Summary

Two tropical sandalwood species (*Santalum album* and *Santalum austrocaledonicum)* were tested for their suitability to produce high value aromatic wood within irrigated plantations at the Gascoyne Research Facility, near Carnarvon, during 2006 and 2022. Approximately 7.3 ha of plantations were established, consisting of a 2.7 ha research plot (P2006) and a 4.6 ha operational plot (P2009). With sandalwood being a root hemi-parasite, one of the main aims of the trials was to compare the effects of different hosts (pot, intermediate and long-term) on *S. album* growth near Carnarvon. The trials also aimed to compare commercial wood (heartwood and sapwood) yields, oil yields and oil quality between *S. album* and *S. austrocaledonicum*.

Both *Alternanthera nana* and *Phyla nodiflora* were suitable pot hosts for *S. album* near Carnarvon. The intermediate host trial showed that *Sesbania formosa*, *Pittosporum angustifolium*, *Acacia stenophylla* and *Acacia coriacea* subsp. *pendens* were all suitable hosts. Within the long-term host trial, mean *S. album* growth was significantly greater near *Melia azedarach*, but *A. coriacea* subsp. pendens, *A. stenophylla* and *P. angustifolium* also appeared suitable.

Although a range of intermediate and long-term hosts were identified as being suitable, it is recommended that *A. coriacea* subsp. *pendens* be preferentially used for this region. This host species appeared to be least affected by the water restrictions after 2013 and it also had relatively good tree shape, not requiring as much pruning within the plantation.

At age 15 years, the *S. austrocaledonicum* trees were significantly larger (diameter 164 mm, height 5.0 m) than the *S. album* trees (diameter 151 mm, height 4.8 m). The *S. austrocaledonicum* also had higher commercial wood (heartwood and sapwood) yields (35.0 kg/tree) than the *S. album* trees (23.5 kg/tree), at age 16 years. However, the mean heartwood oil yield for *S. album* (2.2%) was higher than the *S. austrocaledonicum* (1.5%) trees, at age 15 years. Overall, both *S. album* and *S. austrocaledonicum* appear to be well suited to the growing conditions near Carnarvon, if grown on suitable soil types (*e.g.* brown sandy loam over light clay) and irrigated with a sufficient amount of relatively fresh water (*e.g.* salinity of approximately 330 ppm).

Within the heartwood oil, at age 15 years, both sandalwood species had mean concentrations of *α*-santalol (38-54%), *β*-santalol (22-25%) and t-t-farnesol (1%) within or near ISO 3518:2022E *S. album* standards. However, the mean concentration of cis-lanceol within the *S. austrocaledonicum* oil was 25%, well above the ISO standard of only 0-2%. In contrast, the mean oil concentration of cis-lanceol within the *S. album* oil (2%) met the standard.

Introduction

The Carnarvon region in Western Australia, has been identified as a suitable area to grow high-value tropical sandalwood species, including Indian sandalwood (*Santalum album*) and New Caledonian sandalwood (*Santalum austrocaledonicum*). Sandalwood is valued for its aromatic oils produced within its heartwood, which are highly sought after in the perfume and incense trade. *S. album* and *S. austrocaledonicum* are two of the most valuable sandalwood species, with high oil yields of up to 5-7% (Applegate *et al*., 1990). The oil from each species is also rich in *α*- and *β*-santalol, which gives sandalwood its distinctive fragrance (Adams *et al*., 1975). The value of sandalwood oil is largely determined by the proportion of *α*- and *β*-santalol, but also the proportions of other compounds including farnesol and lanceol. The current International Standard for *S. album* oil requires that it contains 41-55 % *α*-santalol, 16-24 % *β*–santalol, 0-1% farnesol and 0-2% lanceol (ISO 3518 2022E).

Carnarvon appears to be good for growing tropical sandalwood due to its access to relatively fresh water (approximately salinity of 330 ppm) from the Gascoyne River for irrigation, as well as having a relatively warm climate. A small planting of Indian sandalwood established in 1991, near Carnarvon, also showed promising growth rates after 17 years and confirmed the suitability of this region to grow tropical sandalwood (McComb, 2009).

Due to sandalwood being a root hemi-parasite (Hewson and George, 1984), it needs to be established near appropriate host plants. During the early 1990s, the FPC (previously the Department of Conservation and Land Management) successfully established Indian sandalwood and host plants in plantations on the Ord River Irrigation Area (ORIA), near Kununurra, WA. A three-stage host system was used, which consisted of (1) a pot host, (2) intermediate host and (3) a long-term host. The three-stage host system was developed to provide sandalwood with water and nutrients at different stages during its life cycle: pot host 0-2 years, intermediate host 1-5 years, and long-term host 3-20 years. Extensive *S. album* research has shown that *Alternanthera nana* and *Sesbania formosa* are excellent pot and intermediate hosts respectively for the Kununurra region (Radomiljac, 1998; Radomiljac *et al*., 1999). A variety of long-term hosts have also been used in Kununurra, including *Cathormion umbellatum* and *Dalbergia latifolia*. In Carnarvon, similar host species should also be tested, as well as some local species to test their suitability with tropical sandalwood.

The main aim of this trial was to determine whether two high value tropical sandalwood species (*S. album* and *S. austrocaledonicum*) could be successfully grown in plantations near Carnarvon, as well as examine the following:

(1) Compare *S. album* growth rates (height and stem diameter) when planted with different (a) pot, (b) intermediate and (c) long-term hosts, at age 15 years.
(2) Compare growth rates (height and stem diameter) and oil measurements (oil yield % and oil composition %) between *S. album* to *S. austrocaledonicum*, at age 15 years.

(3) Determine the approximate commercial wood (de-barked logs containing both heartwood and sapwood) yields (kg/tree and tonnes/ha) of *S. album* and S. *austrocaledonicum* plantations at age 16 years.

Methods

The tropical sandalwood seedlings (*S. album* and *S. austrocaledonicum*) were planted in 2006 (P2006) and 2009 (P2009), at the Gascoyne Research Facility, DPIRD, approximately 10 km east of Carnarvon (Figure 1). The P2006 site was 2.7 ha in area and the P2009 site was 4.6 ha in area. The soil for both plantings consisted of a brown sandy loam over light clay.

Figure 1. Location of P2006 (2.7 ha) and P2009 (4.6 ha) tropical sandalwood plantations established near Research Road, at the Gascoyne Research Facility, DPIRD, Carnarvon, WA.

Fresh water, with an approximate salinity of only 330 ppm, from the Gascoyne River was used to irrigate both the P2006 and P2009 plantations. The water was delivered to the trees using Netafim™ 'drip-net', with the emitters spaced 500 mm apart. Each emitter delivered approximately 1.6 L/hour.

The P2006 plot contained a total of 240 irrigation lines of 60 m in length (14.4 km), with 28,800 emitters. The P2009 plot contained a total of 180 irrigation lines of 100 m in length (18.0 km), with 36,000 emitters.

The volume of water delivered was approximately 46,000 L/hour for the P2006 plot and 72,000 L/hour for the P2009 plot. During 2006-13, both P2006 and P2009 plantations were watered approximately twice a week. However, after 2013 the watering was reduced to only once per

week, due to drought water restrictions in the Carnarvon region. During 2016-22, both plantations (P2006 & P2009) received a total of approximately 40,000 kL year^{-1}.

Research trials (P2006)

The P2006 site was established in a *tramline* system. Each tramline consisted of two separate Netafim^{TM} drip-net lines, spaced 2.5 m apart, with the tramlines spaced 5 m apart. The irrigation lines were laid on the ground surface in a north-south direction, and each tramline was 60 m long.

In May 2006, 20 intermediate hosts were planted at 3 m intervals (444 stems ha^{-1}), within 20 cm of the eastern irrigation line, within each tramline. At the same time, 40 long-term hosts were planted at 1.5 m intervals (888 stems ha^{-1}), near the western irrigation line, within each tramline. A total of 1,200 intermediate hosts and 2,400 long-term hosts were planted on the 60 tram lines. All of the intermediate and long-term host plants were grown at Chatfield's Nursery, Tammin, WA and were planted at age six months.

In May 2006, approximately 1120 *S. album* seedlings were planted in between each of the intermediate hosts at 3 m intervals. Approximately 80 *S. austrocaledonicum* seedlings were also accidentally planted in the P2006 site in May 2006, mistakenly planted as *S. album*. The *S. album* and *S. austrocaledonicum* seedlings were grown at the FPC Nursery, Wanneroo, and were planted at age six months. In 2006, the stocking of tropical sandalwood at the site was approximately 444 stems ha^{-1}. The different stages of *S. album* seedling and tree growth during the trial at the Gascoyne Research facility in Carnarvon are shown in Figures 2-6.

In 2013 (age 7 years), the tropical sandalwood site was thinned, to a stocking of approximately 290 stems ha^{-1}. Each of the 60 m rows contained between 6 and 13 sandalwood trees.

Within the P2006 plot, three separate trials were established to compare *S. album* growth rates (height and stem diameter) when planted with different (a) pot, (b) intermediate and (c) long-term hosts. A fourth trial also compared growth rates (height and stem diameter) and oil measurements (oil yield % and oil composition %) between two tropical sandalwood species (*S. album* and *S. austrocaledonicum*):

Pot host

The pot-host trial was established in a group of five tramlines and contained two separate host treatments: *Alternanthera nana* and *Phyla nodiflora*. Each tropical sandalwood seedling was grown together with its pot host and were planted in separate pot host treatment lines of 10 seedlings and replicated five times (Figures 1-2).

S. album seedlings were planted between each intermediate host (*Sesbania formosa*), with *Acacia stenophylla* planted on the opposite line as the long-term host. In 2006, there were initially approximately 100 *S. album* seedlings, 100 intermediate hosts and 200 long-term hosts in the pot-host trial.

In April 2021 (age 15 years), there were 30-33 *S. album* trees remaining in each of the two pot host treatments (*A. nana* and *P. nodiflora*). At this age, mean stem diameter (over-bark at 300 mm above the ground) and tree height was measured and compared between treatments.

Intermediate host

The intermediate host trial was established in a group of 20 tramlines, and contained five separate host treatments: *S. formosa*, *Acacia coriacea* subsp. *pendens*, *Acacia stenophylla*, *Acacia trachycarpa* and *Pittosporum angustifolium*. Of these, *A. trachycarpa* survival was poor (<10% within two years) and this species was removed from the trial. The intermediate hosts were planted in separate species treatment lines of 20 seedlings spaced 3 m apart and replicated four times. *S. album* seedlings (together with *P. nodiflora*) were planted between each intermediate host, and *A. stenophylla* was planted on the opposite line as the long-term host.

In 2006, each host treatment contained approximately 60-80 *S. album*, 80 intermediate hosts and 160 long-term hosts. Overall, there were approximately 340 *S. album*, 400 intermediate hosts and 800 long-term hosts.

In April 2021 (age 15 years), there were 35-49 *S. album* trees remaining in each of the four intermediate host treatments (*S. formosa*, *A. coriacea* subsp. *pendens*, *A. stenophylla*, and *P. angustifolium*), with a total of 171 *S. album* trees. At this age, mean stem diameter (over-bark at 300 mm above the ground) and tree height was measured and compared between treatments.

Long-term host

The long-term host trial was established in a group of 20 tramlines and contained five separate host treatments: *Cathormion umbellatum*, *A. coriacea*, *A. stenophylla*, *P. angustifolium* and *Melia azedarach*. Most of the *C. umbellatum* seedlings perished within six months (< 10% survival) at Carnarvon and appeared unsuitable for this region and were removed from the trial. The long-term hosts were planted in separate species treatment lines of 40 seedlings spaced 1.5 m apart and replicated four times. *S. formosa* seedlings were also planted as the intermediate host, and tropical sandalwood seedlings (together with *P. nodiflora*) were planted in between each intermediate host.

In 2006, each host treatment contained approximately 70-80 *S. album*, 80 intermediate hosts and 160 long-term hosts. Overall, there were approximately 380 *S. album*, 400 intermediate hosts and 800 long-term hosts.

In April 2021 (age 15 years), there were 38-48 *S. album* trees remaining in each of the four long-term host treatments (*A. coriacea*, *A. stenophylla*, *P. angustifolium* and *M. azedarach*), with a total of 177 *S. album* trees. At this age, mean stem diameter (over-bark at 300 mm above the ground) and tree height were measured and compared between treatments.

Sandalwood species

In April 2021 (age 15 years), there was a total of 456 *S. album* and 40 *S. austrocaledonicum* remaining in the pot host, intermediate host and long-term host trials. At this age, mean stem diameter (over-bark at 300 mm above the ground) and tree height was measured and compared between the two species. Wood core samples were also taken, and the oil quantity and quality were compared between species.

Operational plot (P2009)

The P2009 operational plot consisted of a single line system, with the sandalwood (and pot hosts), as well as the intermediate and long-term hosts planted on the same line. The 4.6 ha site contained 88 rows of 100 m in length and spaced 5 m apart.

The 4.6 ha site was divided up into five blocks of 17-18 rows each. Between each block, a single row of *Allocasuarina cunninghamiana* seedlings were planted at 2 m intervals, to act as an internal windbreak. *A. cunninghamiana* seedlings were also planted at 2 m intervals as a windbreak on the perimeter of the plot, on the south, west and east sides.

In August 2008, six-month-old intermediate and long-term host seedlings were planted on each line at 2 m intervals. The plantings consisted of mainly three species: *Acacia ampliceps* (intermediate host), *A. coriacea* subsp. *pendens* (long-term host) and *A. stenophylla* (Long-term host). Each host was planted at a density of approximately 330 stems ha^{-1}, with a total host density of approximately 1000 stems ha^{-1}. Besides *A. ampliceps*, some other intermediate hosts were also planted, which were *Acacia acuminata* (narrow phyllode variant), *Acacia sclerosperma* and an *Aquilaria* spp.

In August 2009, *S. album* and *S. austrocaledonicum* seedlings (aged six months) were planted within the P2009 site, next to every third host at approximately 330 stems ha^{-1}. A total of 1300 *S. album* and 80 *S. austrocaledonicum* were established. Most of the *S. album* seedlings were derived from seeds collected from *S. album* trees within the P2006 site (Carnarvon), as well as some from Kununurra, WA. The *S. austrocaledonicum* seedlings were derived from a plantation in Kununurra, WA.

It needs to be noted that 40 of the *S. album* seedlings established in the P2009 plot appeared to be a “hybrid”, displaying morphometrical characteristics of both *S. album* and a local *Santalum*

species (*Santalum lanceolatum*). Although not taxonomically confirmed, these potential hybrid seedlings were not included in the final harvest.

Figure 2. *S. album* seedlings with pot hosts (*P. nodiflora*), age six months, Gascoyne Research Facility, Carnarvon.

Figure 3. *S. album* seedlings planted near drip-net irrigation, four months after establishment, Gascoyne Research Facility, Carnarvon, September 2006

Figure 4. *S. album* seedlings, growing with host plants, age one year, Gascoyne Research Facility, DPIRD, Carnarvon, 2007.

Figure 5. *S. album* trees aged 2 years, growing beneath the intermediate host plant, *Sesbania forma*, Gascoyne Research Facility, DPIRD, Carnarvon, July 2008.

Figure 6. *S. album* tree aged 16 years, growing at the Gascoyne Research Facility, DPIRD, Carnarvon, August 2022.

Measurements and statistical analysis

Growth rates

In the P2006 plot, at age 15 years (April 2021), tree height (m) and stem diameter (mm) over the bark at 300 mm above the ground were measured from each sandalwood tree in each of the four sandalwood research trials: (a) pot host, (b) intermediate host, (c) long-term host and (d) sandalwood species.

In the P2009 plot, at age 12 years (April 2021), a subset of 119 *S. album* trees and 63 *S. austrocaledonicum* trees (aged 12 years) were also measured for tree height (m) and stem diameter (mm). However, the measurements were not statistically compared.

Means from the P2006 trials were compared between treatments within the research trials using one-way analysis of variance (ANOVA) and Tukey's test. SYSTAT® version 11 was used for all statistical analysis.

Wood coring and oil analysis

In April 2021, heartwood core samples were taken at 300 mm above the ground from six separate *S. album* trees aged 12 years and eight separate *S. album* trees aged 15 years. Similarly, six core samples were taken from six separate *S. austrocaledonicum* trees aged both 12 years and 15 years. A total of 26 separate trees were sampled.

The heartwood was separated from the sapwood based on colour. The heartwood was described as having a golden/brown colour, the sapwood had a white-creamy colour, and the transitional wood was more pink in colour. The mean stem diameter from each tree cored was also measured (over the bark) at 300 mm above the ground.

At Wescorp Sandalwood Pty Ltd (Canning Vale, WA), the mean total extractable oil yield within the wood (w/w %) was determined from combined samples from each of the two sandalwood species (*S. album* and *S. austrocaledonicum*), aged both 12 and 15 years, using hydro-distillation. The heartwood oil samples were also analysed for chemical composition (including *α*-santalol, *β*-santalol, *t-t*-farnesol and cis-lanceol) within the oil.

Harvest and wood yields (logs & butts containing heartwood)

During August-October 2022, approximately 631 *S. album* and 40 *S. austrocaledonicum* trees within the Research P2006 plot (aged 16 years) and 1,267 *S. album* and 66 *S. austrocaledonicum* trees within the Operational P2009 plot (aged 13 years) were harvested. The trees were processed for logs containing a cross-sectional heartwood (aromatic oil-bearing wood) diameter of at least 25 mm at the small end of each log (Figure 7). Generally, the heartwood did not extend in the stem above 1 m from the ground, but was highly variable, with some trees containing heartwood up to a height of 2 m, while other trees had none. For heartwood description see *Wood coring and analysis*.

Sandalwood tree butts with a cross-sectional heartwood diameter of at least 25 mm at approximately 150 mm above the ground level were also harvested (Figure 8). The butts were cut off from the log (bole) at approximately150 mm above the ground level. The butt generally only extended to about 300-500 mm below the ground, and the roots were cut away from the butt, no closer than 100 mm from the butt (*i.e*. leaving a 100 mm root stub attached to the butt). The roots were generally small in diameter, had little heartwood and were not included as part of the harvest.

All harvested logs and butts were de-barked on site using a mechanised *tumbler* and/or a high pressure 3,000 psi water cleaner (Figures 7 and 8). The de-barked logs and butts were placed into separate *bulker* bags, based on wood product, sandalwood species and age. On 12 October 2022, the different sandalwood products were transported from Carnarvon to Wescorp Sandalwood Pty Ltd (Canning Vale, WA), where the total approximate air-dry weights were measured for each product. It needs to be noted that although the logs and butts were allowed

to air-dry for approximately 2-8 weeks, the weights were not assessed for the standard air-dry weight of approximately 12% moisture content.

Figure 7. De-barked *S. album* log, age 16 years, Gascoyne Research Facility, Carnarvon. Cross-sectional end of log with golden/brown heartwood in centre, with white/cream sapwood around edge.

Figure 8. De-barked *S. album* butt with roots cut away, age 16 years, Gascoyne Research Facility, Carnarvon. Cross-sectional top of butt with golden/brown heartwood in centre, with white/cream sapwood around edge.

Results

Growth Rates

Pot host

At age 15 years, there were no significant differences in *S. album* stem diameter (141-148 mm) or height (4.6-4.7 m), between treatments established with *A. nana* and *P. nodiflora* (Table 1). In the first 1-2 years, both *A. nana* and *P. nodiflora* appeared to establish well with the sandalwood, and both appeared to be suitable pot hosts for sandalwood, near Carnarvon.

Table 1. Mean stem diameter (mm at 300mm above the ground) and height (m) of *S. album* trees at age 15 years, grown with different pot host species.

Species	Trees	Diam. (mm)	Height. (m)
A. nana	33	159.4 ±3.8	4.6 ±0.1
P. nodiflora	30	149.5 ±4.5	4.7 ±0.1
P-value	-	0.095	0.620

Intermediate host

Mean *S. album* stem diameter (146-156 mm) and height (4.6-4.7 m) were not significantly different between the four intermediate host species treatments, at age 15 years (Table 2). However, all of the *S. formosa* trees had died within 3-4 years, and most of the *P. angustifolium* and *A. stenophylla* trees had died by age 7-8 years. Although the sandalwood trees were not significantly larger on *A. coriacea* subsp. *pendens*, this intermediate host species appeared to be the most resilient and best suited at the Carnarvon site.

It also needs to be noted that a local native species, *Acacia sclerosperma,* self-established within the rows of the trial, within the first two years and appeared to provide support to the sandalwood trees during the trial. This species may also be a suitable host for tropical sandalwood trees grown near Carnarvon.

Table 2. Mean stem diameter (mm at 300mm above the ground) and height (m) of *S. album* trees at age 15 years, grown with different intermediate host species.

Species	Trees	Diam. (mm)	Height. (m)
S. formosa	49	156.1 ±3.7	4.7 ±0.1
A. coriacea subsp. *pendens*	35	145.5 ±4.9	4.6 ±0.2
A. stenophylla	40	148.1 ±3.6	4.7 ±0.1
P. angustifolium	47	147.3 ±4.6	4.7 ±0.1
P-value	-	0.266	0.620

Long-term host

Mean *S. album* stem diameter was significantly greater near *M. azedarach* (159 mm) than near *A. coriacea* subsp. pendens (144 mm) and *P. angustifolium* (138 mm), at age 15 years (*P* = 0.002, Table 3). *S. album* trees near *M. azedarach* were also significantly taller (5.0 m) than near *P. angustifolium* (4.5 m, *P* = 0.020).

Although *S. album* growth near the long-term host *M. azedarach* was better than the other host treatments, it needs to be noted that after age seven years, many of the *M. azedarach* died. This was most likely due to reduced watering after 2013. Although *M. azedarach* appears a good host for *S. album*, it may not be able to withstand the lower watering rates, which sometimes occurs due to water restrictions in Carnarvon.

Although sandalwood growth was not significantly greater near *A. coriacea* subsp. pendens at age 15 years, this host species appeared to be the least affected by the water restrictions after 2013 and should therefore be included as a long-term host in any future plantings of *S. album* in the Carnarvon region.

Again, it needs to be noted that within the planting rows, *A. sclerosperma* self-established within the first two years of the trial. Although not specifically tested, *A. sclerosperma* should also be considered as a potential long-term host for *S. album* near Carnarvon.

Table 3. Mean stem diameter (mm at 300mm above the ground) and height (m) of *S. album* trees at age 15 years, grown with different long-term host species. Values with the same letter were not significantly different, using Tukey's test (*P* > 0.05).

Species	Trees	Diam. (mm)	Height (m)
M. azedarach	45	158.7 ±4.3 a	5.0 ±0.1 a
A. coriacea subsp. *pendens*	46	143.5 ±3.2 b	4.9 ±0.1 ab
A. stenophylla	48	150.3 ±3.5 ab	4.8 ±0.1 ab
P. angustifolium	38	137.7 ±4.4 b	4.5 ±0.1 b
P-value	-	0.002	0.020

Sandalwood species

At age 15 years, the mean stem diameter of the *S. austrocaledonicum* trees (164 mm) were significantly larger than the *S. album* trees (151 mm, *P* = 0.004, Table 4). At the same age, mean tree height from the *S. austrocaledonicum* trees (5.0 m) were also significantly taller than the *S. album* trees (4.8 m, *P* = 0.042).

Table 4. Mean stem diameter (mm at 300 mm above the ground) and height (m) of *S. album* and *S. austrocaledonicum* trees at age 15 years. Values with the same letter were not significantly different, using Tukey's test ($P > 0.05$).

Species	Trees	Diam. (mm)	Height (m)
S. album	456	150.6 ±1.3 b	4.8 ±0.05 b
S. austrocaledonicum	40	163.5 ±4.3 a	5.0 ±0.1 a
P-value	-	0.004	0.042

P2009 plot

In the Operational plot, at age 12 years, the mean stem diameters were 126.1 ± 2.0 mm for *S. album* and 120.5 ± 3.8 mm for *S. austrocaledonicum*. At the same age, the mean tree heights were 4.0 ± 0.1 m for *S. album* and 3.7 ± 0.1 m for *S. austrocaledonicum*.

Oil yield and composition

P2006 plot

In the P2006 research plot, at age 15 years, the mean heartwood oil yields were 2.2% for *S. album* and 1.5% for *S. austrocaledonicum* (Table 5). The quality of the *S. album* oil was relatively good, with *α*-santalol, *β*-santalol, and t-t-farnesol levels within (or slightly above) current ISO standards for *S. album* (ISO 3518:2022E). Within the *S. austrocaledonicum* oil, the mean oil composition levels of *α*-santalol, *β*-santalol and t-t-farnesol were within or near ISO 3518:2022E standards, but the amount of cis-lanceol (25.4%) was well above the standard of only 0-2%.

P2009 plot

In the P2009 operational plot, at age 12 years, the mean heartwood oil yields were 2.2% for *S. album* and 1.3% for *S. austrocaledonicum* (Table 5). In these relatively young trees, the oil quality of *S. album* met ISO 3518:2022E standards for *α*-santalol, *β*-santalol, and t-t-farnesol but had high levels of cis-lanceol (13.1%). Similarly, the oil quality concentrations of the *S. austrocaledonicum* were also within 3518:2022E standards except for cis-lanceol (8.1%)

Table 5. Mean stem diameter (mm), oil yield (w/w%) and oil composition (w/w%) from 6-8 *S. album* and *S. austrocaledonicum* heartwood core samples at 300 mm above the ground, from both P2006 (age 15 years) and P2009 (age 12 years), Gascoyne Research Facility, Carnarvon, April 2021. International Standard ISO 3518:2022E for *S. album* oil composition provided.

				Oil yield	Oil composition (%)			
Plot/species	Age	(mm)	Cores	(%)	*α*-santalol	*β*-santalol	*t-t*-farnesol	*lanceol*
P2006								
S. album	15	187	8	2.2	54.0	25.0	0.1	1.6
S. austrocaledonicum	15	177	6	1.5	38.1	19.1	1.4	25.4
P2009								
S. album	12	152	6	2.2	45.6	22.4	1.3	13.1
S. austrocaledonicum	12	160	6	1.3	47.2	24.7	1.0	8.1
ISO 3518:2022E					41-55	16-24	0-1	0-2

Commercial wood (heartwood and sapwood) yields

P2006 Plot

The mean total commercial wood (heartwood and sapwood) weights in the P2006 research plot, at age 16 years, were 23.5 kg/tree (*S. album*) and 35.0 kg/tree (*S. austrocaledonicum,* Table 6). Although the heartwood proportions were not measured, the commercial wood most likely contained only 25-50% heartwood. For both species, 66-67% of the commercial wood was contained in the logs, 29-33% in the butts and 0-5% was dead wood.

The P2006 research plot (age 16 years) produced approximately 14.9 tonnes of commercial *S. album* wood (heartwood and sapwood) and 1.4 tonnes of commercial *S. austrocaledonicum* wood (Table 7). Within the P2006 plot, the approximate yields per hectare were 5.5 tonnes/ha of commercial *S. album* wood and 0.5 tonnes/ha of commercial *S. austrocaledonicum* wood, totalling approximately 6.0 tonnes/ha.

P2009 Plot

In the P2009 operational plot (age 13 years), the mean commercial wood (heartwood and sapwood) weights were much lower than the P2006 plot. The mean total commercial wood weights were approximately only 3.8 kg/tree for *S. album* and 7.0 kg/tree for *S. austrocaledonicum* (Table 6). Again, the heartwood proportion was not measured, but appeared to be only 25-50% of the commercial wood. The commercial wood for *S. album*, consisted of approximately 61% logs and 39% butts. The proportions were not separated in the *S. austrocaledonicum*.

The total commercial wood yields (heartwood and sapwood) within the 2009 plot were 4.8 tonnes of *S. album* and 0.5 tonnes of *S. austrocaledonicum*, at age 13 years (Table 7). The

approximate yields per hectare were only 1.0 tonnes/ha of commercial *S. album* wood and 0.1 tonnes/ha of commercial *S. austrocaledonicum* wood, totalling approximately 1.1 tonnes/ha.

Table 6. The estimated number of *S. album* and *S. austrocaledonicum* trees and the estimated mean weight per tree (kg/tree) of logs, butts and deadwood containing commercial heartwood and sapwood, from both P2006 (age 16 years) and P2009 (age 13 years), Gascoyne Research Facility, Carnarvon, October 2022.

Species	Age	Trees	Logs (kg/tree)	Butts (kg/tree)	Dead (kg/tree)	Total (kg/tree)
P2006						
S. album	16	631	15.6	6.9	1.1	23.5
S. austrocaledonicum	16	40	23.5	11.5	-	35.0
P2009						
S. album	13	1267	2.3	1.5	-	3.8
S. austrocaledonicum	13	66	7.0*	-	-	7.0

***** *S. austrocaledonicum* (age 13 years) estimated log and butt weights/tree were combined

Table 7. The estimated number of *S. album* and *S. austrocaledonicum* trees and the total tonnage (tonnes) of logs, butts and deadwood containing commercial heartwood and sapwood, from both P2006 (age 16 years) and P2009 (age 13 years), Gascoyne Research Facility, Carnarvon, October 2022.

Species	Age	Trees	Logs (t)	Butts (t)	Dead (t)	Total (t)
P2006						
S. album	16	631	9.822	4.345	0.701	14.868
S. austrocaledonicum	16	40	0.939	0.461	-	1.400
P2009						
S. album	13	1267	2.931	1.834	-	4.765
S. austrocaledonicum	13	66	0.464*	-	-	0.464
Total	-	2004	14.156	6.640	0.701	21.497

***** *S. austrocaledonicum* (age 13 years) total log and butt weights were combined

Discussion

Host species trial

A range of species (pot, intermediate and long-term) proved to be suitable hosts for *S. album* at the Gascoyne Research Facility in Carnarvon. Both *A. nana* and *P. nodiflora* were suitable pot hosts for *S. album* at Carnarvon. In the intermediate host trial, *S. album* tree size at age 15 years (diameter 146-156 mm, height 4.6-4.7 m) was similar when grown near *S. formosa*, *P. angustifolium*, *A. stenophylla* and *A. coriacea* subsp. *pendens.* However, *A. coriacea* subsp. *pendens* appeared to be the most resilient and the best suited intermediate host at the Carnarvon site. It also had good form (more tree-like and not spreading) which potentially makes this species relatively easy to manage (*e.g.* low pruning requirements) within a plantation. Although not part of the trial, *A. sclerosperma* trees also established naturally within the plots from about year two and may also be a useful intermediate host for tropical sandalwood, near Carnarvon. Most of the *A. trachycarpa* host seedlings died within two years of establishment and did not appear suited to the growing conditions at the site.

In the long-term host trial, mean *S. album* growth at 15 years was greatest near *M. azedarach* (diameter 159 mm, height 5.0 m), but the other three host species (*A. coriacea* subsp. pendens, *A. stenophylla* and *P. angustifolium*) also appeared suitable. The majority of the *C. umbellatum* host seedlings died early on in the trial and this species did not appear suited for the Carnarvon region. Although the sandalwood trees were not significantly larger near *A. coriacea* subsp. *pendens*, this species again appeared to be an excellent choice for a long-term host, because it appeared to be the least affected by the water restrictions after 2013. It is recommended that *A. coriacea* subsp. *pendens* be used as both an intermediate and a long-term host in any future plantings of *S. album* in the Carnarvon region.

Sandalwood species trial

At age 15 years, the *S. austrocaledonicum* trees were significantly larger (diameter 164 mm, height 5.0 m) than the *S. album* trees (diameter 151 mm, height 4.8 m). These growth rates in Carnarvon were also relatively good, being slightly higher than that achieved in 16-year-old *S. album* plantation trees grown near Kununurra, WA (diameter 149 mm, Brand *et al*., 2012).

The mean heartwood oil concentration of the *S. album* trees (2.2%) was higher than the *S. austrocaledonicum* (1.5%) trees at age 15 years. However, the oil yields of both species in this study were considerably lower than that recorded in a previous study. Brand *et al.* (2012) recorded mean heartwood oil yields of 5.0% in similar aged 16-year-old *S. album* plantation trees grown near Kununurra, WA.

At Carnarvon, the quality of the heartwood oil was better within *S. album* than *S. austrocaledonicum* trees at age 15 years. Although the mean concentrations of *α*-santalol (38-54%), *β*-santalol (22-25%) and t-t- farnesol (1%) were within or near ISO 3518:2022E *S. album* standards for both sandalwood species, there was a marked difference in the mean

cis-lanceol levels. The mean cis-lanceol concentration in *S. album* oil was 2% (within the ISO standard of 0-2%), while the *S. austrocaledonicum* oil had a very high mean cis-lanceol concentration of 25%. A high concentration of cis-lanceol within the oil is not unusual for *S. austrocaledonicum*, but may potentially lower its oil value, compared to oil that meets the ISO 3518:2022E standard.

At age 16 years, the mean estimated weight of commercial wood (heartwood and sapwood) from the *S. austrocaledonicum* trees (35.0 kg/tree) was greater than the *S. album* trees (23.5 kg/tree). The commercial logs from both species contained about 25-50% heartwood, with most of the commercial wood contained in the logs (66-67%).

Overall, both of the tropical sandalwood species tested at the Gascoyne Research Centre appear to be well suited for this region, at age 15-16 years. Both species had a relatively good growth rate, with *S. austrocaledonicum* having a higher commercial wood yield, but *S. album* having a higher oil yield and better oil quality. Both tropical sandalwood species have the potential to provide good yields of high-quality sandalwood in the Carnarvon region if grown on favourable soil types (*e.g.* brown sandy loam over light clay) and irrigated with a sufficient amount of relatively fresh water (*e.g.* salinity of approximately 330 ppm).

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