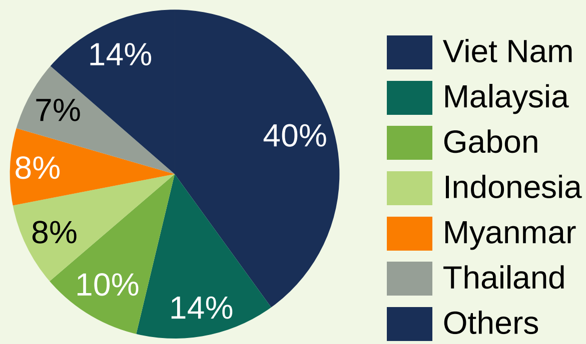
Ply Exporters (ITTO), 2018
%



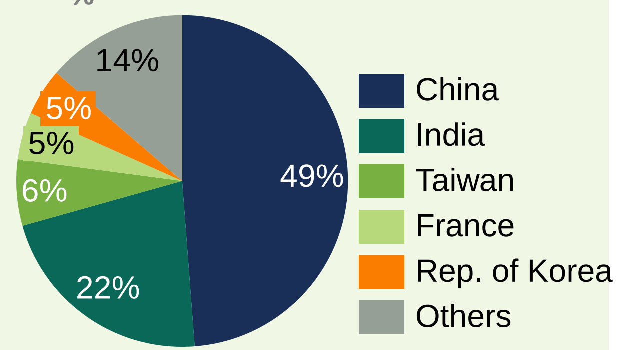
Ply Importers (ITTO), 2018
%



Veneer Exporters (ITTO), 2018
%



Veneer Importers (ITTO), 2018
%

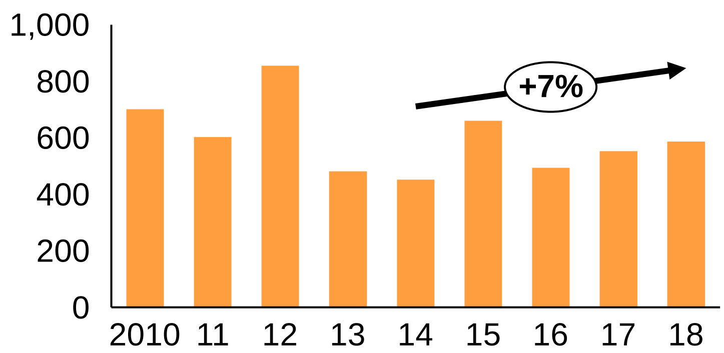


Source: ITTO, Margules Groome

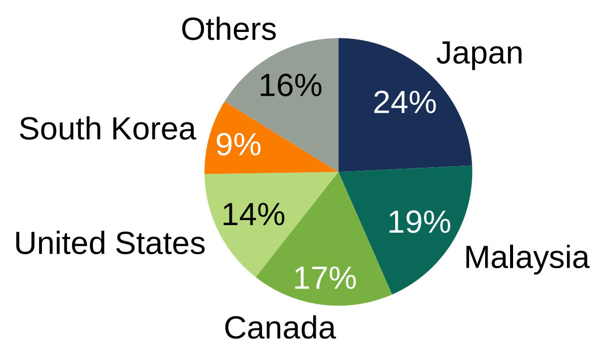
GLOBAL BLOCKBOARD MARKETS

After peaking at the beginning of this decade, blockboard markets appear to send mixed signals in terms of growth potential. Currently blockboard production is mostly consumed domestically

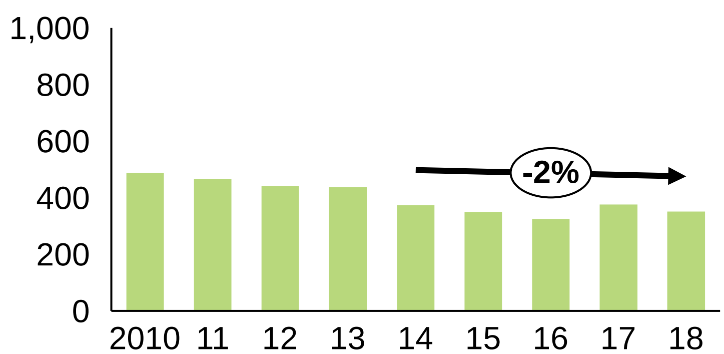
Global Blockboard Imports
'000 m^3, 2018

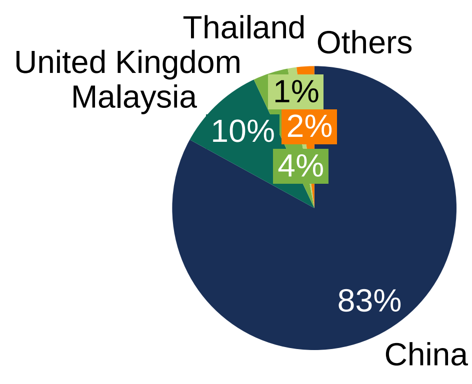


Blockboard Main Trading Countries
%, 2018



Global Blockboard Exports
'000 m^3





Source: GTA

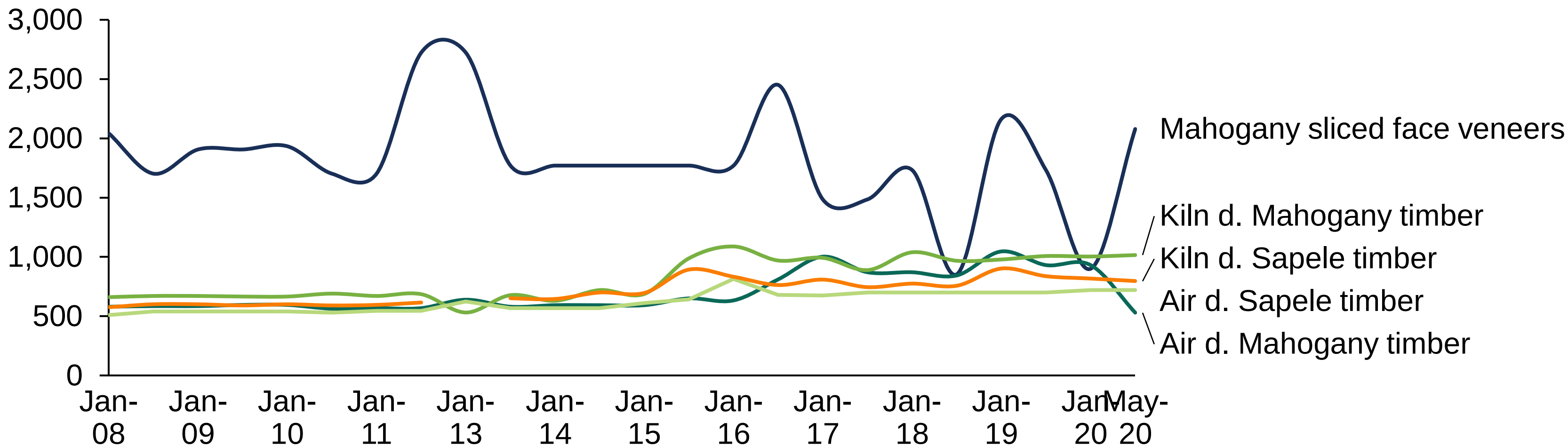
INSIGHTS

- Blockboard is preferred to plywood where strength and stiffness are required (however, its global market is still small - less than 0.6 million m^3 compared with more than 105 million m^3 for plywood)
- Global market is expected to grow, based on growing furniture markets that require long and stable components for shelves or benches
- A high level of competition in most markets is expected as the log resource size and quality is decreasing, thus the need for substitute products such as blockboard
- APAC is expected to remain the leading market with more than 50% market share

GHANA WP EXPORT PRICES TO ASIA

Ghana WP prices starting fluctuating since 2016, likely reason being a change in market conditions in Europe (Belgium, UK) and India as well as the signing of Economic Partnership Agreement (EPA) with the European Union

Ghana WP Exports to EU , Euro /m³



China log & Timber Imports, Yuan /m³

	Aug-2010	Aug-2011	Aug-2013	Aug-2014	Aug-2015	Aug-2016	Aug-2017	Aug-2018	Aug-2019
Logs (Yuan/tonne)									
Sapele	3 200-3 700	3 200-3 700	4 500-5 700	4 500-5 700	3 000-4 000	3 000-4 000	3 000-4 000	3 000-4 000	3 000-4 000
Padauk			3 000-3 800	3 000-3 800	2 400-3 100	2 400-3 100	2 400-3 100	2 400-3 100	2 400-3 100
Acajou			3 100-3 600	3 100-3 600	3 000-3 500	3 000-3 500	3 000-3 500	3 000-3 500	3 000-3 500
Timber (Yuan/m³)									
Sapele grade A	6300-6500	5 000-6 500	6 600-7 000	7 500-7 900	7 500-7 900	7 000-7 500	5 000 -7 500	5 000 -7 500	5 000 -7 500
Padauk				14 500-17 000	14 500-17 000	16 500-18 000	15 000-18 000	15 000-18 000	15 000-18 000
Mahogany				6 500-7 000	6 500-7 000	7 000-7 500	6 500-7 500	6 500-7 500	6 500-7 500

Source: ITTO, Margules Groome

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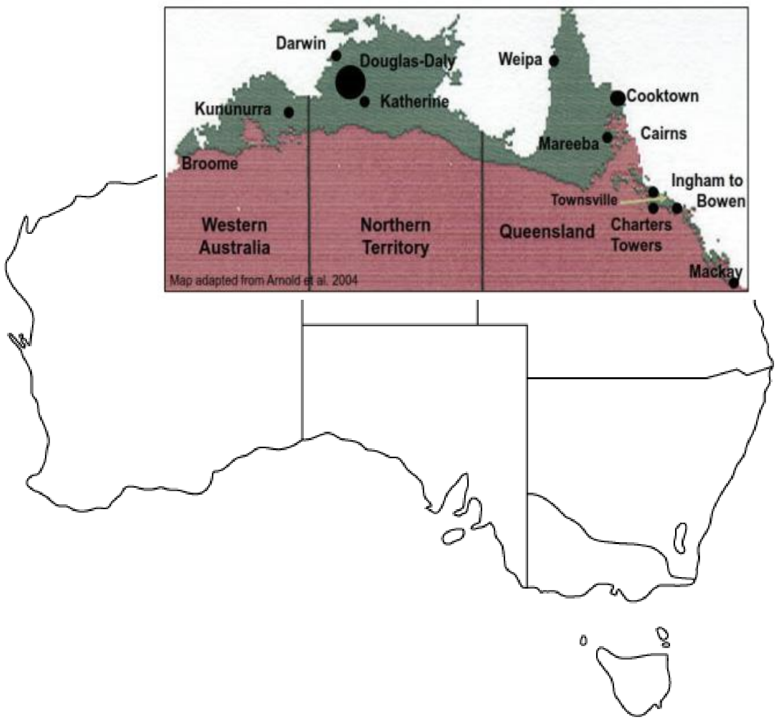
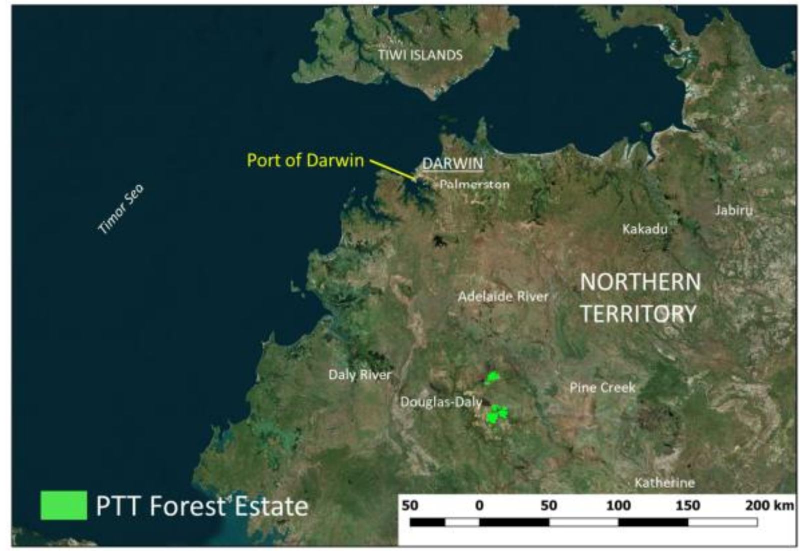
LOG AVAILABILITY & DESCRIPTION

African Mahogany Australia (AMA) manages the world largest African mahogany plantation resource. To maximise investment returns now depends on the tropical hardwoods market acceptance of planation grown *Khaya senegalensis* and the timber suitability for use in high-value wood products

Main African mahogany planted areas in Australia, 2016 – approx. 15 000 ha





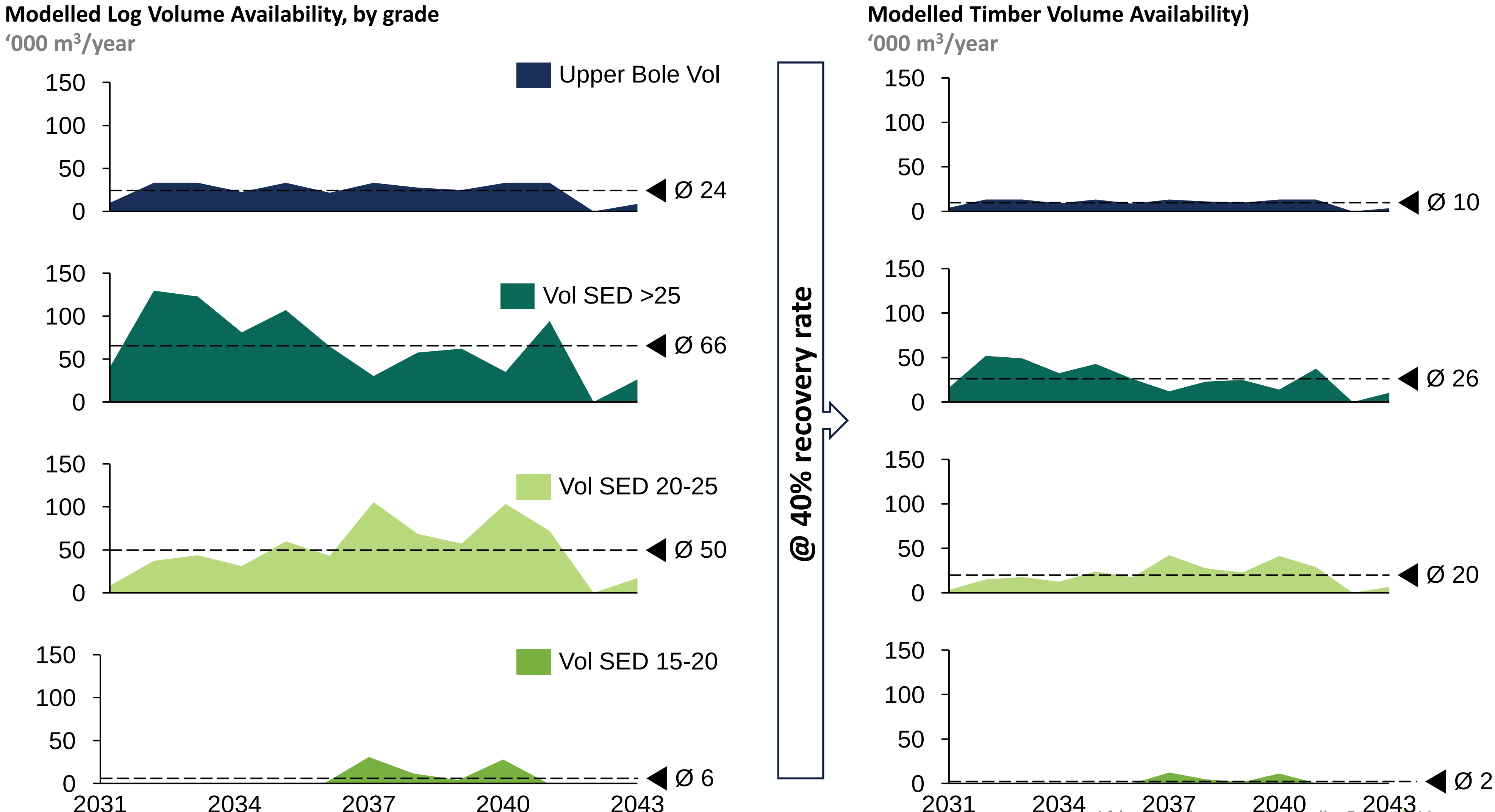
PTT Forest Estate Area Statement as at 31 December 2019

Property	**NSA (ha)**
Gypsy Springs	3 347.8
Kumbyechants	2 039.4
Stray Creek	2 693.9
Total	**8 081.2**

Beside the African mahogany plantations established in China, Malaysia, Sri Lanka and Vietnam, the **Northern Australian plantation represents the largest global area planted.**

LOG AVAILABILITY & DESCRIPTION

Margules Groome's log availability and SED modelling shows approximate 65 000 m³ of logs/year will have a SED of over 25 cm* thus marginally appropriate for peeling and sawmiling



Note *: Ideally sawlogs would be of larger than 30 cm diameter to allow processing by the HWD sawmills

AFRICAN MAHOGANY – NATURAL VS. PLANTATION

Based on its physical characteristics and appearance, African Mahogany Australia (AMA) plantation resource looks to be comparable with its natural counterpart, however more processing trials are needed to clarify some apparent processing issues

- As with any new product and/or wood species to be introduced to the market the majority of investigative research and marketing efforts is directed at comparing the plantation resource with its natural counterpart
- Traditionally natural tropical hardwoods are well accepted due to their mechanical and aesthetical properties – it usually attract a premium price (although prices have remained relatively flat over the last decade and despite resource scarcity)

Natural logs / wood

- A relatively heavy hardwood specie with a 710-810 kg/m^3 dry density in its natural range
- Wood with good working properties and good stability after air drying; it shows interlocking grains that doesn't provide for a good rotary peeling quality, thus, sliced veneering is preferred
- High-value decorative purposes represents the best uses: carpentry, veneer, cabinet making, furniture, joinery, boat building and solid flooring

Plantation logs / wood – AMA recent studies

- Dry density of 550 – 750 kg/ m^3 - comparable with its natural counterpart
- Good sawing and peeling potential however issues exist with regards to boards warping, end-splitting and checking as well as veneer curving after slicing
- Very difficult to colour/impregnate for colour uniformity - Potential for high-value products when non-uniform colouration across the bord is not an issue
- Veneer of good quality and visual appearance however with some issues when slicing

TROPICAL HWD MAIN HIGH-VALUE APPLICATIONS

There are two main end-market segments for tropical timbers based the wood's mechanical visual appearance properties: decorative and utility wood

“Show wood" – Tropical timber used for its decorative and aesthetic properties

- **Africa**: African mahogany, sapele, sipo (utile), frake, framire, okoume (mainly as plywood), niangon edinam, makore, aningeria afrormosia, tchitola
- **South America**: Brazilian mahogany, cedrella, virola, andiroba
- **Southeast Asia**: dark red meranti, merbau, padauk, teak

The main types of furniture using tropical sawnwood as "show wood" are living room and bedroom furniture, tables and chairs, office and hotel furniture.

Manufacturers have very specific requirements for the “show wood” in terms of species, colour consistency, sawnwood grade, moisture content and machining characteristics

“Utility wood” – Tropical timber used for its technical properties (ease of machining, durability, stability)

- **Africa**: obeche, iroko
- **South America**: Brazilian mahogany, simarupa
- **Southeast Asia**: keruing, meranti, ramin

Main products/applications include furniture framing, heavy duty furniture (e.g. industrial/laboratory furniture), shop and exhibition furniture.

- Joinery / indoor & exterior door and frames, windows & frames, staircases, flooring and decking
- Value-added products / furniture: solid and veneered outdoor furniture
- Construction and civil engineering (e.g. bridges) / piers and jetties / farm gates and other fittings
- Trailer flooring and bodies / boat building

Source: FAO Corporate Document Depository: Markets for High-Value Tropical Hardwoods in Europe…”

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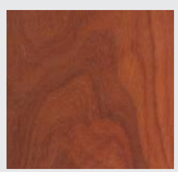
MARGULES GROOME

COMPARABLE EXOTIC SPECIES SPECIFICATIONS

MARGULES GROOME

Species	Country of origin	Colour	Density	Other properties	Main uses	Export markets
Teak[1]	Native to India, Myanmar, Thailand and Vietnam Plantations in Bangladesh, China, India, Indonesia, Lao PDR, Myanmar, Philippines, Sri Lanka, Thailand, Vietnam, Papua New Guinea, Africa, Solomon Islands, Fiji and the tropical America	Heartwood is typically golden or medium brown Sapwood is pale yellow The colour of seasoned wood can vary between and within species 	Seasoned: 680 kg/m^3	Very durable Resistant to termites Moderately resistant to marine borers Ease to machine, yet causes severe blunting of cutting edges Challenging to glue due to the natural oils on the surface Good for applying paints and stains Not suitable for steam bending	• Ship and boat building • Decorative uses such as indoor and outdoor furniture, parquetry, turned objects, carving, lining and panelling, veneer and other small wood objects	India Thailand China EU US
Black walnut[2]	Native to the eastern regions of North America	Heartwood ranges from a golden to rich chocolate brown colour Sapwood is a distinctive creamy white colour. 	Seasoned: 615 kg/m^3 Unseasoned 970 kg/m^3	Vary durable (decay resistant) Susceptible to insect attack Easy to machine and work with hand tools Easy to glue Easy to polish Suitable for steam bending	Premium cabinetry and furniture, carving, turned objects, joinery, veneer, interior paneling and other small wooden objects and novelties In Australia, mainly available as veneer	China Canada Italy Germany Japan

COMPARABLE EXOTIC SPECIES SPECIFICATIONS

Species	Country of origin	Colour	Density	Other properties	Main uses	Export markets
Sapele[3]	Tropical Africa	Heartwood is pink when freshly cut to red brown or purple brown. Sapwood grey pink or cream 	Seasoned: 690 kg/m^3	Durable (decay resistant) Moderate insect/borer resistance Can tear out in some machining operations Easy to work with hand tools Easy to glue Easy to polish	• Veneer, plywood, furniture, cabinetry, flooring, joinery, musical instruments, turned objects boatbuilding and other small specialty wood objects	EU (UK, Netherlands, Belgium, Germany, France, Italy, Spain) US Asia (China)
African padauk[4]	Central and tropical west Africa	Heartwood ranges from a pale pinkish orange to a deep brownish red. 	Seasoned: 745 kg/m^3	Very durable (decay resistant) Resistant to termites and other insects Easy to machine Easy to glue Easy to polish	Veneer, flooring, turned objects, musical instruments, furniture, tool handles, and other small specialty wood objects.	Europe China Japan

Source: 1 - https://www.woodsolutions.com.au/wood-species/teak ; https://brittontimbers.com.au/timbers/teak/: https://www.wood-database.com/teak/; http://www.fao.org/3/a-i5023e.pdf
2: - https://www.woodsolutions.com.au/wood-species/walnut-american-black; https://brittontimbers.com.au/timbers/american-black-walnut/; https://www.wood-database.com/black-walnut/; https://www.nrs.fs.fed.us/pubs/gtr/gtr-p-115papers/01luppold-p-115.pdf
3 – https://brittontimbers.com.au/timbers/sapele/; https://www.wood-database.com/sapele/; https://www.fordaq.com/news/EU_sawn_sapele_imports_meranti_34738.html
4 - https://www.wood-database.com/african-padauk/; https://www.wood-database.com/african-padauk/; https://www.timberindustrynews.com/investigation-of-padauk-export-from-congo-to-eu-impacts-prices/

COMPARABLE EXOTIC SPECIES MARKETS (i)

Teak (Myanmar)

- The Minister of Natural Resources and Environmental Conservation, has called on the **Myanmar Timber Enterprise** (MTE) to further **reduce its harvest levels (by 50%) in 2019/20**. The Minister also announced an **age limit for teak harvests** and urged the **planting of three seedlings for every tree felled** in Mandalay and Sagaing
- The MTE harvesting plan **for 2019-20 includes production of about 5 000 tons of** teak. Some 3 000 tons will come from the Shah State with most of the balance from the Sagaing Region, Chin State and Magwe Division. In addition, **teak will be harvested from mature plantations (30 years and above).** It is understood that **the mature teak plantations are considered 'natural forest'** as the quality of the timber is considered equal to that from the natural forest. **Myanmar is believed to have exported about 80 000 tons of timber to as many as 40 countries in fiscal 2018-19 with teak accounting for around 35% of the total**
- Timber legality assurance - **traceability and legality verification issues for Myanmar's teak exporters due to the strengthening of EUTR**
- **EU imports from Myanmar continue despite EU prohibition**

Source: FORDAQ, globalwood.org, ITTO

COMPARABLE EXOTIC SPECIES MARKETS (ii)

Sapele

- **Sapele is an attractive and increasingly popular Mahogany alternative**
- Its growth in popularity led to over harvesting and subsequent **regulations applied to logging companies throughout Africa**, such as TLTV and VLO, to ensure that sapele is harvested in a sustainable and responsible manner
- Consequently, importers have seen a slowdown in supply
- **Sierra Leone and Cote d'Ivoire have created Sapele plantations**
- **Congo**, although plagued by constant political turmoil, remains **one of the most significant producers of Sapele**
- **Limited supply in the importing markets** is also combined with long lead times rising demand for alternative tropical species
- **Availability is also constrained by political problems in Central African Republic**, shipping delays at Douala Port in Cameroon and reduced overall production capacity following an economic crisis. **Lead times for forward shipments of sapele into Europe may be up to six months** (*Fordaq 2014*)
- In the past, there was **strong direct competition in the European market between African sapele and South East Asian meranti.**
- In the Netherlands, the **SE Asian species meranti was proposed for government funded projects**, which, it was thought to impact negatively the demand for sapele (*Fordaq 2014*)
- Also, in the Middle East markets there has been a continuous **battle between SE Asian and African timbers for market share.**
- Sourcing African hardwoods in thicknesses like 4/4, 5/4, 6/4 is not an option, because African mills do not saw those sizes. **The markets re-cut already-milled boards to the sizes preferred by local builders resulting in additional costs**

Source: FORDAQ, https://www.sapeleoutlet.com/verifiable-sustainable-alternative-to-genuine-mahogany/
https://www.sapeleoutlet.com/lumber-market-issues-north-american-size-preferences-part-2/

COMPARABLE EXOTIC SPECIES MARKETS (iii)

- Slow business in China increases stock. **Timber prices at Zhangjiagang markets fell sharply in 2018 due to high stocks and weak demand, it was only merbau and sapele for which prices remained more resilient**. Traders noticed a steady demand for sapele and merbau logs as they are very popular species. **Sapele is very popular for door manufacture and merbau is the first choice for outdoor furniture and restoration of ancient buildings**.
- **COVID-19 effects, April 2020**: **production rates in Central/West Africa have fallen** especially for those species and specifications for the EU market where ports, especially in the southern European countries, have virtually closed to arrivals except for essential goods and food. It has been reported that **stocks of timbers popular in the EU such as sapele are increasing.** It has been reported that stocks of padouk sawnwood in the Netherlands are only moving very slowly. **There are suggestions that some stockists have mentioned a price of Euro 610 per cubic metre free-on-truck, a situation never before experienced**.
- Wood products of Chinese origin that have been **taxed with 10% upon entry in the US from Sept 24 2018 and with 25% at the end of 2018**
    - 4407.22.00 Okoume, Obeche, Sapele and other specified tropical woods, sawn or chipped lengthwise, sliced or peeled, over 6 mm thick
    - 4407.27.00 Sapele wood sawn or chipped lengthwise, sliced or peeled, over 6 mm thick
- Teak products are on China's 25% tariff list imposed to US from June 2019
    - 44072910 Teak wood, longitudinally sawing, slitting, planing or cutting, whether or not planed, sanded or end-joined

Source: FORDAQ, https://www.sapeleoutlet.com/verifiable-sustainable-alternative-to-genuine-mahogany/
https://www.sapeleoutlet.com/lumber-market-issues-north-american-size-preferences-part-2/

COMPARABLE EXOTIC SPECIES MARKETS (iv)

Padauk

- There are seven species recognised as padauk and they belong to the genus Pterocarpus. African padauk (*P. soyauxi*), sometimes referred to as vermillion, is the only padauk species readily available today. Others occasionally sold include Andaman padauk (*P. dalbergioides*), Angola padauk or muniga, kiaat (P*. angolensis*), Burmese padauk (*P. macrocarpus*), narra (*P. indicus*), and sandalwood padauk (*P. santalinus*).
- Shipments of **padauk sawnwood dispatched from Gabon to Belgium during July 2019 could not satisfy the EUTR**. This had an impact on **padauk sawnwood prices which fell to around euro 700-750 /m³ from recent highs of over euro 1 100 /m³** . The Gabon's Forestry minister faces an uphill task to "put an end to bad practices in the forestry sector and corruption in the administration"
- Logging companies in Gabon are stepping up efforts to market a wider range of species, especially redwoods, but report little interest for this in China and India. (*Fordaq 2019*)
- **US teak and padauk imports were high in October 2019 and well ahead of last year's volume to date**
- **Vietnamese padauk was excluded from the national Hongmu standard for redwood species in China, GB/T 18107-2017, effective 1 July 2018.** According to analysts **these changes only reflect rearrangement of species with different names**. For example, Vietnamese padauk (*Pterocarpus cambodianus Pie*rre) and maidu (*Pterocarpus pedatus Pierre*.) are regarded as the same as Myanmar padauk (*Pterocarpus macarocarpus Kurz*). **In China padauk is categorized within rosewood species as mid to low market value.**

Source: https://www.woodmagazine.com/materials-guide/lumber/wood-species-3/padauk
https://www.forest-trends.org/wp-content/uploads/imported/for173-china-rosewood-report-letter-16-0329-hr-no-crops-pdf.pdf

COMPARABLE EXOTIC SPECIES MARKETS (v)

- The **rosewood industry in China is bound by five national standards**:
  - National Hongmu Standard issued in 2000 by the State Administration for Quality Supervision and Inspection and Quarantine (AQSIQ) in order to regulate quality,
  - AQSIQ regulation specifying label requirements in manufacturing processes (2011),
  - National Development and Reform Commission directive identifying appropriate species for industry use, and
  - Two sectoral standards issued by the Ministry of Commerce (MofCOM).
- **Rosewood species in Myanmar**, including Burmese padauk (*Pterocarpus macrocarpus*) and tamalan (*Dalberia oliveri*), **are rapidly declining**, and it is estimated that if current rates of harvest were to continue, **stocks of both species would be completely consumed in as little as three years** (EIA 2014b). Both are **classified as "reserve" species, meaning any harvesting and trading must be specifically permitted by the Ministry of Environmental Conservation and Forestry** (MOECAF). **Exports are rarely recorded in official trade statistics**.

MID - HIGH VALUE PRODUCTS – CHINA CASE STUDY

SAPELE (沙比利)

- **Price:** AUD 1 200-1 400/m^3 (timber)
- **Product:** Door, Flooring and some furniture
- **Origin: Africa**

Tectona grandis - Teak

- **Price:** AUD 1 200-1 300/m^3 (logs)
- **Product:** High-end flooring and furniture
- **Origin:** Myanmar

PAU ROSA（铁木豆）

- **Price:** AUD 850-1 000/m^3 (timber)
- **Product:** Flooring
- **Origin:** South America

ZEBRA WOOD

- **Price:** AUD 1 400-1 500/m^3 (timber)
- **Product:** Furniture
- **Origin: Africa**

HIGH VALUE PRODUCTS – CHINA CASE STUDY

KEVAZINGO (巴花（非洲花梨）

- **Price:** AUD 3 000-3 200/m^3 (timber)
- **Product:** High-end furniture
- **Origin:** Africa

DALBERGIA BARIENSISPIERRE EX PRAIN(巴里黄檀)

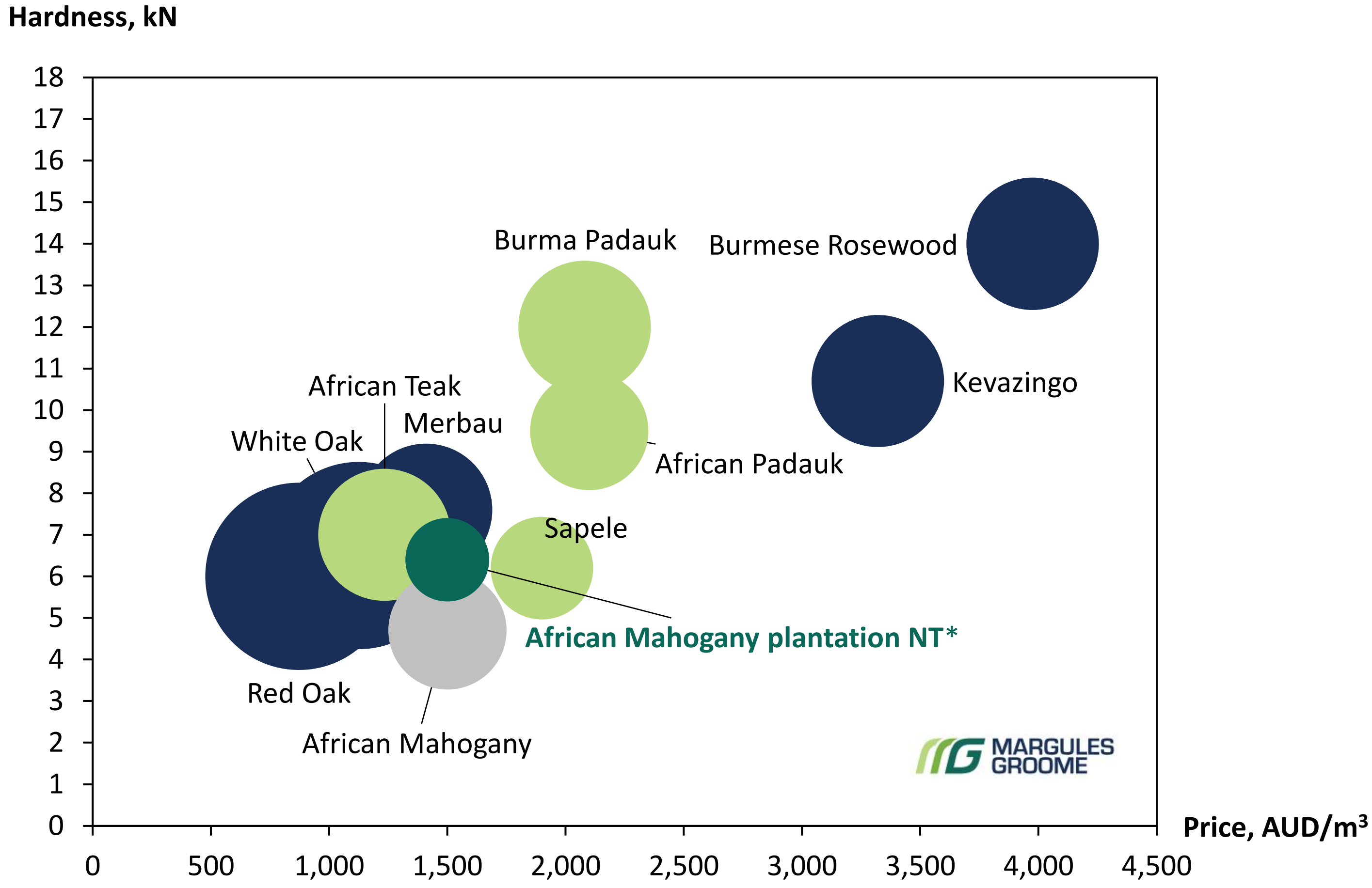
Other Names: Asiatic rosewood, Neang nuon、Burmese Rosewood

- **Price:** AUD 4 000-4 600/m^3 (logS)
- **Product:** High-end furniture
- **Origin:** Myanmar

PTEROCARPUS MACAROCARPUS KURZ (大果紫檀)

- Price: AUD 3 500-3 800/m^3 (logs)
- Product: High-end furniture
- Origin: Myanmar

HWD SPECIES COMPARISON – CIF PRICES, AUD/m^3



Note: Circle size represents species availability / stock, Hardness – kN (Janka test), Price – AUD/m^3

Source: wood-database.com

Note*: based on the African Mahogany Grown in Australia report, 2007

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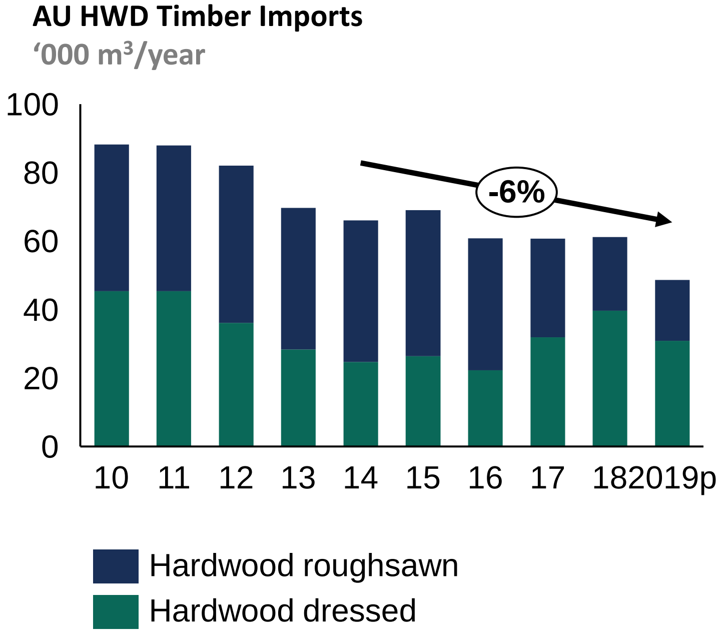
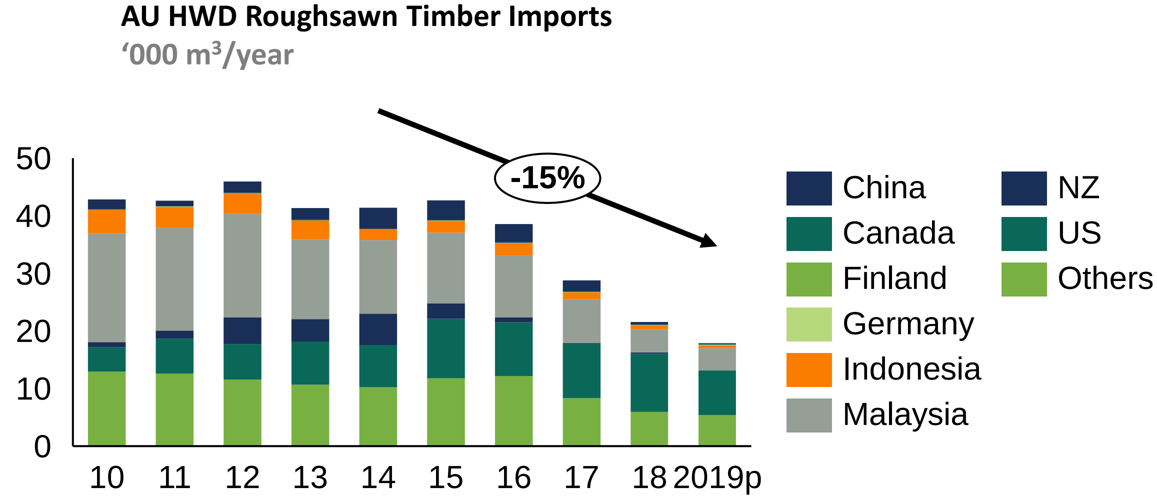
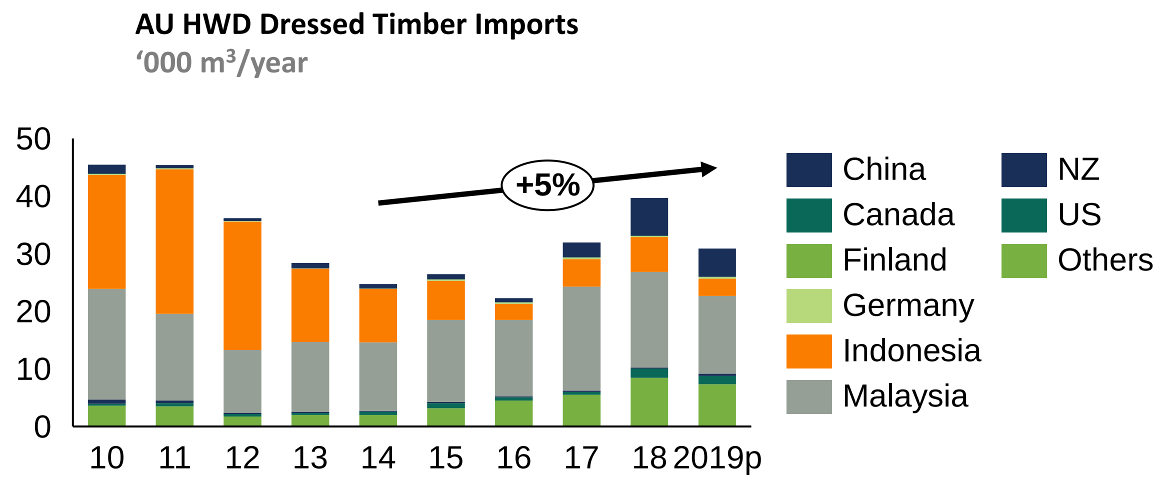
AUSTRALIA HWD IMPORTS

Australian HWD imports continued to decline due to resource availability and the introduction of stricter certification requirements and import regulations



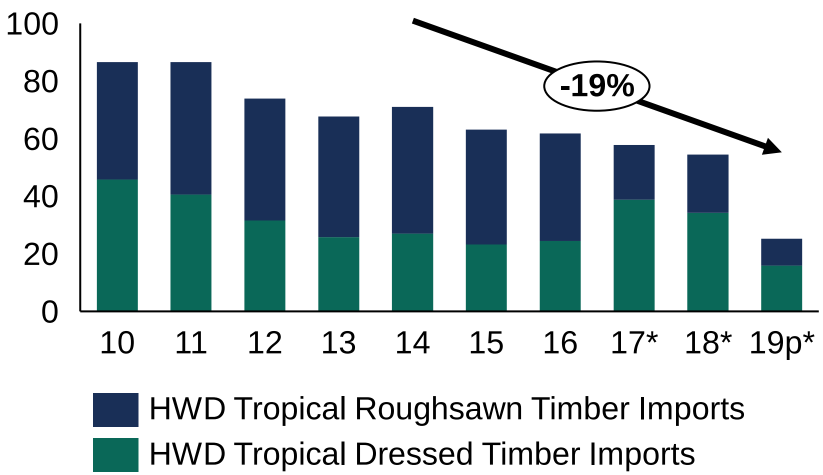




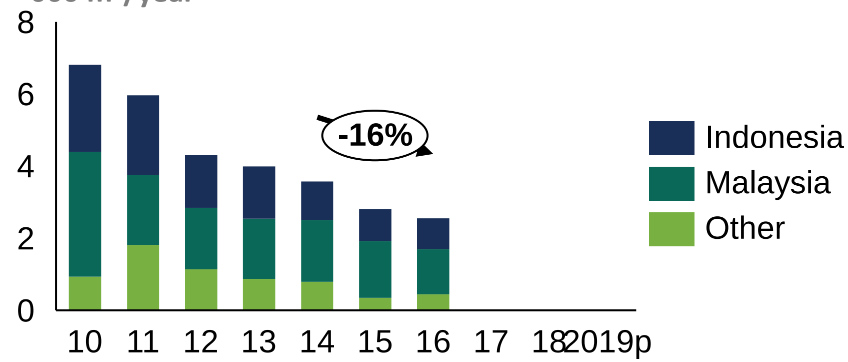
AUSTRALIA TROPICAL HWD IMPORTS

Tropical HWD imports follow the same downward trend affected by resource availability and the introduction of stricter certification requirements and import regulations

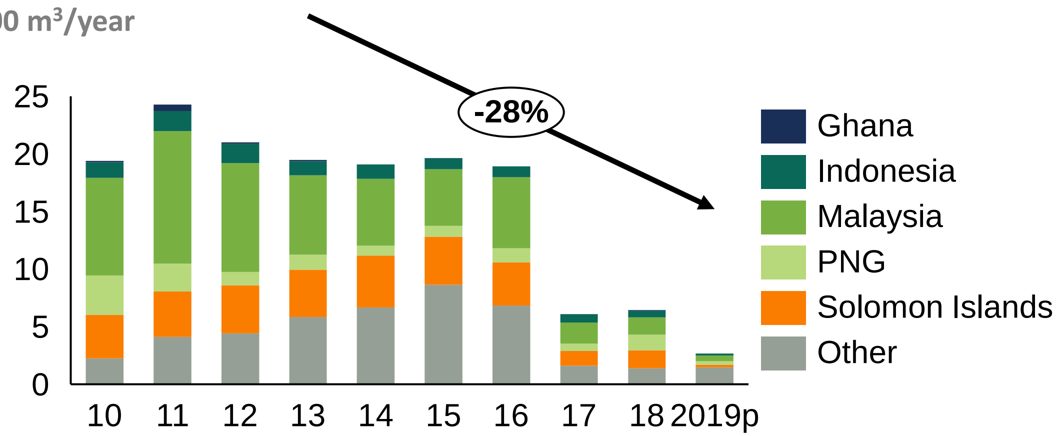
AU HWD Tropical Timber Imports
'000 m^3/year



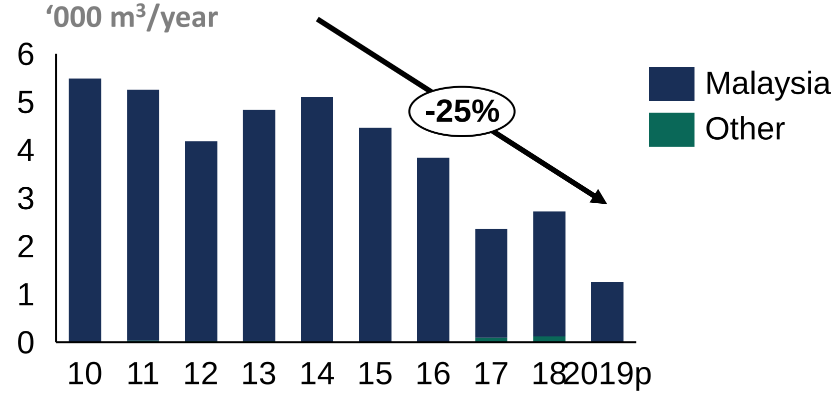
AU HWD Tropical Roughsawn Timber Imports* – Kapur, keruing, merbau
'000 m^3/year



AU HWD Tropical Roughsawn Timber Imports* – other tropical species
'000 m^3/year



AU HWD Tropical Roughsawn Timber Imports* – Meranti, lauan, seraya
'000 m^3/year



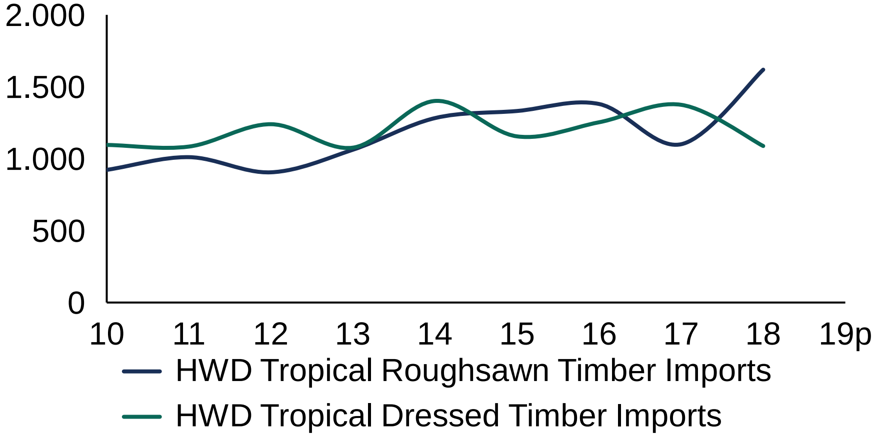
Source: ABARES

*Kapur, keruing, merbau – from 2017 not reported

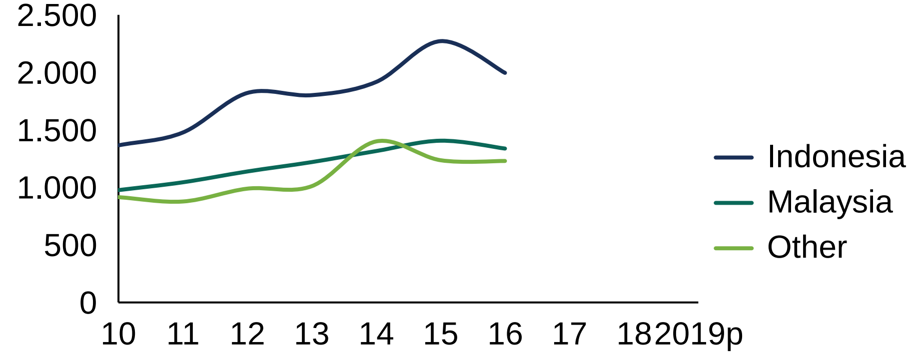
AUSTRALIA TROPICAL HWD IMPORTS

With a few exceptions, the unit value of tropical HWD imports suggests an upward trend – however the data is based on the declared import value and might not be the same as actual market value

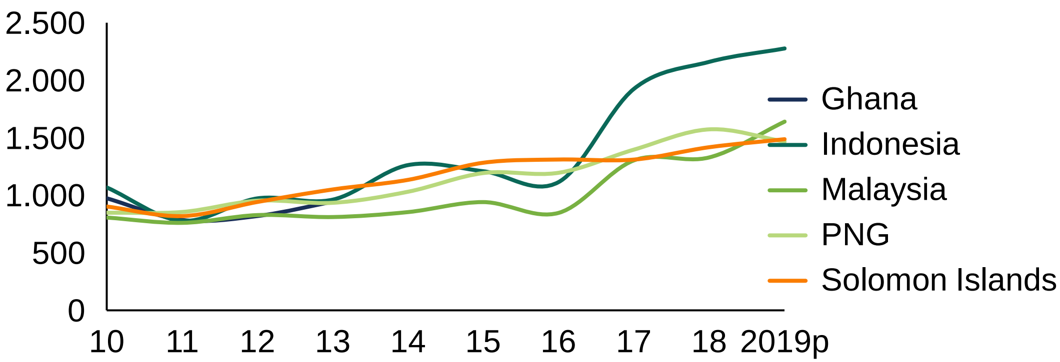
AU HWD Tropical Timber Imports, Unit value, $ / m³



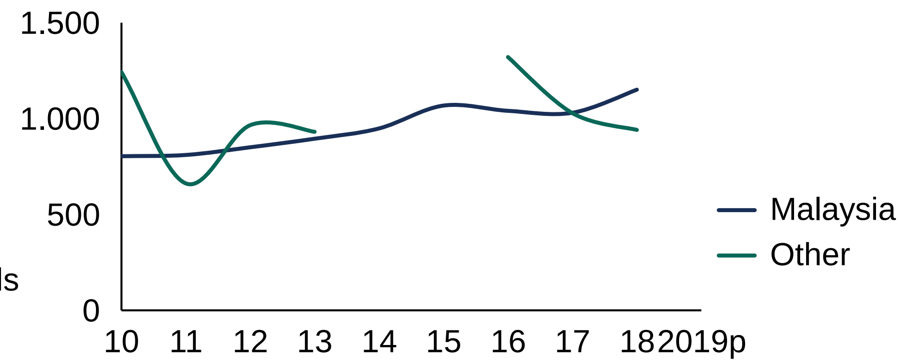
AU HWD Tropical Roughsawn Timber Imports* – Kapur, keruing, merbau, Unit value, $ / m³



AU HWD Tropical Roughsawn Timber Imports* – other tropical species , Unit value, $ / m³



AU HWD Tropical Roughsawn Timber Imports* – Meranti, lauan, seraya, , Unit value, $ / m³



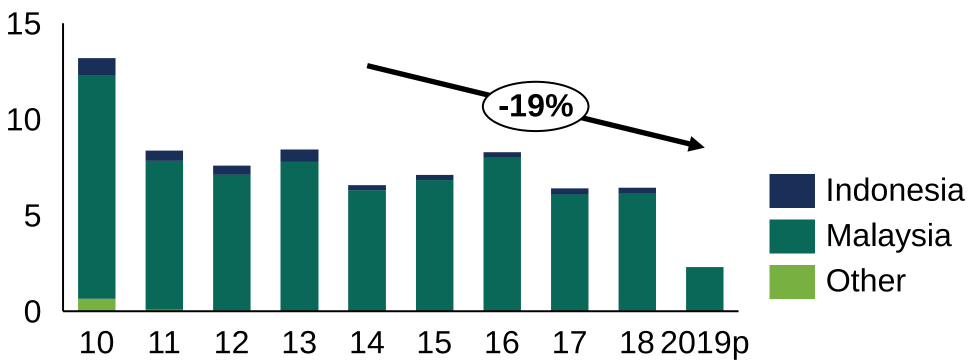
Source: ABARES

*Kapur, keruing, merbau – from 2017 not reported

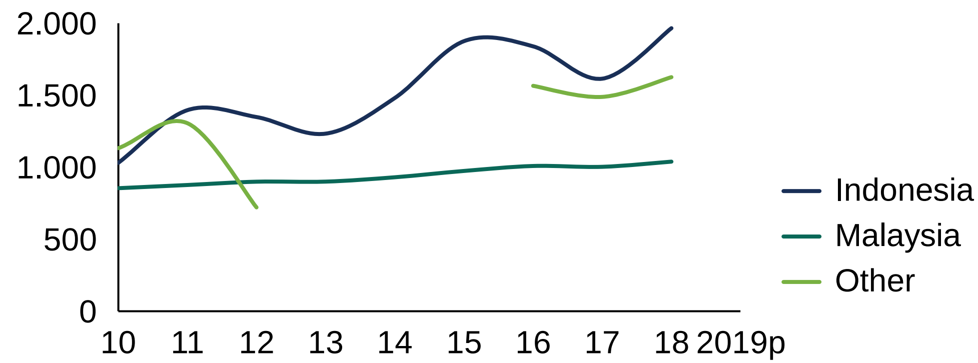
AUSTRALIA HWD TROPICAL IMPORTS

Meranti imports to Australia declined as a result of log supply availability in Malaysia affected by restrictive log export regulations in Sarawak and Sabah due a rapid declining resource

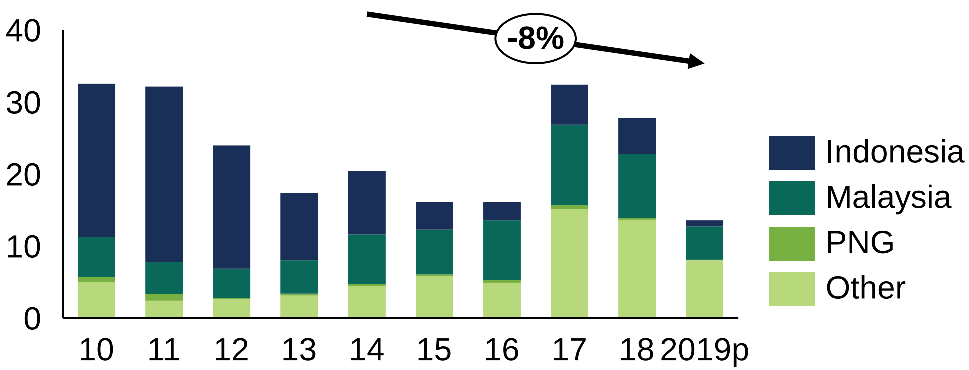
AU HWD Tropical Dressed Timber Imports* – Meranti
‘000 m³/year



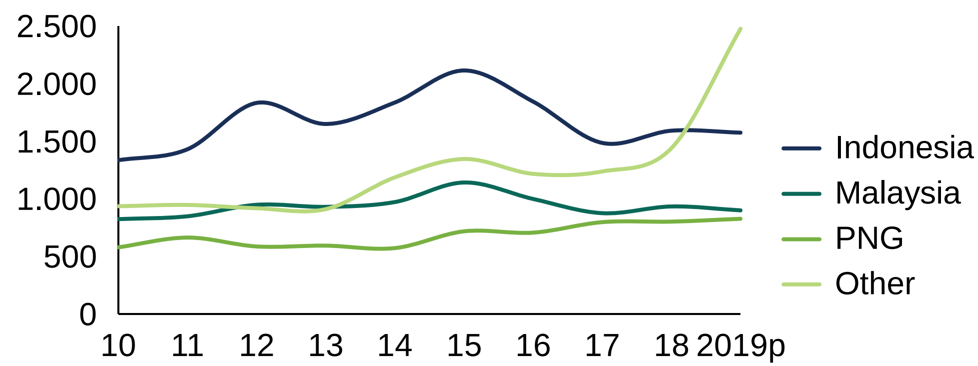
AU HWD Tropical Dressed Timber Imports* – Meranti
Unit value, ‘000 m³/year



AU HWD Tropical Roughsawn Timber Imports* – other species
‘000 m³/year



AU HWD Tropical Roughsawn Timber Imports* – other species
Unit value, $ / m³



Source: ABARES

*Kapur, keruing, merbau – from 2017 not reported

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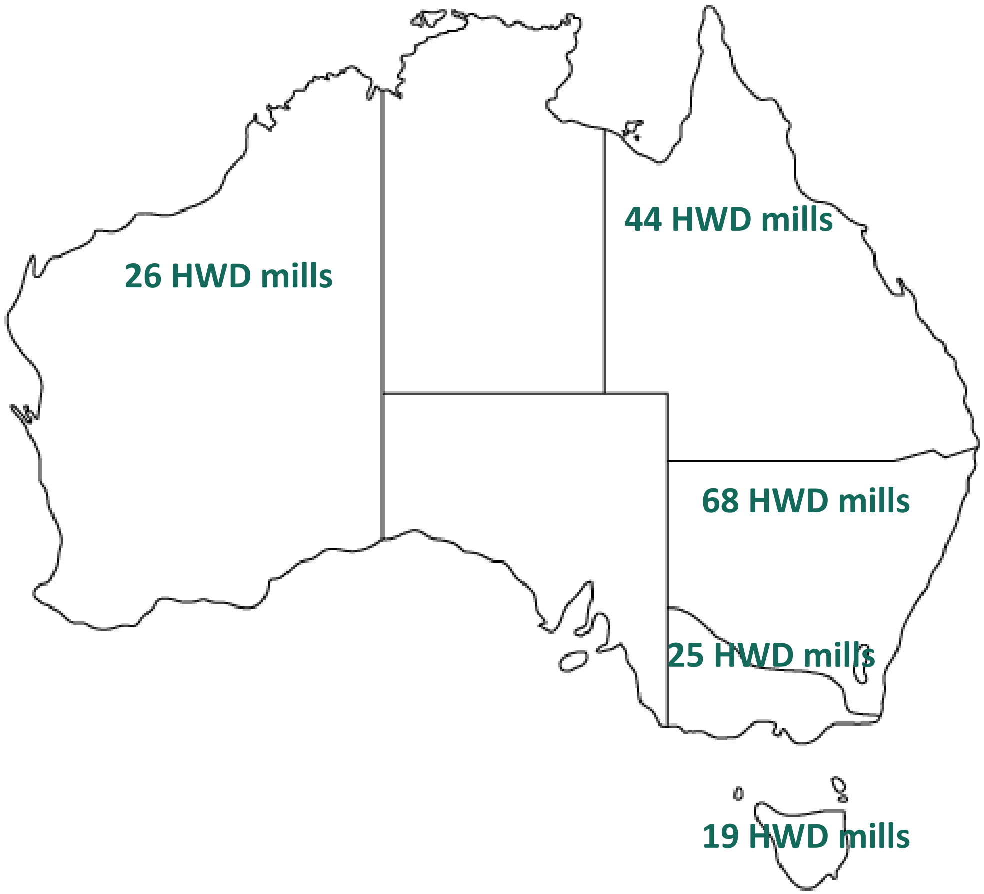
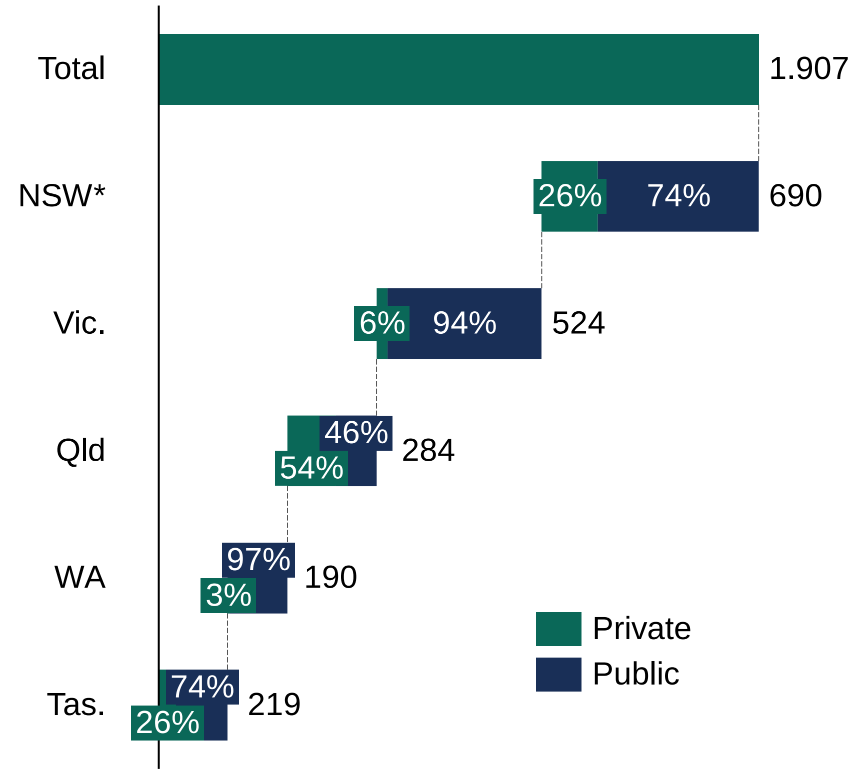
AUSTRALIA HWD PROCESSING SECTOR



Sawlog input, by state and tree ownership, 2016–17
%, '000 m^3



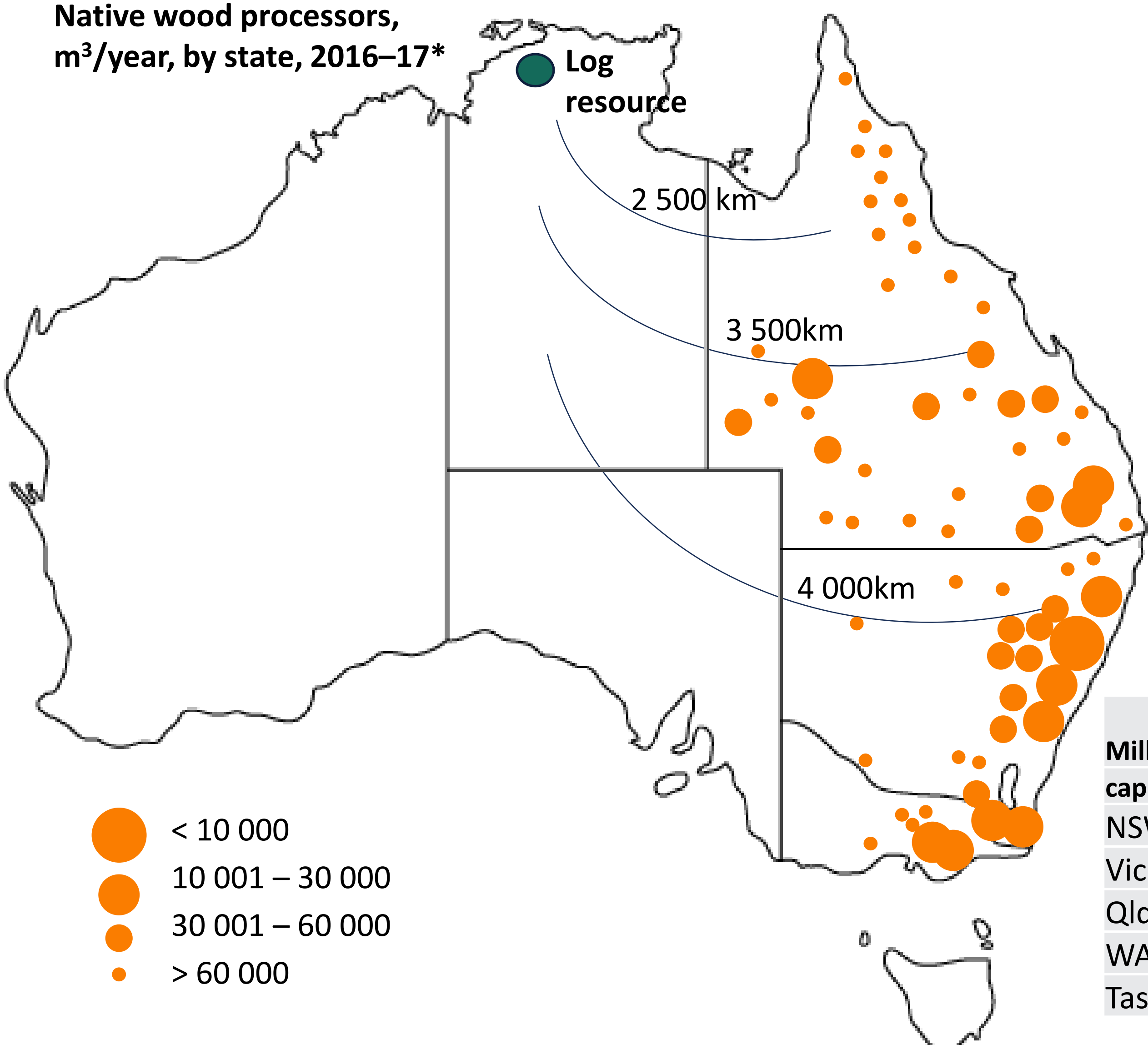
*includes ACT

- Most hardwood products are produced by small mills—74% of the national output of hardwood sawmills in 2016–17 was produced by mills with an annual log input capacity less than 45,000 cubic meters (175 mills).
- Smaller mills typically produce a wider range of products than larger mills and have different processing methods and infrastructure, allowing for greater utilisation of log resources.

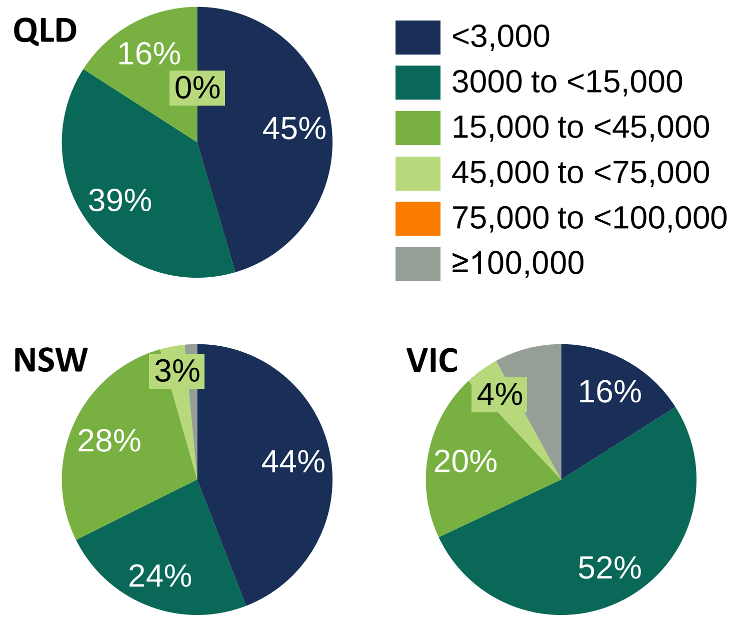
Source: ABARES, Margules Groome

AUSTRALIA HWD PROCESSING SECTOR

Native wood processors, m³/year, by state, 2016–17*



HWD Sawmills size (Sawlog input), by state, 2016–17, %



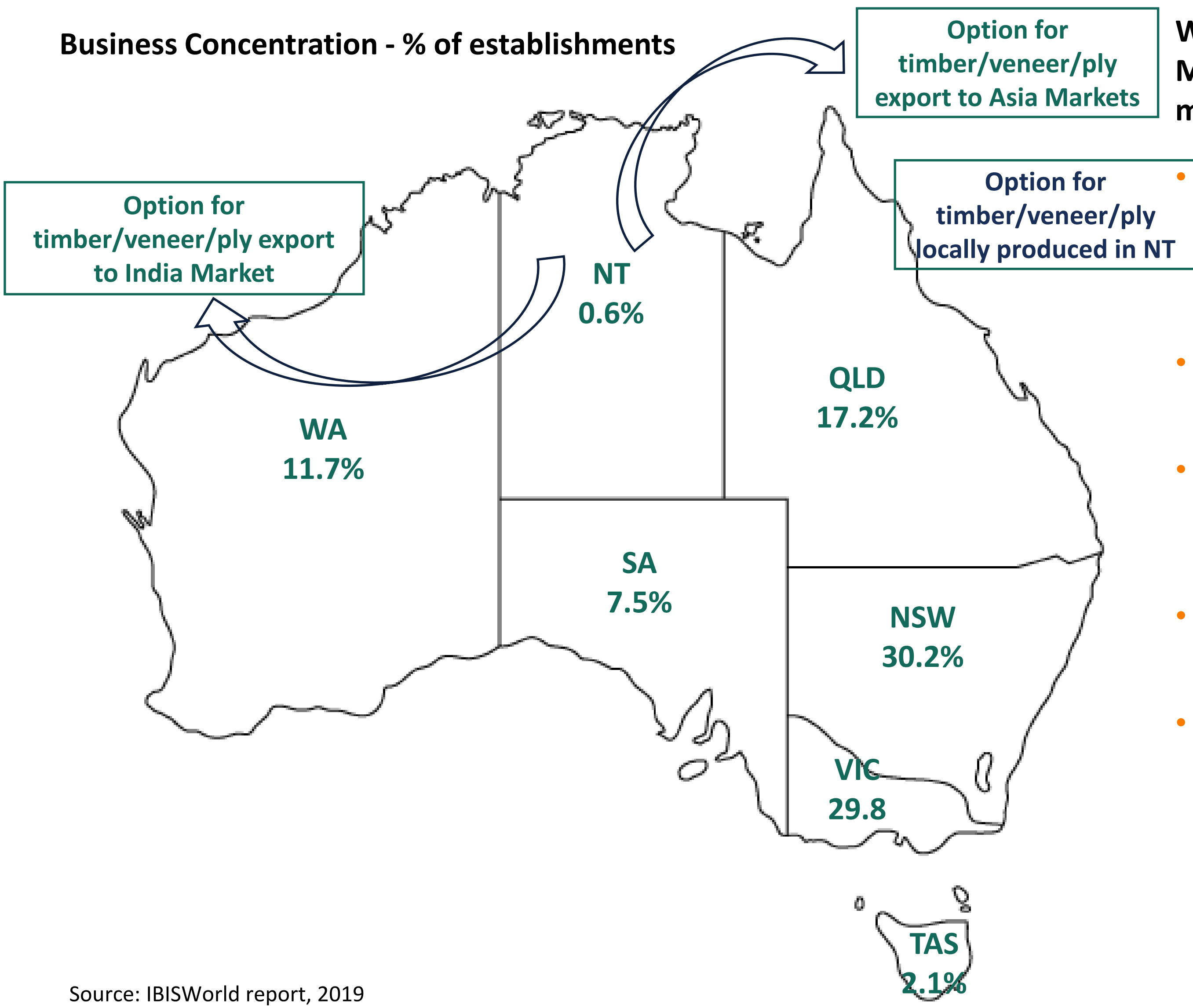
Mill type and state capacity(m³/yr)	No of mills	Total input* ’000 m3	Average input* m³/mill
NSW	68	620	9,121
Vic.	25	539	21,565
Qld	44	276	6,276
WA	26	191	7,348
Tas.	19	211	11,105

***Indicative only**

Source: ABARES, Margules Groome

AUSTRALIA VALUE- ADDING PROCESSING SECTOR

Business Concentration - % of establishments



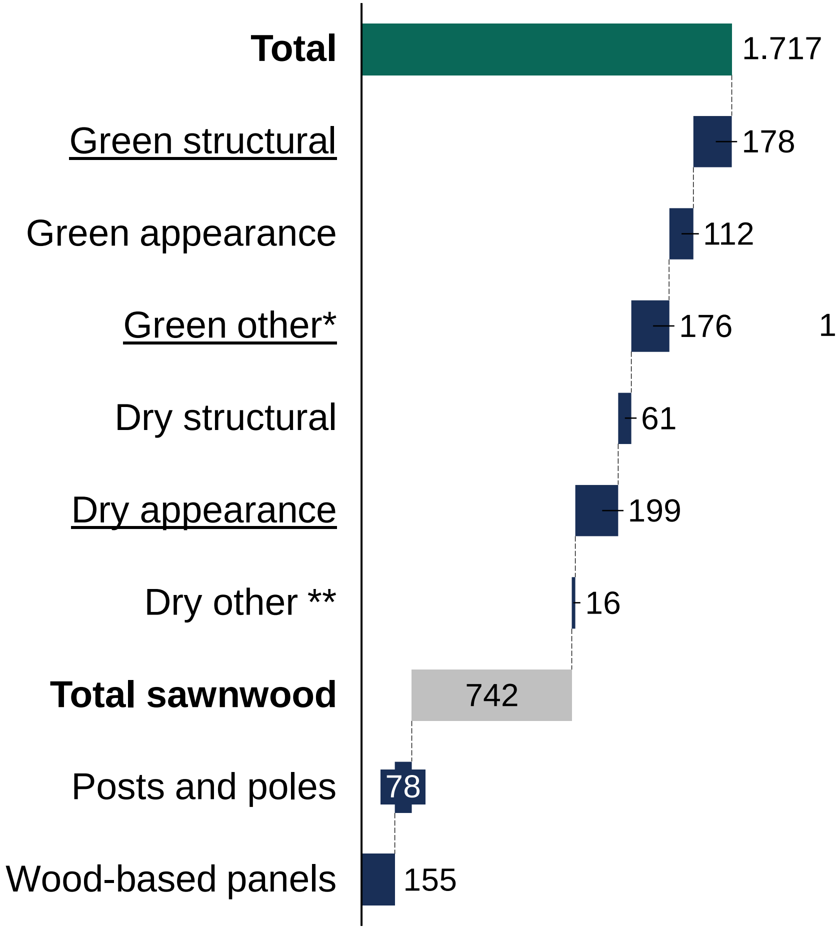
Wooden Furniture and Upholstered Seat Manufacturing in Australia Sector – manufacturing capacities:

- The sector is highly fragmented with many small-scale operators (96% of companies have fewer than 20 employees
- Many of those are very small scale, owner-operated furniture producers
- Are generally located in proximity of the main population and economic centres
- Relative to its population size, Victoria has the most of processing capacity
- WA and SA industry concentration reflects their traditional manufacturing base and availability of skilled workforce as well as log resource (WA=native timbers)

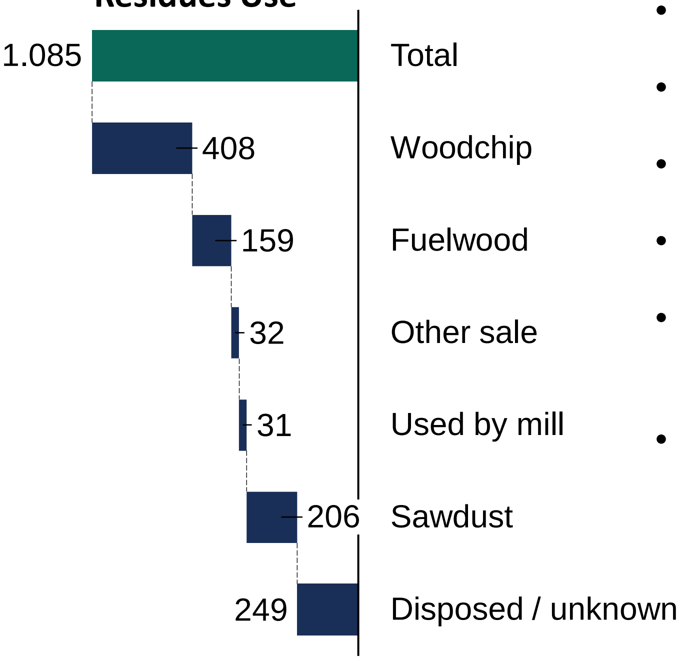
Source: IBISWorld report, 2019

AUSTRALIA HWD MAIN PRODUCTS

HWD Sawmills Production Output, by product type, 2016–17, '000 m^3



HWD Primary Processing Residues Use



Most furniture companies are producing for the domestic market:

- 30-35% dining
- 15-20% lounge
- 15-20% bedroom
- ~ 10% office
- 3 – 5% outdoor
- 5-10% made to order & commercial fittings
- Few furniture manufacturers

* Includes pallets, fencing and landscaping. ** Includes flooring, framing, furniture and pallets.

Source: ABARES, Margules Groome

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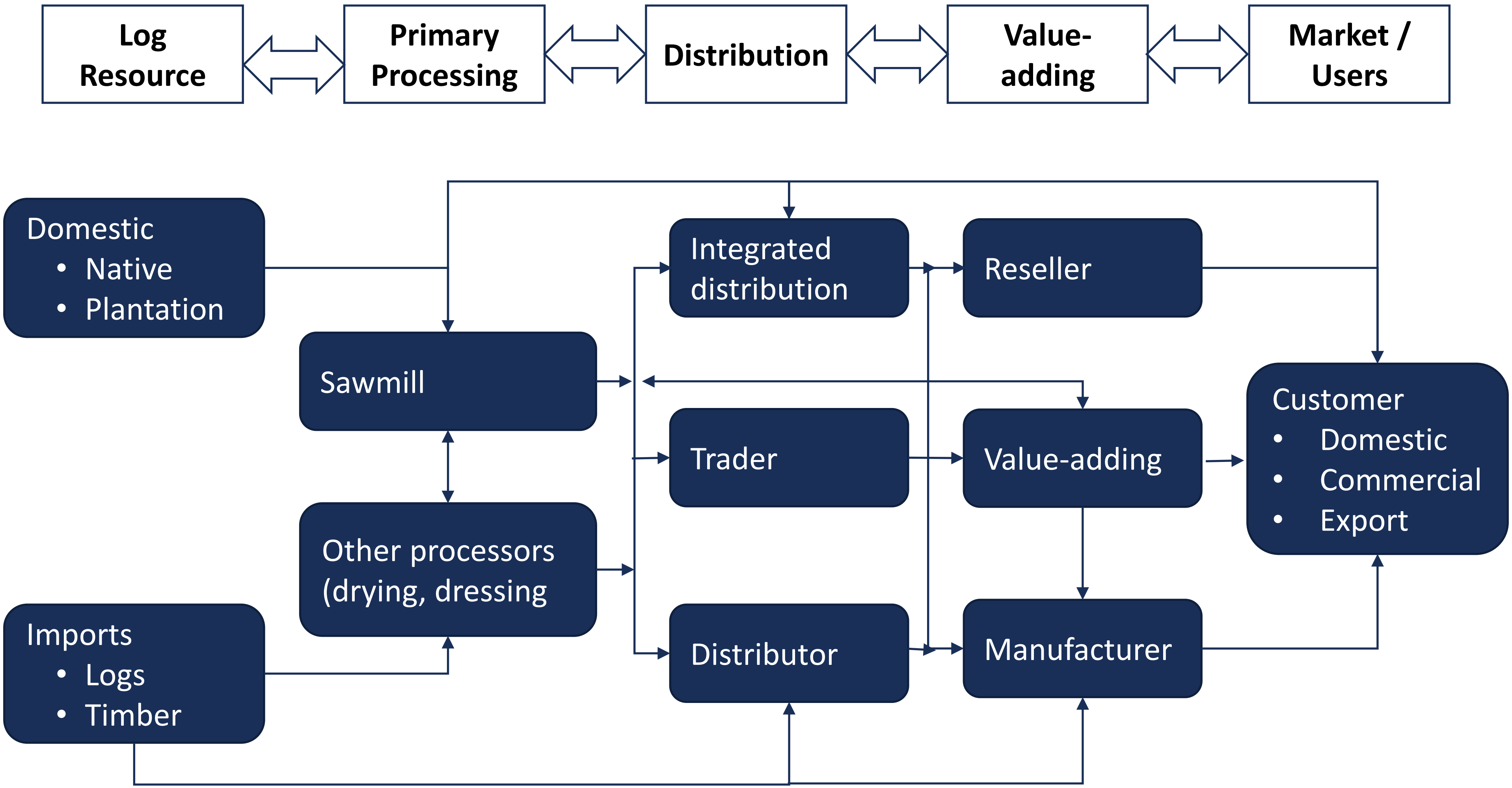
AUSTRALIA HWD SUPPLY CHAIN MAP



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WOOD PRODUCTS KEY REQUIREMENTS

Besides specific log requirements, timber and veneer/plywood manufacturing require various degrees of technological sophistication and access to skilled personnel

Product	Log properties / resource	Location and processing site size	Utilities & consumables
Timber	>20-25 cm diam., min. tapered logs, clear of defects , low nr of dead knots	50-150 km from resource, small / medium-large site	Proper log storage, electricity & heat
Plywood	>20-25 cm diam., min. tapered logs, clear of defects, no dead knots, SWD/HWD	50-150 km from resource, medium-large site	Log storage & conditioning, Adhesives/glues, electricity & heat

Wood Product	Process Technology	Equipment complexity	Maintenance complexity	Operator skill requirement	Direct Employment
Timber / Blockboard	Batch	●○○○	●●○○	●○○○	30...120 FTE
Veneer	Batch	●●○○	●●○○	●●○○	5...60 FTE
Plywood	Batch	●○○○	●●○○	●○○○	40...150 FTE

Low ●●●● High

	Equipment complexity	Maintenance skills	Skills needed
Timber: Log yard receiving – infeed & size sorting – debarking (log & bark) – **sawing (timber, chips & shavings)** – timber sorting, **stickering & stacking** – **drying** – destacking, **trimming & grading** – wrapping & packaging – warehousing, loading & dispatch	2	2	2-3
Plywood: Log yard receiving – infeed & size sorting – debarking (log & bark) **– *(log pond / conditioning)*** – cutting logs in peeler blocks/billets – **veneer peeling – veneer clipping – veneer drying** – veneer layout/glue spreading – cold / **hot pressing** – sanding (and/or lamination) – ply boards trimming – **grading & packing** – warehousing, loading & dispatch	2	3	2-3

Low 1….5 High

MAIN WP/EWP REQUIREMENTS - PLYWOOD

High quality plywood require specific log specifications as well as appropriate log handling & storage techniques/measures

- **Timber in log form / flitches** - In general, criteria relates to **log size, quality and grades, log transport and handling requirements, and log protection and quarantine**.

- **Rotary cut or peeled veneer** - **logs above average diameter, cylindrical in shape and have minimum defects** are sought after. However due to development in manufacturing techniques and **equipment small diameter logs can now be economically utilised through the use of spindleless lathes for example**.

- **Sliced veneers** - **log requirements are more specific and greater emphasis is placed on value of the end product**. Elected pieces of burls, stumps and distorted logs, that provide highly figured and coloured wood suitable for decorative purposes. **These materials are relatively high cost raw materials**. Generally raw material requirements are less stringent for the manufacture of multi-ply plywood as larger quantities of core veneers are required than for 3-ply plywood.

- **Physical characteristics of wood which determines the technical suitability of particular species for veneer or plywood manufacture**.
  - Peeling or slicing characteristics (density, grain distortion, reaction wood, knots, mineral inclusions)
  - Appearance or use characteristics (colour, figure, texture, lustre, odour)
  - Gluing and finishing characteristics (density, grain, glueability, stainability
  - Structural characteristics (strength, resistance to decay, hardness)*

MAIN WP/EWP REQUIREMENTS - BLOCKBOARD

In general, blockboard is considered a value-added product, a by-product of sawmilling and/or plywood manufacturing

- **Small dimension timber / veneer and/or laminated** – blockboard is utilising small dimension / offcuts timber pieces. It has to be **dried and further processed** to eliminate timber movement in service. It **can be used raw**, with no surfacing, when produced with **higher quality appearance timber or laminated with veneers** or reconstituted panel laminates

- **Gluing:** it can be produced by side-length **adhesive gluing** and then cured using elevated temperature and pressure

- **Finger joining & gluing** - it can be produced by **finger joining** in length and sides gluing and then cured using elevated temperature and pressure

- **Physical characteristics of wood which determines the technical suitability of particular species for blockboard manufacture**.
  - ✓ Appearance or use characteristics (colour, figure, texture, lustre, odour) if used for appearance applications
  - ✓ Gluing and finishing characteristics (density, grain, glueability, stainability)
  - ✓ Structural characteristics (strength, resistance to decay, hardness)

PLYWOOD – GRADING REQUIREMENTS – CASE STUDY*

Grade factors	Criteria
General	Logs must be crosscut cleanly at each end perpendicular to their length. All protrusions, limbs and knots are to be trimmed flush with the log surface.
Length	Minimum length is 3.4 m. A minimum length of 2.2 m can be accepted if suitable arrangements can be made for handling and transporting them.
Small end diameter (SED)	Minimum 18 cm.
Large end diameter (LED)	Maximum 70 cm
Knots and limbs	For logs with an SED < 35 cm, the maximum diameter of any knot or limb is 10 cm. For logs with an SED ≥ 35 cm, the maximum diameter of any knot or limb is 20 cm. There is no limit to the number of knots or limbs allowed as long as they do not exceed the max. diameters
Bumps	A log may contain no more than one significant bump in each 1 m of log length. A log may contain any number of bumps that are not significant bumps.
End-splitting	The end of the log may contain minor cracks no more than 5 mm in width.
Scars & evidence of borers	A log may contain scars provided that the log is sound and there is no evidence of any rot beyond the scar itself. A log may contain evidence of borers.
Roundness	Neither end of the log can have a major axis that is more than 20% greater than the minor axis at the end. A log with irregular or “fluted” circumference is not allowable
Sweep	For logs < 5.4 m in length, the maximum permissible sweep is 25% of the SED. For logs ≥ 5.4 m in length, the maximum permissible sweep is 50% of the SED.

Source: ACIAR (Australia) report - A guide to manufacturing rotary veneer and products from small logs
Note*: Case study – Tasmania, Australia

REGIONAL PLYWOOD CAPACITIES DEVELOPMENT

Asian companies continued their investment in new plywood and veneer equipment due to changes in tropical log availability and characteristics as well as due to development of new markets and products (i.e. decorative veneers, combi-ply)

Country	Market	Raw Material	Year
Malaysia	SEA	Mixed tropical	2014
Malaysia	SEA	Mixed tropical	2014
Malaysia	SEA	Mxt trop	2014
Malaysia	SEA	Rubberwood	2014
Malaysia	SEA	Rubberwood	2014
Ecuador	LAM	Mixed tropical	2015
Malaysia	SEA	Mixed tropical	2015
Malaysia	SEA	Mixed tropical	2015
Malaysia	SEA	Mixed tropical	2017
Indonesia	SEA	Albizia, Mixed tropical	2018
Indonesia	SEA	Albizia, Mixed tropical	2018
Malaysia	SEA	Mixed Light Hardwood	2019
Malaysia	SEA	Mixed Light Hardwood	2019

- Sliced veneer recovery of about 50-55% and 60-70% for rotary veneer (dry veneers from plantations hardwoods)
- Conventional peelers with spindle can achieve 65-70% yield (diam. appr. 300mm, under bark).
- With spindleless peeler the yield is about 60% (diam 210mm, above bark)

Insights / quotes:

- "Mahogany is not typically peeled but used as timber for decorative purposes. As a raw material I do not see any obstacles to peel mahogany since it is quite uniform, and the density is not too high
- 10-12 years ago there was a big regression in decorative veneer business worldwide. Approximately 30% of the capacity vanished and a lot of companies went broke; now there are available a lot of used slicers and press dryers
- Mahogany is quite easy to slice and dry. Since the veneer is used to decorative purposes the log requirements are tough. Straight, knotless and correct age are the minimum requirements.
- Also log condition is a must. The veneer outlook is totally different from peeled veneer.
- With peeling the capacity is higher and the log requirements are not so high. Price-wise the decorative veneer is more expensive that peeled"

Source: Personal communication with Raute Oyj representatives

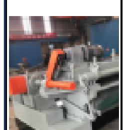
VENEER / PLYWOOD EQUIPMENT - OPTIONS

A large range of veneer peeling and clippers equipment of various level of technology and price are available depends on the log resource and desired production capacity

Examples of large equipment producers include (but not limited to):

- Raute Oj, Finland
- USNR, USA
- Meinan MacWorks, Inc., Japan
- Hanvy machinery, China
- INNOVATOR Machinery,Taiwan
- Grenzebach, Germany
- Suministros Triplay, S.L., Spain
- OMECO Industria e Comercio de Maquinas Ltda., Brazil
- Taichei Machinery, Japan
- Linyi Jinzuo Woohinery dworking Machinery Manuf., China

Other examples of veneer machinery*

	Brand / Producer	Technical details	Price - USD
	ZZCHRYSO - Zhengzhou Chryso Machinery Co. Ltd	8 ft Spindle-less veneer peeling and cutting machine	8 000-50 000
	GT260HY-50F - LINYI GAOTONG IMPORT & EXPORT CO., LTD	Model GT260HY-50F Max length of wood 2600mm / Max diameter of wood 500mm / Left wood diameter 35mm / Veneer peeling thickness 0.6-1.5mm / Size of peeler blade 2700*180*16mm Peeling speed 48 m/min /Total Power 60.7 KW Single roller motor 7.5 kw*2 Double roller motor 11kw*2 / Feeding motor 11 kw /Slitting motor 3 kw Conveyor motor 3 kw/Total weight About 10000KG/Overall size 6000x2300x1650mm	37 800
	GTCO, LINYI GAOTONG IMPORT AND EXPOR TCO., Ltd.	Model GT260SY-45F Max peeling length of log 2600mm/Max diameter of log 450mm/Left log diameter 35mm/Veneer Cutting thickness 0.6 -1.5 mm/Size of peeler blade 2700x180x16mm Cutting speed 43 meters/min/Total Power Single roller motor 7.5 kw/Double roller motor 7.5 kw*2/Feeding motor 7.5 kw/Slitting motor 3 kw/Conveyor motor 2.2kw Total weight About 8000KG/Overall size 5600x2350x1650mm	29 000
	ST, SUMINISTROS TRIPLAY, S.L. Spain	Log adjusting roller conveyor - Log feeding chain conveyor/- LOG DEBARKER - double roller driving (reinforced)- to make log round and peel the bark/- Log adjusting roller conveyor/- Log feeding chain conveyor/- SPINDLE LESS VENEER PEELING CUTTING MACHINE- double roller driving (reinforced)- peeling and cutting wood veneer/- Veneer conveyor/- Stacking unit	On demand

Source: * fordaq.com

SAWMILL EQUIPMENT - OPTIONS

Examples of large equipment producers include (but not limited to):

- Norwood Sawmills
- USNR, USA
- Hundegger USA
- Dieffenbacher USA, Inc.
- Holtec, Germany
- E.ON, Germany
- Linck Holzverarbeitungstechnik GmbH
- ....
- ....
- Hardwood Mills Australia
- A E Gibson & Sons

- A large range of HWD sawmilling equipment exists with global players as well as Australian equipment manufacturers able to offer customizable solutions (based on the available log resource – volume and specifications)
- A sawmill with a 10-15 000 m^3 / month log input can potentially be an efficient solution to process the predicted ~ 15 000 m^3 AMA logs / year
- Potential solutions to be analysed / explore might include medium scale semi-mobile sawmilling equipment

SAWMILL EQUIPMENT - EXAMPLES

A large range of sawmilling equipment of various level of technology and price are available depends on the log resource and desired production capacity

Portable sawmills have some advantages over fixed industrial sawmills (ACIAR/QDAFF, 2014 report), including:

- ability to supply niche markets not serviced by larger processors
- value adding to the smallholder grower
- the flexibility of milling operations – can move to where the resource is located, greatly reducing
- transportation costs
- facilitates operations in inaccessible sites
- allows recovery of small volumes of timber economically
- portable sawmills can handle small diameter logs
- portable sawmills are not as demanding in terms of technology as fixed-site sawmills

However, disadvantages exist, including:

- relatively low productivity – this may be negated by the fact that some areas are not being logged at all due to there being no processing facility nearby
- high labour requirement
- can involve heavy manual handling operations
- the work environment may not conform to proper health and safety regulations
- there may be wide variations in timber dimensions and surface finishes dependent on the standard of the technology being used "

Other examples of sawmilling machinery*

Manufacturer	Price	Model	Engine	Max log diameter	Portability
Lucas Mill 	$14,000	8-30	Kohler Comand Pro V-Twin Closed Loop Electronic Fuel Injection (EFI) Engine	150 cm	Trailer not standard; easily loaded onto a utility or truck
Peterson Sawmill 	$34,000	ASM	27 – 38 hp Kohler petrol engine	180 cm	Trailer not standard, easily loaded onto utility or truck
Mahoe Sawmill 	$55,000	Supermill	Kubota 42 hp turbo diesel engine	90 cm	Custom built trailer as an optional extra
D & L Technologies 	$20,000	8 X 16 Pro	27 hp petrol engine	120 cm	Transportable with standard mobile dolly wheel attachment
Mobile Dimension Saw 	$46,000	12 XLS	Petrol-powered VW engine 67 hp	Unlimited – any size	Heavy duty stainless steel trailer sold separately

Note: Prices valid as 2014 - are **indicative only** and may vary markedly depending on the choice of optional extras and level of technology

Source: ACIAR/QDAFF, 2014 report – Enhancing Key Elements of the value chain for plantation grown wood in Lao PDR, MGC 2018

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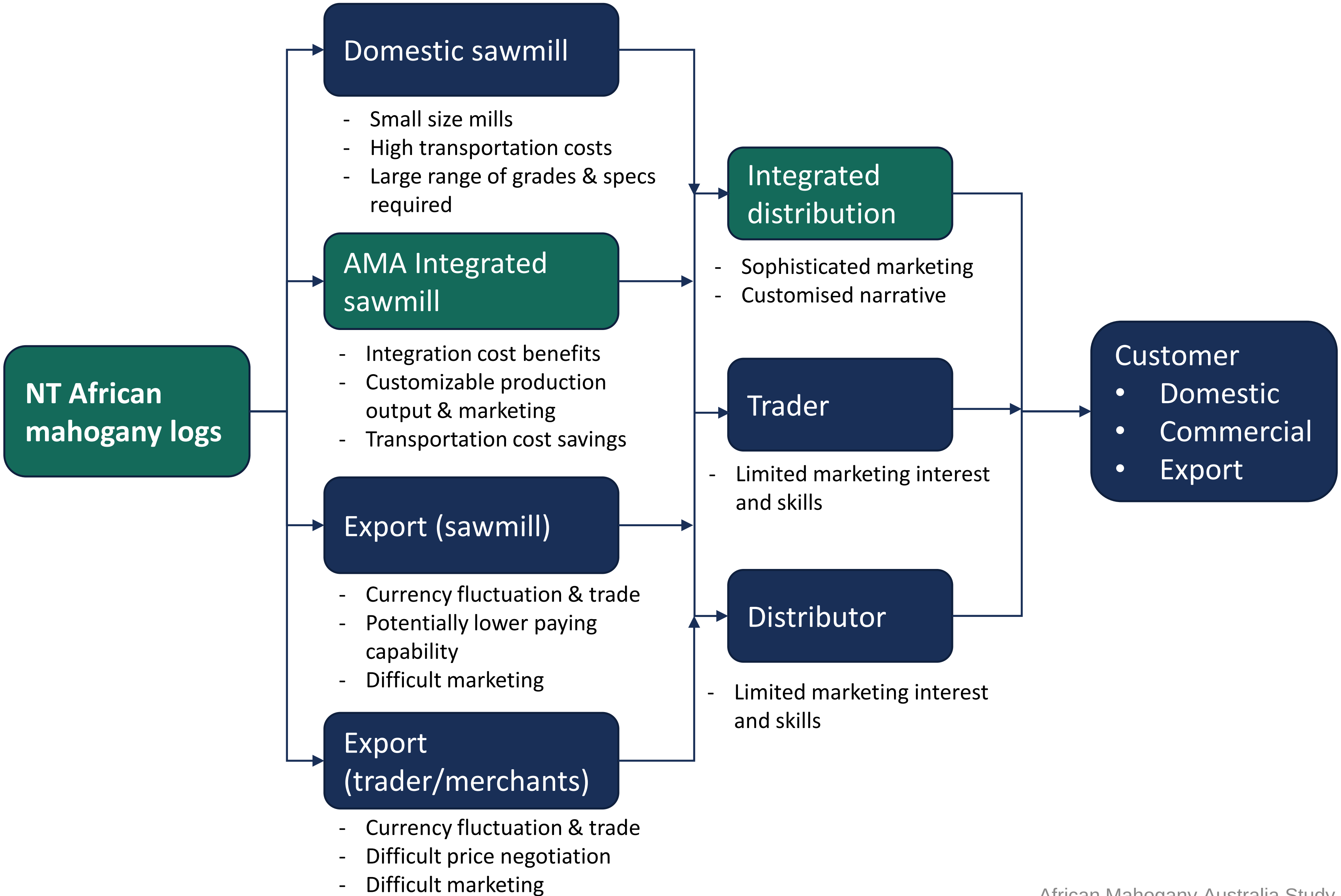
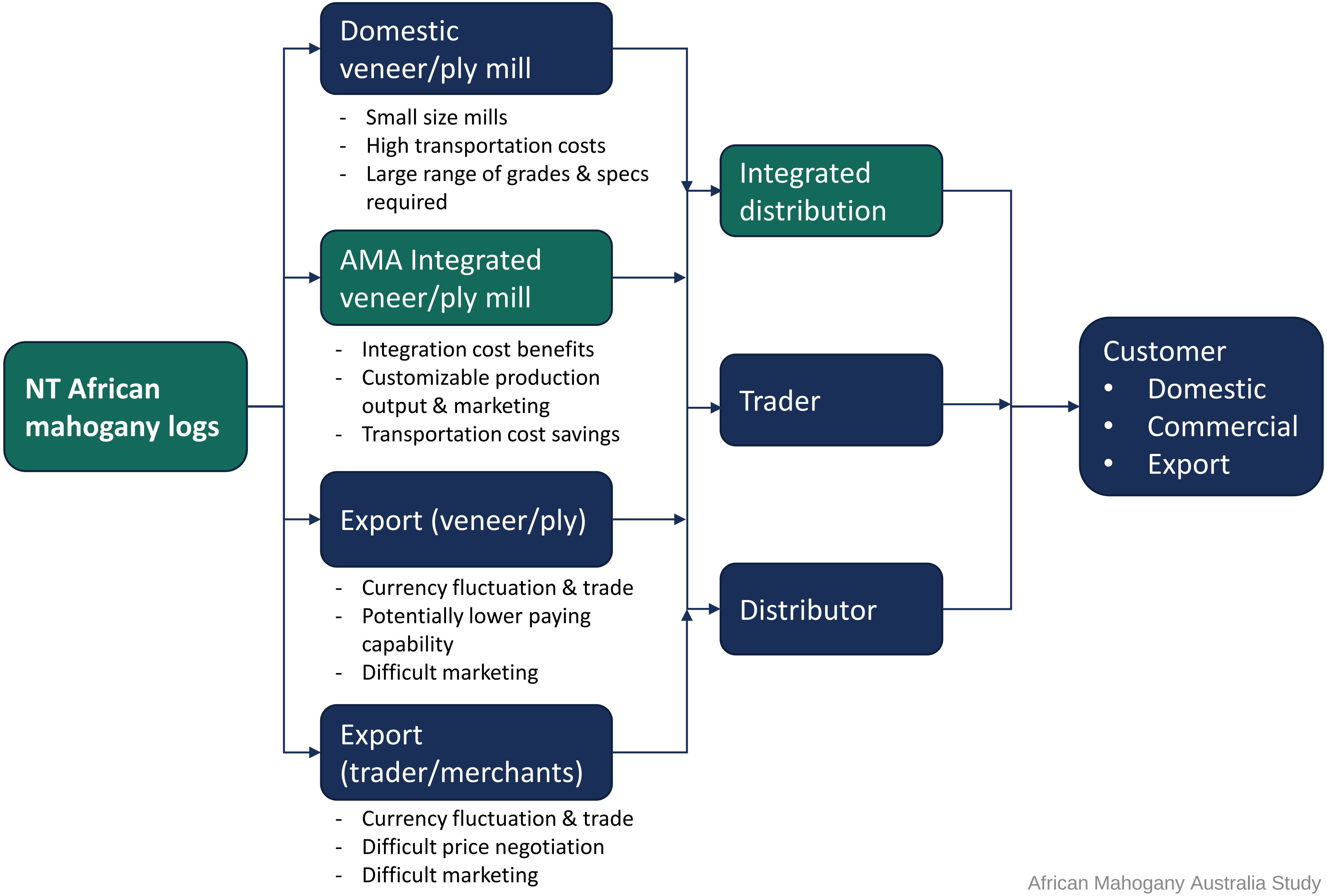
AMA LOG RESOURCE POTENTIAL USE - TIMBER



AMA LOG RESOURCE POTENTIAL USE – VENEER/PLYWOOD



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CERTIFICATION & OPERATING ENVIRONMENT

Global product supply chains are increasingly impacted by market requirements and legislation aimed at demonstrating sustainability credentials. Binding and non-binding are currently in place

1. Reduction of Resource Use

Private and public sustainability efforts are increasingly aimed at reducing carbon footprint, boosting energy efficiency and reducing waste. This is also addressed by the UN's Sustainable Development Goals (SDGs).

2. Corporations Embracing Sustainability

Corporates are beginning to view sustainability as an embedded aspect of their overall mission, as well as a business opportunity. For example, IKEA has committed to 100% renewable or recycled plastic materials and 100% sustainable wood in home furnishing products by 2020.

3. Legislation-driven Sustainability

On the watch list for 2018 will be how European nations and industries change to comply with the Action Plan for the Circular Economy. The legislative dossier sets higher targets for recycling, waste reduction and other initiatives. The FLEGT/EUTR was introduced to ban trade of illegal timber

Responsible Consumption & Production

- By 2030, achieve **the sustainable management** and **efficient use of natural resources development goals**
- **Encourage companies**, especially large and transnational companies, to **adopt sustainable practices and to integrate sustainability information** into their reporting cycle
- Promote **public procurement practices** that are **sustainable**, in accordance with national policies and priorities
- By 2030, ensure that people everywhere have the relevant information and awareness for **sustainable development** and lifestyles in harmony with nature
- Develop and implement tools to monitor sustainable development impacts for **sustainable tourism** that **creates jobs and promotes local culture** and products

Source: https://www.un.org/sustainabledevelopment/

LAWS & POLICIES

In addition to non-binding international agreements, the USA, Europe and Australia have introduced laws & policies aimed to stop the trade of illegal timber

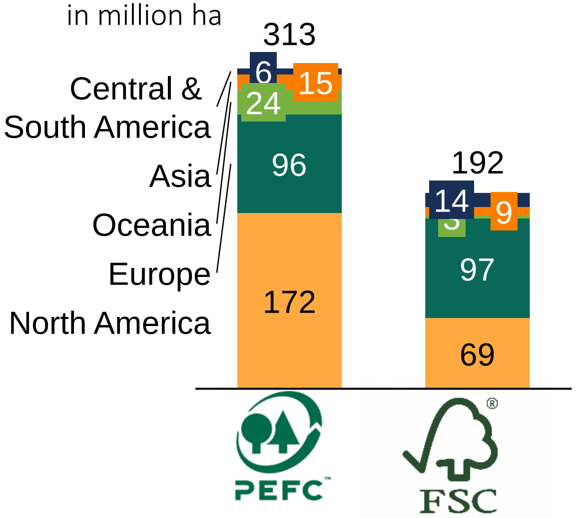
	US Lacey Act	EU Timber Regulation	Australian Illegal Prohibition Act
Key Requirements	Illegal to trade illegal timber. Due care might lower penalties	Illegal to trade illegal timber. Obligation to exercise 'due diligence'	Illegal to trade illegal timber. Obligation to exercise 'due diligence'
Regulated Parties	All entities in the supply chain. The Importer has to file a special declaration.	Applicable to the entity 'first placing timber on the EU market', the 'Operator'.	Applicable to businesses who import timber/products and to domestic businesses that process domestically grown logs.
Product Scope	All plants incl. trees; some exceptions, such as for scientific research and plants that will be transplanted.	Applies to a defined list of timber and timber products, set out in the annex of the EUTR.	The prohibition to import or process illegally logged timber applies to all timber or timber products. The requirement to carry out due diligence only applies to a fixed list of timber/products.
Enforcement	Specialised governmental departments. Civil & criminal penalties are possible, plus forfeiture of the timber/product. Fines up US$500k for corporations and imprisonment up to five years.	'Competent authorities' in each member state. Penalties in force vary across the EU and include fines, imprisonments prohibitions to trade, seizure etc.	enforced by the Australian Government Department of Agriculture. Maximum penalties are five years imprisonment and/or fines of up to AUD$425,000 for a corporation.

FOREST CERTIFICATION = MARKET OPPORTUNITY

MARGULES GROOME

Plantations certification will facilitate market entry and be a major selling point for African mahogany based plantations (timber and veneers/plywood)

Global Certified Forest Area 2017
in million ha



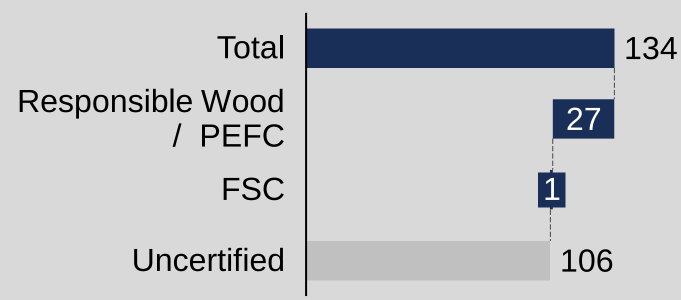
INSIGHTS:

- Globally, the total global certified area amounts to ~431 million ha i.e. >10% of the global forest cover.
- PEFC and FSC concluded that in mid-2017, over 71 million hectares (or 16.5%) of global forest area are double certified.
- 28 forest resources/managers certified (Sustainable Forest Management) in Australia (public native and commercial plantations)
- There is no FSC certified HWD plantation resource in Australia

Scenario A: An AMA FSC. / Responsible Wood certified resource can potentially substitute approx. 5 % of the Australian domestic HWD consumption = high chances of market substitution / penetrations

Certified Forest Area in Australia 2019 , share in %

Certified Forest Area in Australia 2019 , million m^3

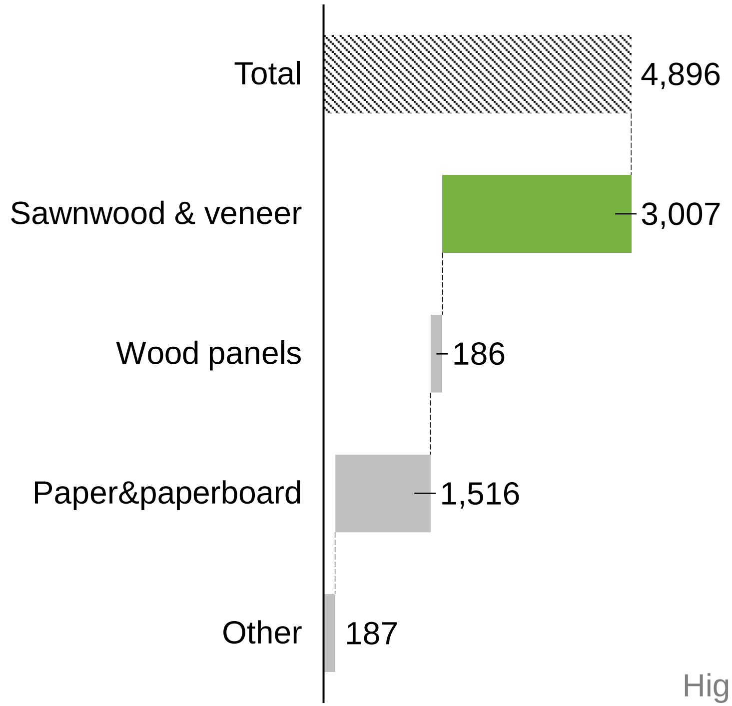


Source: PEFC, FSC, Responsible Wood

AU DOMESTIC MARKET POTENTIAL FOR AMA WP

Domestic demand for sustainable sourced and manufactured WP in Australia continue to be strong. A certified AMA log resource as well as locally manufactured WP have the potential to substitute ~ 5% of the HWD market

HWD Logs Consumption, million m³



~30% recovery

~ 55 000 m³ HWD Imports

+

= ~ 900 000 m³ Timber & plywood production

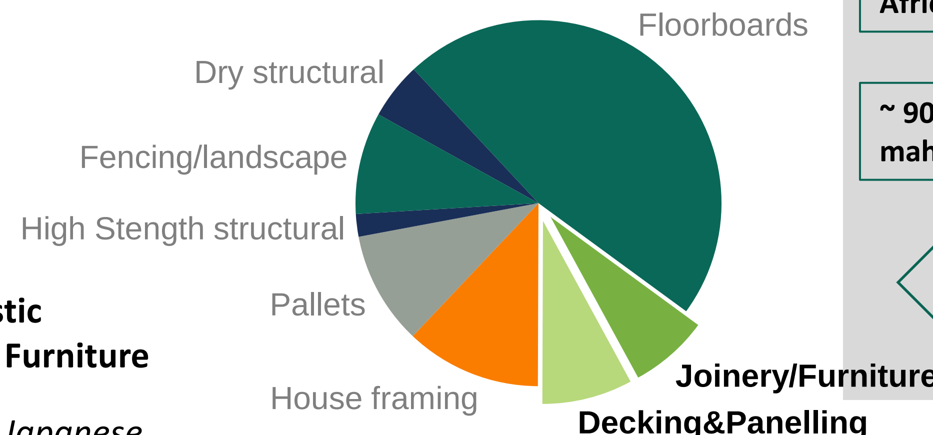
~ 150 000 m³ African mahogany logs

~ 45 000 – 60 000 m³ African mahogany timber*

Or ?

~ 90 000 m³ African mahogany veneer

AU Domestic market Substitution potential



- **Most attractive segment of AU HWD domestic market looks to be the Panelling / Joinery / Furniture**
- *Export markets could target interior flooring Japanese and Chinese markets where durability requirements are lower*

*** For timber recovery rates in the 30-40% rage**

TA ANN / TASMANIA LOG RESOURCE CASE STUDY

MARGULES GROOME

A foreign (Malaysian) and Australian joint-venture that proved to be a lucrative solution for both sides – it has provided a higher value selling price for the AU logs as well as value added profit / export benefits for the Malaysian investor

Issues

Ta Ann: Top 6 Malaysian company / Top Global Tropical Plywood manufacturer

- **Diminishing local (Sarawak) tropical log resource**
- **Established presence in high paying export market (Japan)**
- **Over production capacity exists in Sarawak due to a shortage of local log supply**
- **Need for high value HWD veneer for quality plywood for export markets**
- **High cost unreliable tropical imports from Africa**

Timber Tasmania: Tasmanian Government owned forestry company

- **Regrowth HWD resource available for harvest**
- **Small domestic processing market for this kind of log specs**
- **Low value export market as woodchips**
- **Government support for domestic value added processing in Tasmania**

Solution

Foreign investment / Joint Venture Processing company / Production exported

Result

- **Ta Ann Tasmania (TAT) established in 2005**
- **Ta Ann Tasmania invested over $79 million to develop two veneer mills - the Huon mill built in 2007 and the Smithton mill in 2008 – and in 2015 commissioned a new plywood manufacturing plant in Smithton.**
- **The rotary veneer mills require log billets of between 20-70cm diameter with the average about 35 cm**
- **Veneers exported for ply production / plywood exported as well sold in the AU domestic market**
- **In 2015 the company opened its new plywood plant with an installed capacity of 36,000m3/year to produce a premium grade, zero-emission product sold in the Australian market**

PEFC PRODUCT CERTIFIED paa ENGINEERED WOOD JAS-ANZ

Source: taantas.com.au, Margules Groome

MARGULES GROOME

A second foreign (Malaysian) investment in Australia betting on value adding processing in Australia, in proximity of the log resource - as opposite to log export to Malaysia and processing in Sarawak

Issues

Shin Yang: Top 6 Malaysian company / Top Global Tropical Plywood manufacturer

- **Diminishing local (Sarawak) natural tropical log resource with only smaller diameter logs available**
- **Established high paying export market (Japan)**
- **Over production capacity / over sized processing equipment existent in Sarawak**
- **Need for high value HWD veneer for quality plywood for export markets**
- **Used to import HWD logs from Tasmania to produce face/back veneers for its high quality plywood (2018-2019)**
- **Time / transportation costs / lack of log quality control = low recovery rates in Sarawak**

Solution

Foreign investment / Potential for Production to be exported and/or for AU domestic use

Potential Result

- **Intention to build a rotary veneer mill at Bell Bay to utilize a range of plantation and native HWD logs**
- **Forest resource currently predominantly chipped for export**
- **~ AUD 60 million investment required – for production of green rotary peeled veneer leaf in the first stage, dried rotary peeled veneer leaf in the second stage and a third stage where LVL or plywood is manufactured**
- **Initially it is proposed that all the rotary peel veneer leaf will be wholly exported, but once the plywood line is installed about 30% of the veneer leaf will be converted to plywood/LVL**

Wood Inflow		Estimated Outflow	
Eucalyptus logs	250,000 tpa	Total cumulative outflow at each stage	
		Stage 1 Veneer	48,000m^3
		Stage 1 Woodchip	18,000 t
		Stage 2 Export Veneer	96,000m^3
		Stage 2 Woodchip	80,000 t
		Stage 3 Export Veneer	66,000m^3
		Stage 3 Woodchip	80,000t
		Stage 3 Plywood	30,000m^3

Source: epa.tas.gov.au, Margules Groome, tasmanianbusinessreporter.net.au, tasmps.greens.org.au

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RECOMMENDATIONS

Based on the current market conditions both sawmilling, veneer/plywood processing and high-end blockboard options looks possible subject to further research and considerations

- Local processing of AMA logs in timber, and/or veneer/plywood, as well as value-added blockboard, for domestic use and/or exports appears to be a potential alternative to log exports
  - It can offer an alternative to domestic log sales over very large distances (high transportation costs) to NT or QLD based HWD sawmills
  - It appears to be a more attractive proposition compared to log exports where the purchaser has a strong bargaining power and sales can be negatively affected by currency fluctuations and high marketing costs
  - Integration benefits (log production – processing – distribution) exists
  - High potential for customisable production output and better/more informed marketing and market access strategies
- A joint venture with an Asian processor with existing market access to Japan, SKorea and Europe can be a possible operating model
- Domestic timber / blockboard production appears to be a possible option for the AMA log resource with timber and EWP destined for the solid furniture production market
- Blockboard appears to be a good potential high-value product able to utilise lower quality timber pieces as well as high quality veneers to produce a quality panel product
- Veneer/plywood processing is also a possibility - however, current examples of domestically produced sliced veneer shows that Australian logs shipped in containers abroad for processing and import of sliced veneer is a better economic solution due to high AU operating costs (a pre-feasibility study could assist on determining the best options)
- A certified AMA resource has the potential to substitute domestic HWD timber for medium-high value uses
- Australian market demand for sustainable HWD demand continue – however it is a market highly dependable on consumer trends (species, colors, natural features, stained/natural)

Market Testing Recommendations – Next Steps

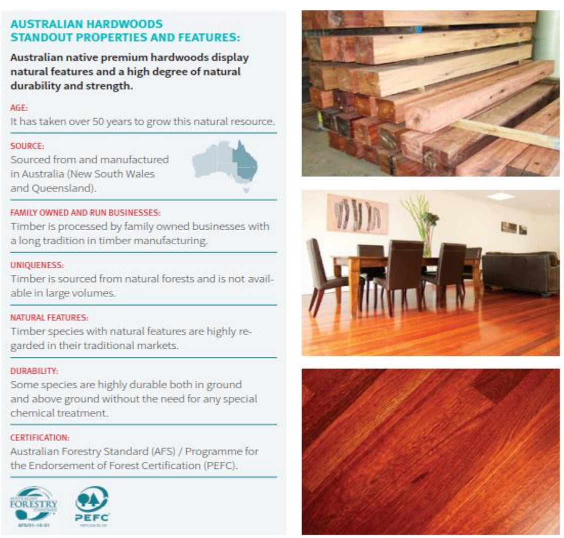
New / lesser-known wood species entrants have to overcome a range of barriers when entering an established market with existing players and products. Potential strategies include:

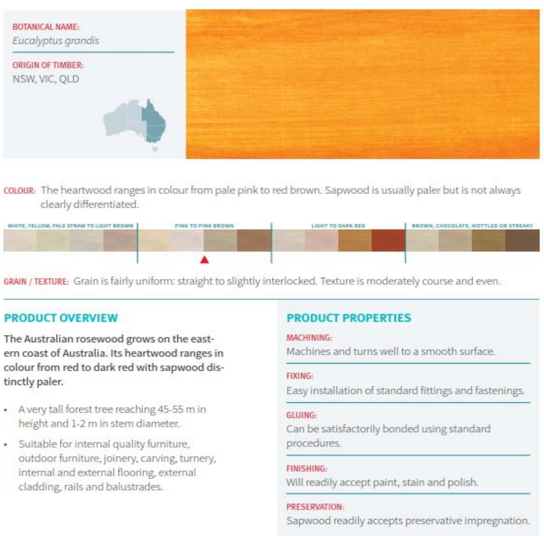
- Determination of wood properties, workability and a knowledge of product life cycle are extremely important (*Plantation wood species are always compared with their natural equivalent*)
- Physical and mechanical properties, appearance, glueability, finishing potential and serviceability have to be determined and presented to the users / market
- Extensive market and consumer preference studies need to be conducted

Preparing answers specific questions:

- *How durable is this timber? How easy is to cut it? Can it be easily dried? Can I use it for external applications? Is it better than A, B, C species – why?*
- *Which glues can I use for this specie? Can it be stained? Clear coated?*
- *How stable is in interior applications – does it move in dry / humid environments?*
- *Can you provide us with some specimens of timber to test the market?*
- *Can you provide 1 m³ of dried / dressed timber as I would like to build furniture to test the market?*

<u>Examples of promotional material for "new" species*</u>





*Source: Margules Groome Development Project

Market Testing Recommendations – Next Steps

A. Proof of concept – design / manufacturing – production of a sample / shop floor customer preference – intention to buy survey

- Create awareness of the "new" timber species among the local (or outsourced – foreign) industrial designers – provide them with timber specimens and technical specifications datasheets (results of the R&D and testing work)
- Based on the wood visual appearance and mechanical properties, design a product that can later be replicated – that has the potential to be manufactured at larger scale volumes if markets accept and demand it
- Display the new product in well-established furniture / interior design showroom(s) and conduct thorough survey(s) of consumer preference and capacity to pay for it
- Advertise the project and promote the new "Australian grown sustainable timber" that the product is made off – complement it with the "Australian designed and made" promotional message

Case study: Holmesglen Institute of TAFE - The Centre for Design, Arts and Science -The Furnishing and Joinery Manufacturing Department successfully completed a joint project with a local Melbourne industrial designer, local furniture manufacturer Silver Lynx Furniture and Bevmarks retail stores to **design, prototype, manufacture and market an original bedroom suite***.

AUSTRALIAN MADE AUSTRALIAN GROWN PRODUCT OF AUSTRALIA

- Source: Holmesglen Institute of TAFE annual report; https://bevmarks.com.au/content/albany-bed, https://www.australianmade.com.au/why-buy-australian-made/about-the-logo/

Market Testing Recommendations – Next Steps

B. Furniture design competition – targeted to industrial design students within TAFE and University sectors

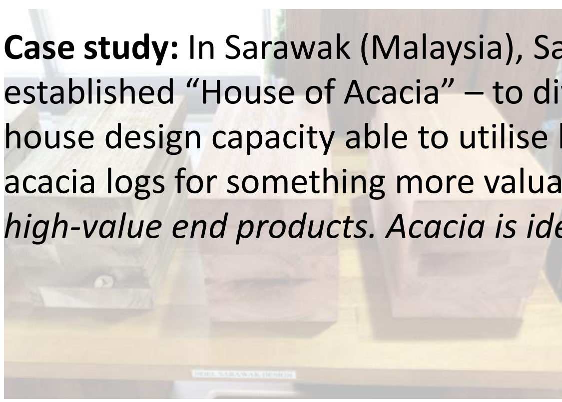
The main idea is to start “fresh” - without the need to change old design habits and personal preference for particular wood species, designs and / or finishes: create awareness of the new timber species and its properties and get new product design ideas that can be further adapted or introduced to markets

Case study: ACIAR (Australia) development project in Laos, organised and run a design competition among the National University of Laos: **Design new furniture products using Lao PDR plantation grown teak timber.** A significant number of furniture designs using plantation grown teak were submitted, designs evaluated and ranked. The winners licensed their designs and entered in commercial agreements with local furniture manufacturers to produce and sell plantation teak furniture in the domestic market and promote it to international furniture Expos. The competition was widely advertised in the visual and printed media in Laos promoting the value potential of the locally grown teak plantation resources.

Note: Initially, Lao plantation teak timber was tested at Uni of Melbourne as well as NUOL Laos.

C. Design scholarship / Internship – co-host with furniture manufacturers, industrial design graduates and focus their attention on designing with the new species of timber – tailor the new products to specific markets based on solid market and consumer preference studies

Case study: In Sarawak (Malaysia), Samling (one of the top global plywood producers) supported by the local Government established “House of Acacia” – to diversify its product offerings and add value to its plantation logs by developing in-house design capacity able to utilise locally grown certified *Acacia mangium* plantation resource. It promoted the use of acacia logs for something more valuable than the woodchips for pulp production – a versatile material that “*can be used in high-value end products. Acacia is ideal for furniture and building materials, both indoor and outdoor*.”



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Appendix 2: Market focussed processing studies of plantation grown African mahogany

Frank Miller, African Mahogany Australia

Introduction

Previous studies have demonstrated promising processing outcomes from young mahogany grown in Queensland (Zbonak *et al*. 2010). The Market Scoping Study (MSS) (Appendix 1) identified, that due to the long supply chain distances within Australia, that local processing was an important option for maximising the value of timber produced in the NT. The MSS recommended that current milling options and timber handling options should be evaluated.

Following the processing studies undertaken by QDAF (Sections 5-7 of this report), the industry partners (African Mahogany Australia and Huntley Management) initiated further processing studies to investigate the suite of processing options available to optimise value from the plantation mahogany timber resource. Three issues were investigated:

- The potential for local sawn timber production in the NT
- The potential of veneer production through slicing
- The options for colour modification to enhance the appearance of young mahogany.

The material obtained from the milling has been used to exhibit the characteristics of Northern Australian plantation mahogany. Material of excellent feature and suitable quality has been produced and has enabled the estate managers to provide samples to potential customers in China, and to commence the next step in having feature furniture produced to showcase the timber locally.

This trial investigated milling and drying processes under local NT conditions and assessed the quality and feature of timber produced from logs of varying ages. The following is a brief outline of the results of the trial and a discussion of the issues that arose and next steps.

Milling Trial

Methodology

African mahogany logs were selected from three stands of differing age, two in the Douglas Daly and the other from Coastal Plains near Darwin. The logs were milled in Katherine NT. 53 logs from 27 trees and three separate locations were selected, harvested, measured and transported to Katherine to be milled using a Wood Miser bandsaw mill.

Table 1. Summary of the properties and number of trees and logs supplied.

Property	Age	Trees	Lengths
Stray Creek	11	9	18
Why Not	13	9	18
Coastal Plains RF	14	9	16

The logs were milled under the supervision of Dr Graeme Palmer from Southern Cross University, from 8-9 August, 2018.

Logs were milled green and racked and air dried in Katherine and moved to finish drying in the Douglas Daly from 9th August to the 22nd February 2019. Moisture content using a moisture meter was measured at 15% at time of dressing.

Logs were marked and measured, and timber was tracked from milling through to skip dressing to establish recovery rates using a wood miser mill. Impact of taper and log length on recovery is discussed later.

Results and Discussion

Table 2. Summary of log measurements and rough sawn recovery

Property	Tree #	DBH (OB) cm	Volume (m^3)	Recovered Volume	Recovery %
Stray Ck	S1	28.5	0.203	0.070	
Stray Ck	S4	25.9	0.174	0.091	
Stray Ck	S5	26.3	0.181	0.069	
Stray Ck	S6	26.4	0.216	0.075	
Stray Ck	S7	27.1	0.188	0.075	
Stray Ck	S8	26.7	0.210	0.116	
		26.8	**1.173**	**0.495**	**42%**
Why Not	W1	26.2	0.189	0.062	
Why Not	W2	27.0	0.243	0.074	
Why Not	W3	28.5	0.230	0.083	
Why Not	W4	30.4	0.281	0.120	
Why Not	W6	28.6	0.183	0.032	
Why Not	W7	30.0	0.268	0.106	
Why Not	W8	25.3	0.244	0.041	
		28.0	**1.637**	**0.517**	**32%**
Coastal Plains	CP1	40.9	0.368	0.159	
Coastal Plains	CP1-2	24.6	0.116	0.052	
Coastal Plains	CP2	20.4	0.111	0.080	
Coastal Plains	CP2-2	22.7	0.073	0.025	
Coastal Plains	CP3	31.5	0.148	0.059	
Coastal Plains	CP4	29.9	0.218	0.054	
Coastal Plains	CP5	35.7	0.340	0.144	
Coastal Plains	CP6	27.9	0.150	0.071	
Coastal Plains	CP7	41.0	0.336	0.150	
Coastal Plains	CP7-2	27.0	0.109	0.033	
Coastal Plains	CP8	31.8	0.270	0.084	
Coastal Plains	CP9	29.7	0.215	0.067	
		30.3	**2.453**	**0.979**	**40%**
Gross Recovery			**5.263**	**1.990**	**38%**
Dressed recovery				**0.837**	**16%**

During the milling, racking and sorting prior to dressing the timber, it was observed that the most influential factors that impacted recovery were log length, taper and racking technique.

Log length impacted on recovery due to the significant taper of the log. A focus on recovering boards of shorter length that were impacted by taper would have yielded higher recovery.

It was found that rack sticks were placed too far apart, resulting in unacceptable movement (mainly bowing) of mostly the 25mm boards. This significantly reduced the amount of timber that was taken to be dressed.

Table 3. Log and recovery data by property

Property	DBH (OB) cm	Volume (m^3)	Recovered Volume	Recovery %	Average taper (diam loss per m [cm])	Average log length (m)
Stray Creek	**26.8**	**1.173**	**0.495**	**42%**	3.7	1.66
Why Not	**28.0**	**1.637**	**0.517**	**32%**	4.2	1.84
Coastal Plains	**30.3**	**2.453**	**0.979**	**40%**	2.5	1.99
Gross Recovery		**5.263**	**1.990**	**38%**		
Dressed recovery			**0.837**	**16%**		

The variation in recovery rates was analysed by assessing log shape and size. As seen by the log biometrics (average taper, diameter loss per metre of log), the Coastal Plains logs were most cylindrical, with a change of 2.5cm in diameter per metre of log. The Why Not logs had the most taper with 4.2cm change in diameter per metre. When combined with taper, log length certainly influenced recovery – with the shortest average log length (Stray Creek) yielding the highest recovery despite having greater taper (3.7 cm m^{-1} vs 2.5 cm m^{-1} Table 2) than logs from Coastal Plains.

Colour

There was noticeably more colour in the heartwood of the older logs. The WhyNot logs (age 13) and the Coastal Plains logs (age 14) both showed good heartwood colouring (>67% of diameter), the Stray Creek (age 11) logs did not show strong colouring in the heartwood.

Timber from Stray Creek was sent to Southern Cross University to be tested in staining trials – see Staining section below.

Observations

Boards with no defects– 61% of total boards assessed were free of any movement, checking, splitting, knots and other defects

Timber movement – as mentioned there was unacceptable timber movement in thinner boards when drying. It was evident that sticker spacing for the timber was inadequate, with bowing occurring between stickers in thinner boards.

End splitting –occurred in 12.5% of 88 boards that were assessed. 82% of boards containing end splits contained centre pith

Checking – occurred in 10.2% of the 88 boards assessed. 18% of the boards with checking also contained centre pith

Centre Pith - 32% of the boards contained centre pith – this is a function of milling smaller logs. Future studies should focus on technology available to minimise centre pith in the milling pattern.

Other – wane, knot, bow – 14.7% of boards contain other defects.

Image 1: Logs at Bob Cavanagh's yard

Image 3: Stacked timber

Image 4: Timber being dressed at Nortruss in Winnellie, NT

Image 2: Log being milled on the Woodmiser mill at Katherine

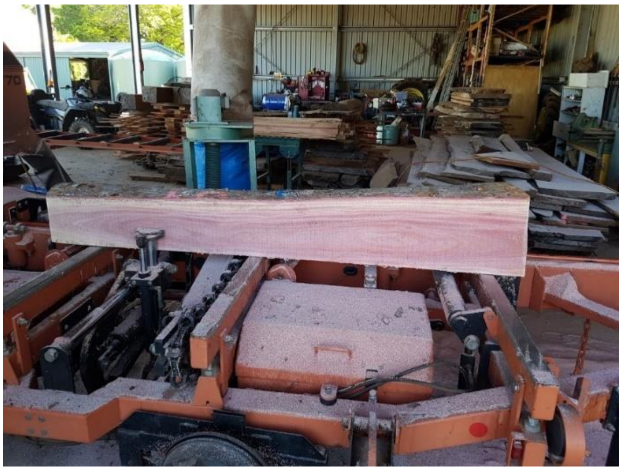

Image 5: Dressed boards

Veneer Trial

This trial investigated the production of face grade sliced veneer from 14-year-old *Khaya senegalensis*.

Methodology

Logs of suitable size for slicing (Image 6) were selected from the Huntley Management mahogany plantation at Elderslie (Qld). Logs were transported to Tasmania and sliced at Tasmania Specialty Veneers in Somerset, North West Tasmania, one of few mills in Australia that produce sliced veneer.

Results and Discussion

Table 4. Summary of flitches and recovery from slicing trial undertaken at Tasmanian Specialty Veneers

Log No	Flitch No	Length	Width	Depth	Flitch volume	Leaf ex Kleis	Production
		m	mm	mm	**m^3**	m^2	m^2m^{-3}
8	1	3000	240	300	0.2160	329	1523
2	2	3000	180	240	0.1296	151	1167
7	3	3000	290	290	0.2523	310	1232
6	4	3000	280	230	0.1932	247	1281
10	5	3000	280	300	0.2520	335	1330
4	6	3000	250	260	0.1950	273	1401
3	7	3000	260	260	0.2028	263	1295
1	8	3000	270	250	0.2025	291	1437
5	9	3000	260	290	0.2262	287	1270
				total m^3	**1.8696**	**2488**	
					Mean m^2m^{-3}		1331

The feature and grain characteristics of the finished veneers (Figure 8) demonstrated the high quality that could be achieved with sliced veneers from young mahogany.

Image 6: Logs loaded in Qld for transport to Tasmania for slicing.

Image 7: It was found that the veneer leaves curled vigorously following slicing

Image 8 a: Veneer panels produced from the Elderslie flitches

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Image 8 b: Veneer panels produced from the Elderslie flitches that were sent to Tasmania

The results from the slicing trial demonstrated that small flitch size reduces recovery of sliced veneer. This is analogous to the rounding losses incurred in rotary veneer production and is related to the same high taper and sweep of mahogany logs as observed by McGavin and Venn (2018). This supports the approach that due to the strong taper in Khaya logs, shorter lengths will ensure greater recovery rates.

It will be important to develop a prescriptions for each target product from Khaya logs based on the dimensions and characteristics of the logs. This will maximise the recovery from the resource and hence it's value.

Summary

The recovery of sawn timber in the milling trial ranged from 32-42% of whole log volume. The performance of the timber whilst drying varied. This was largely dependent on milled timber dimensions, where many of the 25mm boards possessed unacceptable movement (bow, wane etc)

The slicing trial produced attractive veneer slices.. The quality and feature of the recoverable material was judged as good. Slicing small billets is not feasible for this species.

Based on the appearance of the boards and veneers produced 12 to14-year-old Khaya produced timber that can be used for high-end furniture and other feature grade applications.

The trials provided material of premium quality (colour, dimension and free of defect), that can be used to demonstrate the construction of furniture and other high value appearance applications.

Colour, stability, and feature were all acceptable in logs greater than 13 years old. The 12-year-old logs, although stable did not display the same heartwood development as the 14-year-old logs.

This study will be used to progress developing a prescription for processing and drying of Khaya logs.

These trials indicated promising processing outcomes from young mahogany, but highlighted the need for prescriptive processing and drying, regardless of target product.

References

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Zbonak, A., Brown, T., Harding, K., Innes T and Davies M., 2010, Wood properties and processing outcomes for plantation grown African mahogany (Khaya senegalensis) trees from Clare, Queensland (18- and 20-year-old) and Katherine, Northern Territory (14-year-old), The State of Queensland, Department of Employment, Economic Development and Innovation

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Appendix 3 COLOUR MODIFICATION OF PLANTED MAHOGANY WOOD

Graeme Palmer, Southern Cross University

Introduction

African Mahogany (*Khaya senegalensis*) has been successfully adapted to plantation production of forest wood products in tropical Australia. African Mahogany Australia currently manages ~14,000 hectares of plantation near in the Douglas Daly Region in the Northern Territory, and has sought to study the quality of 10 year old stems taken as thinned stems from plantations. Of particular interest has been the challenge of varied colour of the young wood ranging from the usual red brown hue in the oldest heartwood, through a transition to sapwood that presents white or cream coloured void of the rich colour that characterises the highly valued joinery timber.

This report describes research efforts that examines the potential of post-harvest coloration of the wood to create a uniform colouring throughout. The effect of both polar (water) and non-polar (di-ethyl ether) based (commercially available) stains being applied through immersion or pressure impregnation was explored. The aim was to determine how deep the stain would penetrate into the heartwood, and whether a complete colouration throughout wood samples of commercially typical dimensions can be achieved.

Methodology

Wood samples as received

13 sawn boards of variable dimensions were selected from a sawing study conducted in Katherine NT. These boards were shipped to Southern Cross University , carrying supplier-defined labelling of 8 variations. Boards were from 4 trees in Why Not plantation (Labels W6-1, W7-1, W7-2, W8-1) two trees from Stray Creek plantation (Labels S1-1, S2-1) and two from the Coastal Plain plantation (Labels CP4-1, CP5-2). The eight cleanest and straightest slabs were chosen for experimental sample cutting (Figure 1). Note: Temperatures during storage, treatment (soaking) and drying were very high, ranging between 35 and >40°C. The experiment was conducted mid-Nov to early Dec 2018.

Figure 1. - Wood slabs as received and chosen for sample cutting, including their labelling

Preparations

1.1. Treatments and labelling

It was important that the variations in the delivered slabs were mirrored in the trials, therefore each variation was used as a repeat in the trial = 8 repeats

Further, it was important that the source of each individual sample can be traced back, therefore the label on each sample was to reflect the delivered slabs' labelling.

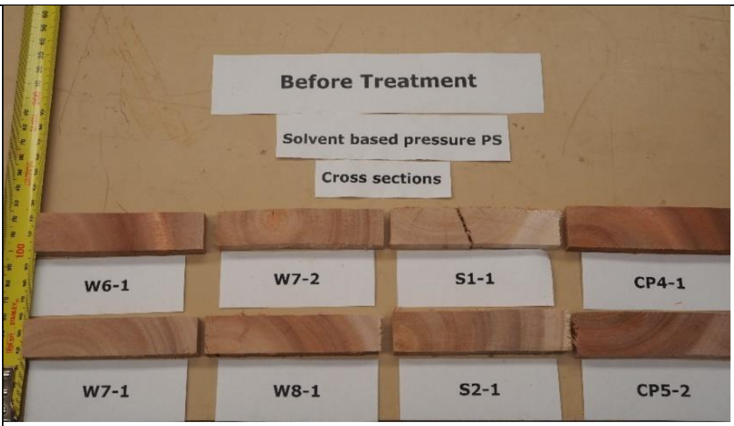
All treatments and corresponding labels of individual samples are listed in Table 1. Figure 2 shows the longitudinal surfaces of all samples before treatment.

Table 1: treatments and treatment labelling

Treatment	Treat code	Sample repeat number	Total code
Solvent based pressure PS	1	W6-1, W7-1, W7-2, W8-1, S1-1, S2-1, CP4-1, CP5-2	1W6-1, 1W7-1, 1W7-2, 1W8-1, 1S1-1, 1S2-1, 1CP4-1, 1CP5-2
Water based pressure PW	2	W6-1,W7-1, W7-2, W8-1, S1-1, S2-1, CP4-1, CP5-2	2W6-1, 2W7-1, 2W7-2, 2W8-1, 2S1-1, 2S2-1, 2CP4-1, 2CP5-2
Solvent based immersion IS	3	W6-1,W7-1, W7-2, W8-1, S1-1, S2-1, CP4-1, CP5-2	3W6-1, 3W7-1, 3W7-2, 3W8-1, 3S1-1, 3S2-1, 3CP4-1, 3CP5-2
Water based immersion IW	4	W6-1,W7-1, W7-2, W8-1, S1-1, S2-1, CP4-1, CP5-2	4W6-1, 4W7-1, 4W7-2, 4W8-1, 4S1-1, 4S2-1, 4CP4-1, 4CP5-2

1.2. Cutting of sample pieces

All samples were cut to the dimensions 25 mm (radial) x 100 mm (tangential) x 310 mm (longitudinal). For each sample a corresponding thin section of ~ 5mm thickness was prepared as a crosscut for imaging before treatments (residual sample length was not less than 300mm). The crosscut was to contain as much as possible of the interfaces and gradations in colour between strongly coloured inner heartwood and sapwood. All samples were labelled in pencil and permanent marker on each end face, which was then sealed under silicone paint to prevent stain being soaked or pressured into end faces, and to prevent the fading of labels. One piece of each board was cut for density and MC determinations, with variable dimensions recorded.

PS (Tmt 1)	
PW (Tmt 2)	
IS (Tmt 3)	

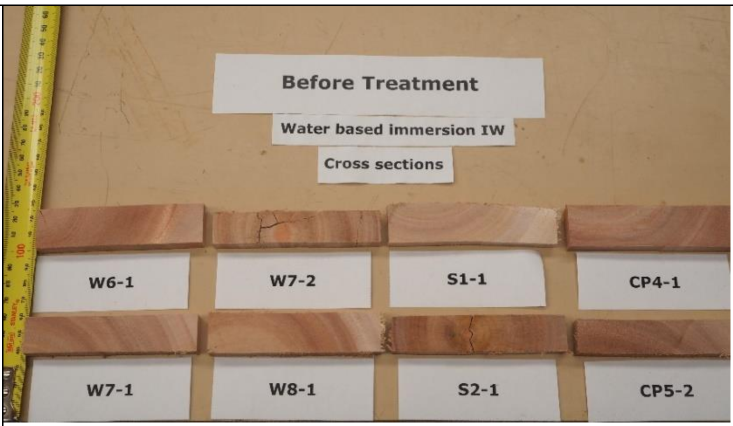
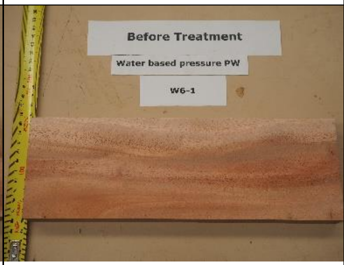
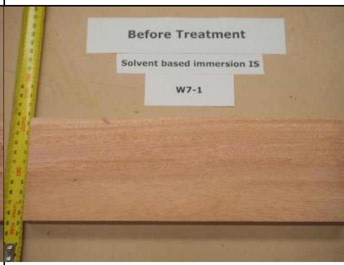
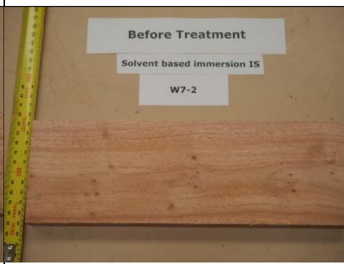
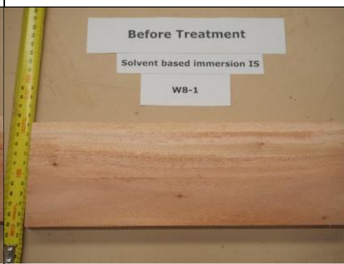
IW (Tmt 4)	

Figure 2. Cross cut (transverse) thin sections of the samples before treatment

PS	PW	IS	IW
			
1W6-1	2W6-1	3W6-1	4W6-1
			
1W7-1	2W7-1	3W7-1	4W7-1
			
1W7-2	2W7-2	3W7-2	4W7-2
			
1W8-1	2W8-1	3W8-1	4W8-1
			
1S1-1	2S1-1	3S1-1	4S1-1

1S2-1

2S2-1

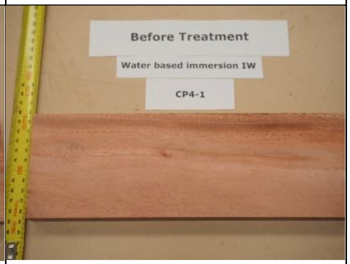
3S2-1

4S2-1

1CP4-1

2CP4-1

3CP4-1



4CP4-1

1CP5-2

2CP5-2

3CP5-2

4CP5-2

Figure 3. – All samples and their labels before treatment, presenting longitudinal treatment surfaces

Moisture Content (MC) and Density Determinations

Two separate pieces of each slab (due to the variability of colouring) were cut, labelled, dimensions recorded, weighed. Then the pieces were divided into 2 groups, for MC and for density determinations. For MC-determination the pieces were oven-dried to constant mass (24 h at 105°C), dimensions recorded and weighed. Moisture content was calculated according to the formula MC = $(M_{moist}-M_o)/M_o$ x 100%, (o = oven dry).

For density determination (Density r, includes pores and micropores) the formulas

Density $r_u = M_u/V_u$ (u = MC, only between 0-25% allowed, which was confirmed from MC determinations) and

Density $r_o = M_o/V_o$ (g/cm^3) were applied.

Process of immersion treatment

Lidded plastic pails were filled with 4-8 samples, sitting upright with gaps between them; then the pail was filled with the treatment solution, either solvent (Tmt 3) or water based

(Tmt 4) stain, until the samples were fully covered, held down by a custom-made wooden grid and a half-brick on top to prevent floating; lids were lightly closed and the samples soaked for 1 week.

On removal from the bath the samples were lightly padded dry, left for dripping off, and then weighed (1st weighing); then samples were dried at ambient temperature, and weighed after 24 h, and after drying fully (when at constant mass).

Process of pressure impregnation treatment

4 samples at a time were placed into a cylindrical pressure treatment vessel, the vessel sealed off carefully; a light vacuum (~25% of full vacuum) was applied and the vessel was flooded with treatment solution (calculated and measured quantity); pressure of ~12kPa, was applied for ~1h. After treatment the pressure was quickly released to expel excessive treatment solution from the samples. Once at normal pressure the vessel was opened and samples removed; the remaining treatment solution was measured to determine quantity used up in wood; the same procedures as in immersion treatment were applied for sample weighing and drying.

Results

1. Moisture Content and Density

Moisture Content (MC) ranged from 11.1 % (S2-1) to 24.2 % (W6-1; see Appendix). Density r_u ranged from 0.63 g/cm^3 (W7-2) to 0.87 g/cm^3 (CP4-1), and density r_o ranged from 0.55 g/cm^3 (CP5-2) to 0.75 g/cm^3 (CP4-1)

A bending/warping of the oven-dried samples was observed, specifically in the radial and tangential directions, making determination of dimensions challenging. Averaging of the measured dimensions over two repeat samples was used to determine the volume for density calculations.

2. Treatments

All samples achieved a uniform staining of the surfaces, some examples are shown in Figure 4, independent of treatment, however, little penetration of colour was achieved as observed on the cross cuts faces of the samples. With the exception of colour in solvent applied under pressure, stain did not penetrate into the wood. For the solvent treated samples under pressure, modest penetration was observed which was inconsistent and shallow (Figure 5).

Sample Label	Outside staining after treatment
W7-1	
CP4-1	
CP5-2	

Figure 4. – examples of the outside staining of samples after treatment

PS (Tmt 1)

PW (Tmt 2)

IS (Tmt 3)

IW (Tmt 4)

Figure 5. Cross sections of all samples after treatment; no penetration of stain observable; samples are positioned in the same order as in Figure 2.

Summary

The experiments have shown clearly that the wood of African mahogany that is in transition from sapwood to heartwood exhibits little of the characteristic red brown colour of mature heartwood. It will not be penetrated sufficiently with coloured pigments in water or organic solvents, either by vacuum pressure or cold soak methods.

The difficulty penetrating wood with liquids leaves few options to modify colour effectively. Manufacturing of decorative panels of sliced veneer, with coatings of uniform colour, present no impediment to utilisation for this purpose as pigmented liquids colour surfaces adequately. Without a matching solid wood offering, furniture remains out of reach for the plantation grown product, unless a buyer is willing to adapt coatings to finished products. Despite this, decorative wall panels in commercial buildings is a lucrative and large market that offer an option for the young plantation grown wood.

Table 2. Supplementary Information: Determination of MC and densities ru (as delivered) and ro (oven-dry) of Khaya senegalensis wood slabs; Mass mu = sample mass as delivered, Mass mo = sample mass oven-dry, two repeats

$Mass_u$ (g)	$Mass_0$ (g)	MC indiv samples (%)	Av MC per variety (%)	Label	Volume V_u (cm3)	Mass m_u (g)	Density r_u (g/cm^3)	Average Density r_u per variety (g/cm^3)	Volume V_0 (cm3)	Density r_0 (g/cm^3)	Average Density r_o per variety (g/cm^3)
111.3	86.5	28.7	24.19	**W6-1**	141.67	111.3	0.79	0.79	130.72	0.66	0.68
108.1	90.3	19.7			137.19	108.1	0.79		130.91	0.69	
76.6	67.5	13.5	13.97	**W7-1**	111.45	76.6	0.69	0.68	102.28	0.66	0.65
79.2	69.2	14.5			117.13	79.2	0.68		107.61	0.64	
69.4	62.3	11.4	11.53	**W7-2**	110.53	69.4	0.63	0.65	105.57	0.59	0.61
78.5	70.3	11.7			117.07	78.5	0.67		112.41	0.63	
78.5	68.8	14.1	14.71	**W8-1**	116.68	78.5	0.67	0.67	111.12	0.62	0.62
75.3	65.3	15.3			111.57	75.3	0.67		103.67	0.63	
126.1	111.1	13.5	13.98	**S1-1**	175.09	126.1	0.72	0.72	164.50	0.68	0.67
125.8	109.9	14.5			174.90	125.8	0.72		166.73	0.66	
79.6	77.1	3.2	11.12	**S2-1**	111.03	79.6	0.72	0.73	109.81	0.70	0.70
85.2	71.6	19.0			115.31	85.2	0.74		102.18	0.70	
108.6	95.3	14.0	14.77	**CP4-1**	143.62	108.6	0.76	0.81	134.16	0.71	0.75
116.5	100.8	15.6			133.81	116.5	0.87		126.95	0.79	
79.4	69.8	13.8	13.57	**CP5-2**	124.83	79.4	0.64	0.65	143.54	0.49	0.55
82.2	72.5	13.4			124.49	82.2	0.66		116.65	0.62	