Integrated biomass residue management in Sandalwood Plantations

IEA Bioenergy: Task 43

December 2021

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Cover photo by QUINTIS (Australia) Pty Limited

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December 2021

Published by IEA Bioenergy

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Summary

Sandalwood plantations in Australia offer a unique opportunity in the supply of woody biomass into regional bio-hubs in support of the circular economy. The plantations are established in such configurations that for each sandalwood tree planted, on average two long-term host trees are planted to support the growth of this hemiparasitic crop. As a result, a significant proportion of the aboveground biomass in the plantation is not a sandalwood product and is considered to be waste. To support emerging local and regional biomass markets and to improve the sustainable management of the tropical sandalwood plantation resource, this study explores the potential availability and market feasibility of integrated biomass supply for bioproducts. A desktop biomass assessment was performed to ascertain indicative market viabilities by determining biomass quantities from plot based-measures and developing host species-specific aboveground biomass profiles. These species profiles and the unique planting configurations were combined and extrapolated across the sandalwood plantation estate to estimate the current and project woody biomass profile of the plantation. Results indicate that at a mature age (15 years), up to 10 oven-dry tonnes of woody biomass is potentially available per hectare of sandalwood plantations. Increasing host species selection and optimised planting configurations may enable increased biomass availability. This work was made possible with the support of QUINTIS (Australia) Pty Limited and lays the groundwork for future productive research outcomes.

1. Introduction

The usage of forestry and agriculture biomass as feedstock supply for emerging bio economies represents the basis of a sustainable circular economy. Integrated land management techniques and mindset changes are key to fundamentally transforming previously considered waste products into suitable feedstock for markets. As such, the concept of a circular has gained momentum since the United Nations introduced the Sustainable Development Goals. In Australia it is estimated that a circular economy can contribute to a cost saving of AUD 26 Billion by 2025, based on the principles of reducing waste, keeping products and materials in use and regenerating natural systems [1].

Northern Australia forestry and forest products industries have an estimated annual production output of ca. AUD 84 million and support more than 1240 direct and 620 indirect jobs [2]. Many of the key forestry industries in the region have been based on establishing the underlying plantation forest resource, and as plantations mature, they are now approaching or transitioning to harvesting and sale into markets. Indian Sandalwood (*Santalum album*) is one of those plantation resources with an average price of AUD 78,000 per tonne of heartwood [2]. QUINTIS Pty Limited has sandalwood plantations totalling more than 14,000 hectares in Western Australia, Northern Territory and Queensland, with products, particularly oils, exported primarily for the fragrance and pharmaceutical industries. Sandalwood is the only plantation forestry in Australia that is routinely grown in a mixed species system, and with irrigation.

Sandalwood is a non-obligate hemiparasite, for commercial production it must be grown in conjunction with a range of host trees to enable its growth and yield [3]. The most common host species include *Senna siamea*, *Cathormion umbellatum*, *Dalbergia lanceolaria*, *Dalbergia latifolia*, *Acacia trachycarpa*, *Acacia shirleyi*, *Albizia lebbeck* and *Sesbania formosa*. The first four species are considered long-term hosts and remain present in the plantation until the final harvest. The latter four species are short-term hosts and die a few years after planting. All trees are planted simultaneously and the average ratio between sandalwood and long-term host trees is 1:2. Thus for each sandalwood tree, there are two long-term host trees planted within or between rows depending on the configuration of the plantation. This crop, therefore, produces high volumes of waste host tree woody biomass at the end of the 15 to 20-year rotation. At present, this residue material is not utilised for any commercial or industrial benefit, furthermore, there has been little to no research into the use of these residues (material availability, operational implications, financial viability, etc.) to support bio economies and contribute to tomorrows circular economy.

It is proposed that the concepts of a circular economy be extended to the sandalwood plantation sector in Australia, to further enable biomass supply and resiliency in rural communities. Sandalwood plantations in Australia represent a niche but growing sector with unique challenges and potential for biomass production. As the current sandalwood estate in Australia matures, sandalwood growers are looking at sustainable ways to recover value from the host trees and promote regional industries by integrating waste woody biomass into circular economies. This study reports on the potential for waste woody biomass from sandalwood plantations in northern Australia managed by QUINTIS Pty Limited in support of their transition from linear waste disposal to waste recovery via regional circular economies. Harvesting of Sandalwood plantations have commenced at an economic scale in 2021 at a harvesting rate of 500-600 ha per year, including the removal of sandalwood and host trees, and this is set to expand over the coming decades. The study assesses the theoretical biomass resource potentially available from commercial bio economies; the spatial and temporal distribution of woody biomass supply from the estate across three different Australian States and Territories; and discusses the opportunity for regional bio-based hubs. The findings provide strategic guidance for sandalwood growers to explore the effective management (collection, quantify, process, etc.) of biomass commodity streams from production and waste streams in a cost-effective and environmentally sustainable way.

2. Study area

This study focuses on the irrigated QUINTIS Pty Limited sandalwood estate (Figure 1) which covers approximately 14,000 ha in the tropical savanna climates of the Burdekin (-19.575825, 147.405058) North Queensland and the Douglas-Daly (-13.7955, 131.5257) and Katherine (-14.466667, 132.266667) regions of the Northern Territory, as well as the semi-arid climate of Kununurra (-15.773611, 128.738611) in Western Australia.

The oldest part of the estate is located near Kununurra WA and covers approximately 7,000 ha across the Ord River Irrigation Area (ORIA) and Kingston Rest. The closest town is Kununurra, approximately 45 km from the NT border, situated among the ranges of the northeast Kimberly region. The Ord River Dam and the Ord River Diversion dam conserve the water for the town and upstream irrigation for tropical agriculture crops. According to the 2016 Census, Kununurra has a population of 5,308 and an unemployment rate of 4.6%. The town has an indigenous population of 22.9%. With an average annual rainfall of 800 mm, the climate is classified as semi-arid with distinct dry and wet seasons. The dry season runs from April to September, with a build-up season from October to December and a monsoon period between January and March

Approximately 6,000 ha of sandalwood are planted between Mataranka, the Douglas-Daly and Katherine in the NT. Mataranka has a population of 350 people, of which 29.5% are Aboriginal and/or Torres Strait Islander and an unemployment rate of 9.6%. The town is located 107 km south of Katherine and 420 km southeast of the territory capital of Darwin. Katherine is the Territory's fourth-largest settlement with a population of 6,300 people, an unemployment rate of 4.5% and 25.4% Aboriginal and/or Torres Strait Islander people. Situated on the banks of the

Katherine River and the Daly River System, the area is prone to flooding during the wet monsoon season (November to April). Further north, 154km south of Darwin, the Daly River comes together with the Douglas River catchment in the Douglas-Daly region.

Another 1,500 hectares of Indian sandalwood is grown in the Dry Tropics of the Burdekin region of north Queensland. The region is located between Townsville and Bowen on the delta of the Burdekin River. About 50 km inland from the Coral Sea, the area is home to sugarcane irrigated with water from the Burdekin Falls Dam on the Burdekin River.

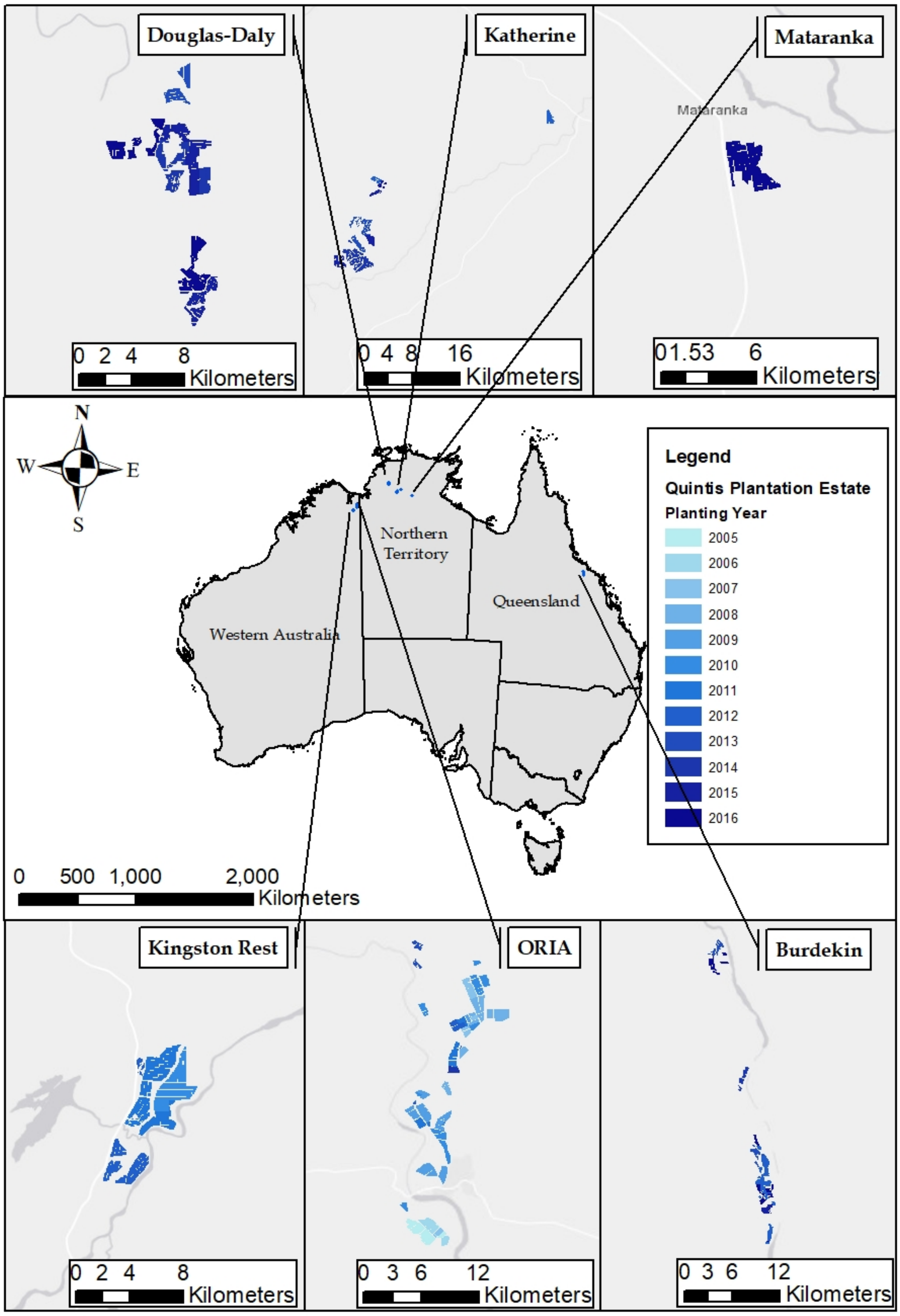

Figure 1. Map of the QUINTIS Pty Limited estate in Western Australia, Northern Territory and Queensland. Areas in blue indicate the different properties across northern Australia managed by QUINTIS Pty Limited. Planting years of the estate are provided.

3. Methodology

This research originally proposed to include components in the field that determine the underlying biomass profile through destructive sampling and collect productivity and cost data for biomass collection activities for all aspects of the crop's lifecycle (pruning and final harvest). However, due to the global COVID-19 pandemic, intra- and interstate travel in Australia was restricted and these elements of the study were altered according to The University of the Sunshine Coast COVID-19 Safe Plan for Face-to-Face Off-Campus Activities. As a consequence the study used the following approach:

- Determine host species-specific aboveground biomass (AGB) profiles in a plot-based biomass assessment to analyse the suitability of altered host plants and/or planting configurations to enhance biomass yield and determine their likely commercial implications.
- Determine the AGB plantation profile from the plot-based plantation inventory assessments and specific plantation configuration provided by QUINTIS Pty Limited.
- Provide a limited market insight for use of biomass feedstock on-site or off-site to a regional marketplace to develop a suite of recommendations surrounding the feasibility of biomass utilisation in sandalwood plantations.
- Establish ongoing trials to evaluate new host species that have the potential to promote sandalwood growth and improve biomass feedstock recovery. This will include one or more field plantings of sandalwood and host trees and a pot-based trial examining the hosting efficiency of new hosts that may provide improved biomass production (yield and quality) (**Appendices 1-2-3**).

3.1. PLOT-BASED AGB ASSESSMENT

Throughout the QUINTIS sandalwood estate, 186 permanent sample plots (PSP) are established that represent different regions, properties, planting configurations, planting years, site preparation, soil types, genetics and irrigation types. The plots are 0.1152 ha in size and are measured bi-annually. Data records included the species, row number, tree number, diameter at breast height (DBH), diameter at ground level (DGL), number of stems, heights, and defects. The DBH was measured for 80% of the trees, the remaining 20% was indicated as 'dead' or 'blank'. The total tree height was recorded for 12% of the stems, however, host trees are pruned at a set height to stimulate the growth of sandalwood. Therefore, heights are rather uniform across a plantation at a mature age (between 7 and 8 m).

The AGB in kg for all stems was calculated based on:

- the individual tree DBH for single stem trees, or Root Mean Square (RMS) of the DBHs of multistem trees
- the average tree height (Figure 2) was calculated respective to the planting or establishment year.

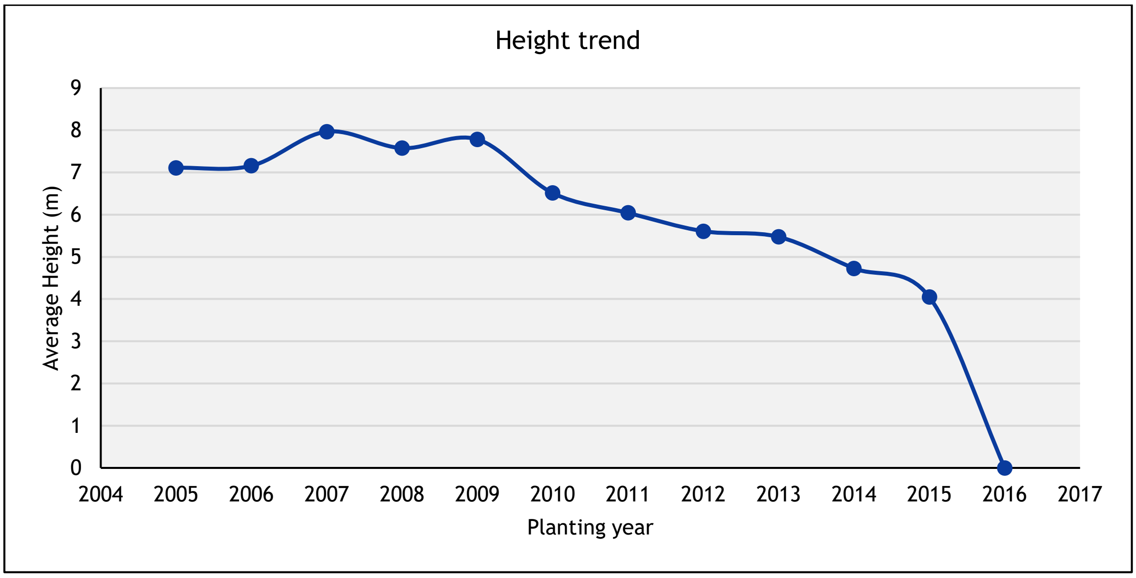

Figure 2. Average height trend of the PSP trees (incl. sandalwood and host trees) respective of the planting year.

The allometric equation developed for tropical trees by Chave et al. (2014) was used to calculate the AGB of every tree:

$$AGB_{est} = 0.0673 * (\rho DBH^2 H)^{0.976}$$

Where: AGB_{est} is an estimate of the aboveground tree biomass (kg of oven-dry matter);

ρ is the species-specific wood oven-dry density (g cm^{-3});

DBH is the diameter at breast height (cm); and

H is the tree height (m).

The AGB of all individual trees per plot was calculated. Different allometric equations were tested and compared, including species-specific equations where available. The equation by Chave et al. (2014) was found most suitable to the entire dataset, as it provided plausible AGB estimates based on the experience of the research team. Standing dead trees and blanks returned a zero-value for AGB, however, were included in further assessments as they are representative of each PSP and its respective configuration. Table 1 presents the different density (ρ) values of the host tree species used for the conversion of the tree volume (m^3) to mass (kg) at various moisture contents. The distribution of tree species according to the inventory is also presented in Table 1.

Table 1. Distribution and density (ρ) values of sandalwood and host tree species.

Species	Species code	Air-dry density (kg/m3)	Oven-dry density (kg/m3)	Reference	Share of Species in PSP
Santalum album	Sa	940	752	[5]	53%
Senna siamea	Cs	800	640	[6,7]	14%

Cathormion umbellatum	Cu	840	672	[8]	15%
Dalbergia latifolia	Dlat	830	750	[9,10]	1%
Dalbergia lanceolaria	Dlan	712	570	[11]	12%
Acacia trachycarpa	At	770	616	[12]	2%
Acacia shirleyi	As	1020	833	[13]	2%
Albizia lebbeck	Al	635	550	[9,14]	0%
Sesbania formosa	Sf	625	500	[15]	1%
Moisture Content (MC)		12%			

From the AGB calculated per tree, the average AGB of each species per planting year was calculated. The number of trees measured per species is indicated in Table 2.

Table 2. The number of sandalwood and host trees measured in the PSP data for the respective years since planting.

Planting year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Sa*	130	181	185	229	398	779	588	1776	1585	1358	1177	64
Cs	48		58	40	114	231	219	559	502	440	30	
Cu	42	65	50	98	129	55		989	340	250	272	16
Dlat						11		39	35	40	78	11
Dlan		61	17	35	58	267	290	32	411	284	369	5
At								15	65	92	72	14
As										147	171	
Al						17		27	4			
Sf						1			1	2	85	15
SUM	220	307	310	402	699	1361	1097	3437	2943	2613	2254	125

* See Table 1, Species codes for each species' abbreviation.

3.2. PLANTATION AGB PROFILE

The species-specific AGB estimates were used to calculate the total theoretical biomass potential across QUINTIS Sandalwood plantations. The theoretical biomass potential is defined as the total annual production of woody biomass in a region. Generally, the theoretical biomass potential is the notional stand production level and is the upper-bound measure before losses incurred due to supply chains, conversion and distribution.

Across the QUINTIS Sandalwood estate, each stand or patch is characterized by a planting configuration with respective interrow and within row spacings between sandalwood and host trees. The combination of sandalwood and host trees is also unique for each configuration. For a total of 150 different configurations, the number of stems per hectare (SPH) for sandalwood and each host species was provided.

Multiplied by the patch or stand area, the number of stems of each species for every patch or stand can be calculated based on the SPH retrieved from the configuration. In order to calculate the AGB for a specific patch or area, the number of stems of a specific host species was multiplied by its species-specific AGB estimate calculated from the plot-based measures. This measure accounts for dead or missing trees that are characteristic of each configuration based on PSP data. The planting year of a plantation patch or area determined which AGB value for a species needed to be used to estimate the current theoretical biomass potential of that particular patch or area. This process was replicated for each area across the estate.

In addition, this study estimated the projected theoretical biomass potential based on a mature age plantation. Therefore, mature age PSP data of the planting years '05-'09 was averaged using the sum-product rule according to the number of stems. The species-specific weighted average AGB was multiplied by the number of stems of the respective species within the configuration of each patch or area. This estimate projected the amount of biomass that is theoretically available at a harvest age across the estate, regardless of the year an area was planted.

4. Results

4.1. PLANTATION INVENTORY ASSESSMENT

Table 3 presents the average AGB (kg) for each tree species planted in the QUINTIS Sandalwood estate according to the year it was planted, starting with 2005 being the most mature plantation. The AGB averages (kg) for species and planting years are based on basic density which is considered oven-dry.

Over a 15-20 year rotation, it was noted that there is a linear trend in the DBH increments (R^2 = 0.82, which is expected given that diameters will keep increasing if the plantation rotation is extended (Figure 3).

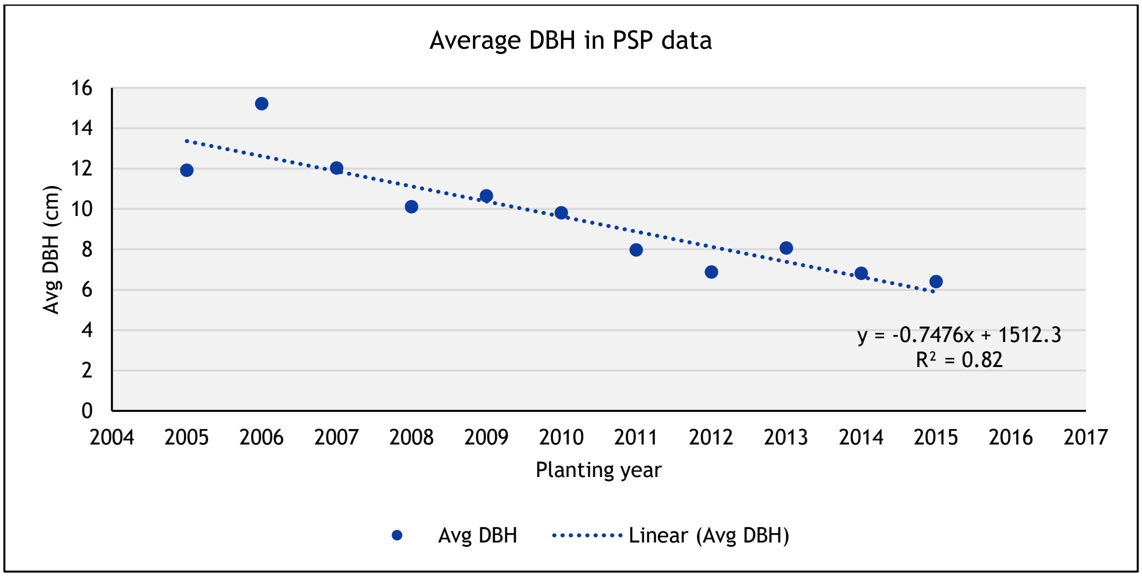

Figure 3. Average DBH of the PSP trees (incl sandalwood and host trees) respective of the planting year.

However, pruning of the host trees is a common practice in sandalwood plantations to allow sufficient light to reach the sandalwood trees and improve overall growth. Thus, pruning of the tops of the host trees is a limiting factor in tree growth and is visible in the height trend in Figure 2. From this figure, we can suggest that "maturity" is reached at a height of 7 m and therefore we consider plantations planted between 2005 and 2009 mature. As a result, a weighted average of AGB for the years '05-'09 was calculated for each species planting within those years based on the average AGB for each species and the number of trees measured. It is worth noting that the species (*S. siamea*, *C. umbellatum* and *D. lanceolaria*) for which a '05-'09 average is available, are the most commonly planted long-term host species and of the highest interest for biomass recovery.

Table 3. The average oven-dry AGB (kg) of sandalwood and host trees as calculated from the PSP data for the respective years since planting. The Weighted Average '05-'09 represents a mature age estimate of AGB for those species from which mature trees are available across the PSP data. The number of stems and the average height (m) is also included in the table.

Planting year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Weighted Average '05 -'09
Number of stems	220	307	310	402	699	1361	1097	3437	2943	2613	2254	125	
Average height (m)	7.11	7.16	7.97	7.58	7.78	6.51	6.04	5.61	5.47	4.73	4.05		7.58
Average AGB (kg) per species per year													
Sa*	13.21	16.35	27.29	23.17	27.19	16.11	13.04	9.90	10.55	6.44	3.84		23.02
Cs	16.86		36.06	26.04	28.83	11.40	9.53	17.77	13.41	10.39	10.11		27.80
Cu	29.34	12.98	29.13	11.65	11.95	14.97		6.79	3.82	2.10	2.22		16.19
Dlat						7.15		0.87	5.12	0.01	10.14		
Dlan		63.71	60.51	42.63	29.93	25.00	14.05	15.92	15.01	10.25	5.45		47.62
At								5.76	5.96	5.24	3.32		
As										4.31	2.99		
Al						3.72		0.35	15.88				
Sf						26.69				91.06	35.46		
Average AGB (kg) per year	19.80	31.01	38.25	25.87	24.47	15.00	12.20	8.20	8.72	16.23	9.19		

* See Table 1, Species codes for each species' abbreviation.

4.2. BIOMASS ASSESSMENT

4.2.1. Current plantation AGB profile

Figure 4 presents the current notional total AGB (tonnes) available from each of the long-term host species across the QUINTIS Sandalwood estate. Short-term hosts were discarded from the study as they significantly skewed the results of total biomass availability, as the biomass from these species was not available at a final harvest. Some of the short-term host trees have a high yield of biomass (eg. *S. formosa*), however, their wood quality and high abundance of wood-boring insect attack, makes them unsuitable for future markets. In addition, short-term hosts often die within the first 5 years of planting and will no longer be present at a final harvest age.

From Figure 4, there is an increase in the total AGB between planting years 2005 and 2010 as the sandalwood plantation estate increases in size and the plantations approach maturity. This increase is likely to be related to the increase in plantation establishment since 2005. After 2010, there is a decline in the current AGB availability caused by immature and growing trees, and a plateau in plantation establishment of 1200-1500 ha per year.

The species-specific profiles vary more significantly since 2010, caused by the introduction of a higher variety of different configurations, the addition of new host species such as *D. latifolia*.

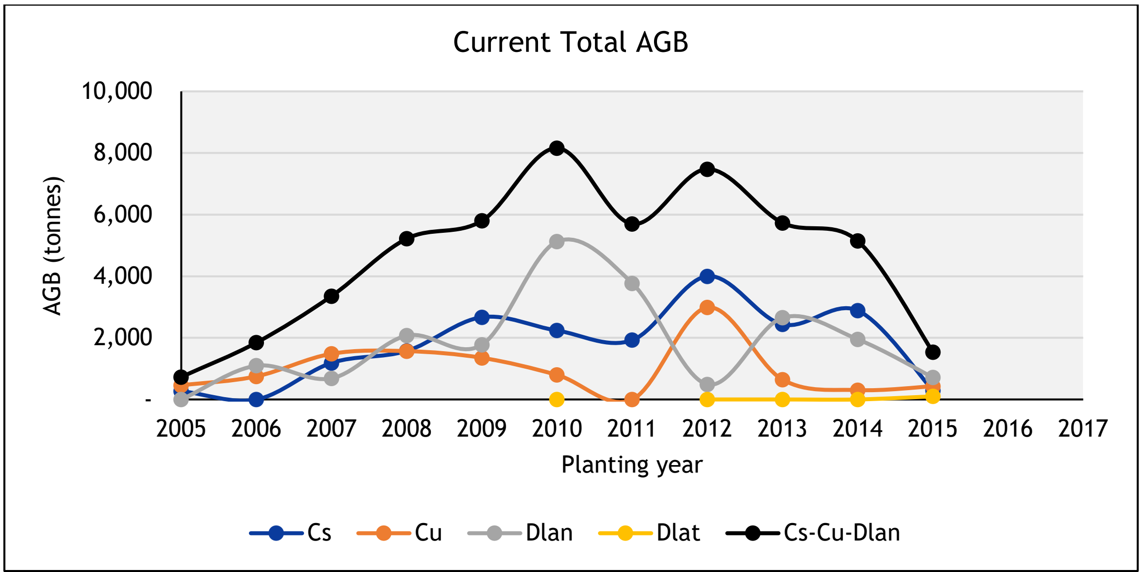

Figure 4. Total current AGB (tonnes) availability in the QUINTIS Sandalwood estate for the different long term host species. Sums for the most common (Cs - Cu - Dlan) host species are represented by the black line.

Figure 5 presents the average AGB per hectare of the most common long-term host species, for each year of planting. The current total AGB (tonnes) of each species in each year derived from Figure 4, was divided by the sum of the plantation area established within that same year. The figure below shows a logical decreasing trend in the average AGB as more recently established plantations are yet to reach maturity and therefore have accumulated less biomass. Annual average AGB values between each of the long-term host species (Cs – Cu – Dlan) are fluctuating as a result of changes in planting frequencies related to the planting configurations. At a mature age (years '05-'09), between 4 and 7 dry tonnes of AGB is available from the species *S. siamea*, *C. umbellatum* and *D. lanceolaria*.

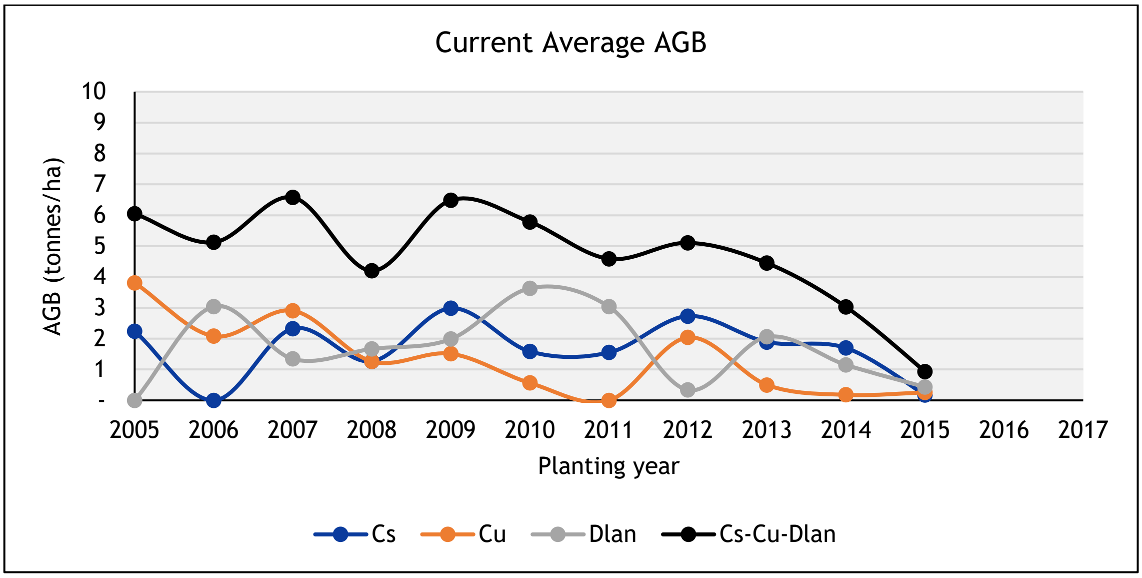

Figure 5. Average current AGB (tonnes/ha) availability in the QUINTIS Sandalwood estate for the most common long-term host (Cs - Cu - Dlan) species and their combined average AGB.

4.2.2. Projected plantation AGB profile

Figure 6 presents the total AGB (tonnes) for the most common long-term host species assuming the plantation has reached a mature age. For each year, the graph projects the potential AGB harvest from all *S. siamea*, *C. umbellatum* and *D. lanceolaria* trees at the end of the rotation. The graph shows a general increase in biomass as more areas are planted and the estate has expanded. The dip in 2013 indicated that either a smaller plantation area was established that year, or a higher number of other species than the abovementioned were planted. The dip in the planting year 2017 is explained by the incomplete establishment of new plantations at the time of data records.

The figure also indicates that *D. lanceolaria* trees deliver the highest amount of potential biomass, followed by *S. siamea* and *C. umbellatum*. It is worth noting that *C. umbellatum* accumulates significantly less biomass per tree (16.19 kg) compared to *S. siamea* (27.80 kg) according to the PSP plot data for mature trees planted between ’05 and ’09. However, as a smaller tree, *C. umbellatum* has a higher planting density and smaller within-row spacing. The projected average AGB for *S. siamea* is 2.78 tonnes/ha, for *C. umbellatum* 2.08 tonnes/ha and for *D. lanceolaria* the average AGB is 5.57 tonnes/ha.

Figure 6 does not account for rotation replanting after harvest. The provided data was derived from 2018 plot-based measures, at a time no harvesting within the QUINTIS Sandalwood estate had commenced.

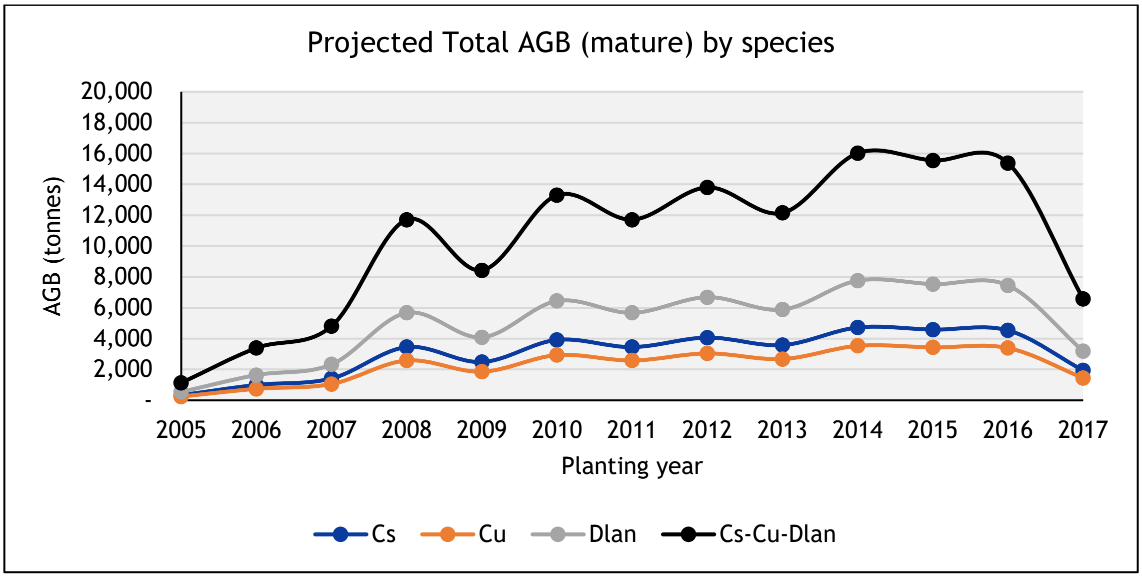

Figure 6. Total projected AGB (tonnes) availability per year in the QUINTIS Sandalwood estate for the most common long-term host (Cs - Cu - Dlan) species based on mature age trees.

Figure 7, presents the total AGB (tonnes) for the same long-term host species assuming the plantation has reached a mature age and projects the resource on a state/territory basis. Between 2005-'11 the chart shows a fairly steady increase in the WA estate. From planting the year 2012 onwards, the QUINTIS Pty Limited estates in the Northern Territory and Queensland are established. These projections indicate that there will be a rather significant shift from WA to NT harvesting of sandalwood and host tees as plantations mature.

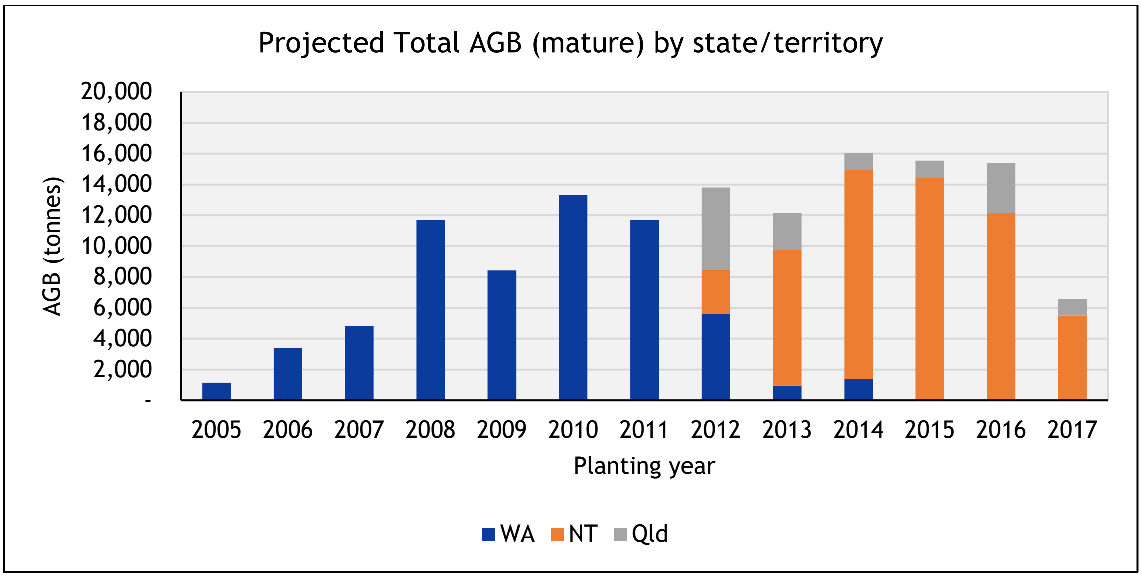

Figure 7. Total state/territory projected AGB (tonnes) availability per year in the QUINTIS Sandalwood estate based on mature age trees.

The cumulative and projected biomass availability from long-term host (Cs - Cu - Dlan) species in the QUINTIS Sandalwood estate planted between 2005 and 2017 is estimated at 133,962 tonnes.

5. Discussion: Biomass distribution and markets

The aboveground biomass of host species, as a proxy theoretically available waste woody biomass from sandalwood plantations, shows there is a significant amount of biomass available in support of regional bio economies in three different Australian States and Territories. Due to its mixed-species silviculture and array of different planting configurations, sandalwood plantations offer a very unique opportunity for woody biomass supply. With an average planting ratio of two long-term host trees for each sandalwood tree, there is a significant amount of waste or by-product that is not currently utilised or ending up in sandalwood supply chains and markets.

The woody biomass assessment is a measure of the theoretical potential. Often, this would be considered an upper limit of biomass availability as losses occur across biomass supply chains [16,17]. However, in this study, the theoretical potential is a realistic estimation of the available potential (i.e. biomass available at the processing facility).

During the harvesting of the plantation, most of the biomass will be collectable Almost all of the sandalwood biomass is removed from the site for commercial use. The site then undergoes significant preparation before plantation reestablishment. This includes the removal and disposal of excess biomass (hosts). After host removal, the site will be raked, cultivated, laser levelled (in flood irrigated sites), and mounded.

It is also important to note that in this study only biomass from long-term host trees at a final harvest is considered in the estimates. Additional waste biomass is available from short-term hosts species. Often these trees only survive until the first five years of the plantation rotation, as they are often subject to insect borer attacks and die. Sandalwood plantations also undergo periodic pruning of host trees to suppress their growth and enable more direct light to reach the sandalwood trees. The pruning of sandalwood plantations delivers mostly finer biomass material, that might not be feasible from a collection and transport perspective. The pruning biomass is mulched and quickly breaks down to deliver significant nutrients back into the plantation soils. Without mulching, pruning waste can disrupt forestry operations and in flood systems inhibit water flow. Finally, only the stem/heartwood of sandalwood is considered of value and thus any other sandalwood residue, could be an addition to the total woody biomass supply. In order to quantify the biomass from short term hosts, pruning waste and sandalwood residue, additional research is required.

As a tropical tree crop grown in the tropical savanna and semi-arid climate of remote northern Australia, the plantations are reliant on irrigation and abundant water supply. Despite their remoteness, most sandalwood estates are therefore in the proximity of large river systems for flood irrigation with good access to transport and regional communities. This can be considered an advantage in efforts to contribute to a circular economy. Given the fairly small footprint of the sandalwood estate and their condensed regional establishment, waste products could be easily dispatched to local bio-hubs or central processing facilities.

In the 2021 dry season, the first significant (>100 ha) harvesting of sandalwood took place at QUINTIS Pty Limited. Areas planted in 2005 were harvested at a mature age, predominantly in the Western Australian Kununurra region. The footprint of plantations established in 2005 is relatively small but will expand significantly over time as QUINTIS has rapidly expanded their plantation estate until 2010. A plateau in plantation established occurred since 2010, however, second rotation planting of plantations will commence in 2023. Thus, the plantation manager sits at the forefront of exploring different and more sustainable market opportunities for sandalwood by-products and woody biomass derived from waste host trees. Over time, their volumes of host tree biomass and host-species range will increase which enables the company to explore an array of market opportunities for this by-product.

The spatial distribution of the QUINTIS Sandalwood plantations across three different Australian States and Territories limits the potential of establishing a single bio-hub to process all biomass into one or multiple markets. However, on a state-by-state scale, different hubs can be established. In Western Australia, the Kinston Rest and ORIA estates lie within 70 km of the regional town and distribution centre of Kununurra. In the Northern Territory, the Katherine estate is nearby of the town of Katherine, the Mataranka estate is nearby the town of Mataranka and roughly 100 km away from Katherine. The Douglas-Daly estate is roughly 200 km away from Katherine and Darwin. In Queensland, the Burdekin estate is located 150 km away from Townsville or just under 100 km away from Ayr. The Burdekin estate co-exists with an abundance of sugarcane fields and sugar rail networks that could facilitate more efficient transport. As a result, the markets of woody biomass will be significantly different between each property or part of the estate. Markets for the biomass may include biochar, horticultural mulch, wood-plastic composites, wood vinegar, boxing materials, niche timbers and carvings.

6. Conclusion and next steps

This study found that Sandalwood plantations offer a unique opportunity in the supply of woody biomass that could potentially feed regional circular economies through localised bio-hubs. Most of the waste biomass from host trees in sandalwood plantations is readily available for collection and transport.

Additional biomass can be sourced from sandalwood residues, host-tree residues from intermittent pruning or short-term host, however, more research is required to quantify the potential of these sources and evaluate their quality before market sales.

> The current and projected sandalwood plantation profile offers good insight for QUINTIS Pty Limited in their current and future potential biomass supply from host trees. This information enables the plantation grower to strategically develop market opportunities for the waste woody biomass and offer employment and business opportunities for some of Australia’s most remotes regions.

Future research should aim to validate this desktop analysis of the biomass potential with field measures or waste biomass generated after sandalwood harvest. Following this attempt, species-specific biomass profiles can be evaluated across the sandalwood estate and enable strategic decision making for sandalwood growers. Depending on the required outcomes or the available markets, sandalwood growers can make a more guided decision on host species and planting configuration when establishing or replanting sandalwood plantations.

Acknowledgments

This project was funded and supported by the IEA Bioenergy Task 43 project ‘Integrated biomass residue management in Sandalwood Plantations‘ and in-kind and a cash contribution from QUINTIS Pty Limited in support of fieldwork, trial establishment, consumables, travel and

technical assistance.

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Appendices

Appendix 1 - Experimental Commencement Report: Sandalwood potted host trial

Report written: 7/12/2021
Author: David Lee
Experiment Number: 27.A SWD

Trial rational

This experiment aims to evaluate the hosting ability of long term sandalwood hosts including commercial and novel hosts for *S. album* and *S. lanceolatum*. This will inform QUINTIS Pty Limited about the efficiency of different hosts and the practicality of switching to new hosts and allow a direct comparison of the two sandalwood species abilities to grow with different host species. This experiment will also facilitate investigation of the benefits (e.g., physiological studies of nutritional contribution and water uptake) different hosts have for the sandalwood trees from the two *Santalum* species.

Objectives

To investigate host potential of existing and novel species to host two Santalum species by evaluating:

- Haustoria development (number, size, health, other)
- Sandalwood and host growth
- Sandalwood and host survival
- Physiological studies of water use and nutritional contribution of hosts to the sandalwood trees.

Trial Location

DAF Nursery Gympie (1 Cartwright Road, Gympie 4570, QLD Australia)

Treatments and design

Sandalwood species to test:

1. *S. album*
2. *S. lanceolatum*

A range of host plants was delivered to Gympie from the nursery QUINTIS Pty Ltd use in Townsville on the 19th of October 2021. Some of the plants were very small (approximately 5-9 cm tall) so they were held in the nursery at Cartwright Road for a month in the hope they would be suitable for transplanting. The plants that came from QUINTIS Pty Ltd and those available in the Cartwright Road nursery are detailed in Table 4.

Table 4. Plants available for the sandalwood host trial and their source.

Species	Pot size	Source
Santalum album L. [Common name: Indian sandalwood]	200 cc (came with *Alternanthera nana* R.Br. as the pot host in pot)	QUINTIS Pty Ltd nursery

Santalum lanceolatum R. Br [Common name: northern sandalwood]	200 cc	DAF nursery
Cathormium umbellatum (Vahl) Kosterm [Common name: Cathormion] Host 1	90 cc	QUINTIS Pty Ltd nursery
Dalbergia lanceolara L.f. [Common name: NA] Host 2	90 cc (too small to plant)	QUINTIS Pty Ltd nursery
Dalbergia latifolia Roxb. (= D. emarginata) [Common name: North Indian Rosewood] Host 3	90 cc	QUINTIS Pty Ltd nursery
Sesbania formosa F.Muell.) N.T.Burb. [Common name: White Dragon Tree] Host 4	90 cc	QUINTIS Pty Ltd nursery
Casuarina cunninghamiana Miq.[Common Name: River She-Oak] Host 5	90 cc	QUINTIS Pty Ltd nursery
Acacia shirleyi Maiden [Common name: Lancewood] Host 6	90 cc (too small to plant)	QUINTIS Pty Ltd nursery
Digitaria ciliaris (Retz.) Koeler [Common name NA] naturalised grass species. Host 7	NA (propagated from a rooted node directly into the pot)	DAF nursery
Control (no host) Host 8	-	-
Melaleuca quinquenervia (Cav.) S.T.Blake [Common Name: broad-leaved paperbark] Host 9	200 cc	DAF nursery

Pots used to establish the trial

Black polyethene plant bags 200 mm x 200 mm, 5.0 l.

Potting mix

The potting mix to establish the trial was 3 part composted pine bark and 1 part of a pine bark fines 80% / 20% washed river sand potting mix to ensure good drainage.

Fertilising

Shortly after the establishment, soluble fertiliser Peters® Excel an NPK (Ca, Mg) fertiliser was added to the mix using a handheld watering can. Two watering cans with 10 g of dissolved Peters® Excel fertiliser covered the entire trial. Note we did not add a slow-release fertiliser as the phosphate may impact the development of haustoria (impeding strigolactone signals from the host plants that help the parasitic plant to detect the host; Akiyama and Hayahi 2006).

Trial establishment

Seven of the nine host options (hosts 1, 3, 4, 5, 7, 8 & 9) were available to be established in the potted host trial which was established on the 18th of November 2021 (Figure 7). The trial is comprised of 252 pots (2 sandalwood species x 7 host treatments x 18 replicates). The initial pot size for the trial was 5 l, based on nursery space requirements and plant availability. Eighteen replicates of each host species could be established with the plan that 6 replicates of each host treatment per sandalwood species be destructively harvested at the following intervals:

- 4-6 months after the trial was established. (Number of pots and plants involved: 2 sandalwood species x 7 host treatments x 6 replicates = 84 pots),
- 12-18 months after trial establishment depending on plant development (these will be transferred to 20 l pots at the time of the first destructive sampling. (Number of pots and plants involved: 2 sandalwood species x 7 host treatments x 6 replicates = 84 pots),
- 18-36 months after trial establishment depending on plant development (these pots will be transferred to 50-100 l pots at the time of the first destructive sampling. (Number of pots and plants involved: 2 sandalwood species x 7 host treatments x 6 replicates = 84 pots).

Hosts 2, *Dalbergia lanceolaria* seedlings are now growing and might be potted up if sufficient seedlings reach a size where they can be used in host trials. Host 6, *Acacia shirleyi* seedlings are not healthy at the time of writing of this commencement report and they are unlikely to be available for this study. If either of these species is included in an add-on trial to this one, then 1-2 of the hosts from this trial (27.A SWD) will be included in the add-on to link the two trials.

Two weeks after the establishment of the trial survival is 100% across all treatments.

The trial will be randomised approximately 2 months after the trial was established.

The trial was fertilised twice with the fertiliser Peters® Excel to promote plant health and vigour. This is applied as a liquid fertiliser to the pots using a watering can. One watering can with 10 g of fertiliser was sufficient for each sandalwood species (126 pots).

Measurements to date

At the initiation of trial 27.A SWD, the heights of the sandalwood and hosts was recorded for all pots to allow us to use this information as a covariate if appropriate.

Figure 8. Sandalwood host trial established at the DAF Gympie nursery on the 18th of November 2021.

Appendix 2 – FOR-RDV-REP-Establishment report R116-QLD-REV1

Appendix 3 – FOR-RDV-REP-Establishment report R117-QLD-REV1

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