Comparison of oil concentration and oil quality from *Santalum spicatum* and *S. album* plantations, 8–25 years old, with those from mature *S. spicatum* natural stands

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Summary

During February to November 2004, core samples were taken from 41 trees growing in three *Santalum spicatum* plantations in the Wheatbelt (W1–W3: age 8–11 y); one *S. spicatum* plantation (aged 20–25 y) from Curtin University; one *Santalum album* plantation (aged 15 y) also from Curtin University; and two mature natural stands of *S. spicatum* (aged >50 y). Each tree was cored at 150 mm and 700 mm above ground to compare heartwood percentage; oil concentration; and α-santalol, β-santalol and t,t-farnesol contents within the oil. Oils were extracted from the whole core samples (heartwood + sapwood) using ethanol, and the chemical composition was determined using a gas chromatography flame ionisation detector (GC-FID) and a mass-selective detector (GC-MS).

Santalum spicatum from the three Wheatbelt plantations had significantly lower proportions of heartwood (28–48%) than those from Curtin University (61–69%) and the natural stands (64–79%), at 150 mm and 700 mm above the ground. *Santalum album* at age 15 y had 57–59% heartwood at both sampling heights.

The mean total extractable oil concentrations from *S. spicatum* plantations growing at Curtin University, W1 and W2 (2.2–3.6%), were similar to those from mature natural stands (2.3–3.1%), at both 150 mm and 700 mm. The mean oil concentration from W3 (0.7–0.8%), however, was significantly less than the mean oil concentration from mature *S. spicatum*. The *S. album* plantation had a mean oil concentration of 1.3–2.3%.

Within the oil, W1 and Curtin University plantations had α-santalol (5.5–27.3%) and β-santalol (2.1–10.5%) contents similar to or greater than those in the natural stands (3.1–8.0% α-santalol; 1.3–3.0% β-santalol), at both sampling heights. W2 had poor oil quality with only 0.1–2.4% α-santalol and 0–0.6% β-santalol. As expected, the *S. album* had significantly more α- and β-santalol within the oil than *S. spicatum*.

Mean t,t-farnesol content within the oil from W2 and W3 (28.3–38.7%) was significantly greater than within the oil from the mature *S. spicatum* (10.0–16.2%), at both sampling heights. *Santalum album* had the lowest t,t-farnesol content of only 0.1%.

Keywords: plantations; heartwood; oils; α-santalol; β-santalol; t,t-farnesol; *Santalum spicatum*; *Santalum album*

Introduction

Western Australian sandalwood (*Santalum spicatum* (R.Br.) A.DC) is emerging as a small to medium commercial plantation industry, suitable for the over-350 mm annual rainfall zone of Western Australia (WA). At present, *S. spicatum* harvesting occurs almost exclusively from mature natural stands, in the semi-arid inland regions. During 1997–2007, however, over 5000 ha of *S. spicatum* has been planted in the WA 'Wheatbelt' by private companies, the state government and farmers. During the next decade, plantation-grown *S. spicatum* is poised to enter the sandalwood market. Initial growth rates from these plantations have been encouraging, with stem diameters increasing at up to 10 mm y^{-1} (at 150 mm above ground) for the first 6 y (Brand *et al*. 2004). However, there is very limited information on the development of heartwood and oil. Because the heartwood contains most of the fragrant oils, the proportion of heartwood, oil concentration and oil quality generally set the price of sandalwood. Therefore, more information on heartwood and oil production in young trees is required to help predict the value of *S. spicatum* plantations.

Some 15 species occur in the genus *Santalum*, many of which have valuable aromatic oils within their heartwood (Barrett and Fox 1995). The value of the wood varies between species, due mainly to differences in the mean oil concentration and quality. Oil quality is related to the amounts of α-santalol and β-santalol within the oil, which gives sandalwood species their unique fragrance (Adams *et al*. 1975). Besides the santalols, sandalwood oils contain a range of other compounds, including trans, trans-farnesol, which is one of the main compounds within *S. spicatum* oil (Brophy *et al*. 1991).

Powdered sandalwood is commonly used to make incense, while the extracted oils from grindings and chips are used in perfumes, soaps, cosmetics and medicines. In perfumery, the heavy, sweet scent of sandalwood oil and its fixative properties are difficult to reproduce (Naipawar 1988). It is reputed to have antipyretic, antiseptic and diuretic properties and as being effective in treatment of bronchitis, cystitis and in alleviating migraine (Rai 1990).

Indian sandalwood (*Santalum album* L.) is considered the most valuable of the sandalwood species, with mature heartwood typically containing 5–7% oil with over 85% total santalol (McKinnell 1990; Rai 1990). In contrast, *S. spicatum* is considered one of the least valuable of the commercial sandalwood species, with the wood (heartwood + sapwood) containing up to 3% oil and up to 40% total santalol. *Santalum spicatum* generally has a lower oil concentration and quality than many of the other sandalwood species, but unlike many of the tropical sandalwood species it can be successfully grown in plantations without irrigation in regions of WA with a mean annual rainfall as low as 350 mm.

After harvesting, sandalwood oils are commonly extracted from the ground wood using methods such as steam distillation or solvent extraction. A non-destructive method of sampling sandalwood trees entails taking core samples through the centre of the stem. Studies have shown, however, that oil content varies between different sections of individual trees. Piggott *et al*. (1997) found that within a single *S. spicatum* tree, total extractable oil, and the levels of α-santalol and β-santalol within the oil, all decreased with increasing height in the tree. The level of farnesol within the oil, however, increased higher up in the tree. Therefore, to more accurately estimate the oil content within a tree, core samples should be taken from at least two positions within the tree, such as near the base and higher up the stem. In addition, the total extractable oil concentration and oil quality (i.e. α-santalol and β-santalol content) should always be expressed together when determining the value of sandalwood. A sandalwood tree that has a relatively high oil concentration but a low oil quality or vice-versa may not be very valuable.

The aim of this study was to determine if the oil concentration, oil quality and heartwood content in *S. spicatum* was (a) lower in young trees grown in plantations than in mature natural stands; and (b) different between locations and genotypes. Oil and heartwood results from *S. album* trees grown in a plantation were also included to provide a baseline for comparison.

Methods

Natural stands

In May 2004, six naturally occurring *S. spicatum* trees growing in a single population at Ninghan Station near Paynes Find were sampled. In November 2004, another six naturally occurring *S. spicatum* trees growing in a single population at Walling Rock Station, near Menzies, were sampled (Table 1). Within each population, sampled trees were between 20 m and 200 m distant from each other. At both locations, the trees had stem diameters equal to or greater than 118 mm at 150 mm above the ground, and were defined as mature. *Santalum spicatum* stem diameters at 150 mm above the ground typically increase at only 1–2 mm y^{-1} in these semi-arid regions (Loneragan 1990), suggesting that the selected trees were older than 50 y.

The Paynes Find *S. spicatum* population was on the ‘Doney’ land system (Pringle *et al*. 1994), described as alluvial plains, with calcareous red loam soils, with *Acacia* shrubs, including *A. burkittii* Benth., *A. ramulosa* W.Fitzg. and *A. tetragonophylla* F.Muell. The mean annual rainfall at Paynes Find is 282 mm and the mean annual evaporation about 2400 mm. The Menzies *S. spicatum* population site was on the ‘Marmion’ land system (Pringle *et al*. 1994), described as undulating red sandplains, with *Casuarina pauper* L.A.S.Johnson, *A. ramulosa* and *A. tetragonophylla*. The mean annual rainfall at Menzies is 252 mm and the mean annual evaporation about 2800 mm.

Wheatbelt plantations

During February–March 2004, six *S. spicatum* trees were sampled in each of three separate plantations (W1, W2, W3), age 8–11 y, in the Wheatbelt, WA (Table 1). For commercial confidentiality reasons, the location of each plantation cannot be described. Each site consisted of a sandy duplex soil type, with light clay occurring within 0.4–1.0 m from the surface. The mean annual rainfall at each site is 421–498 mm and the mean annual evaporation is 1600–1900 mm.

Within each plantation, six-month-old *A. acuminata* Benth. seedlings were established as host plants to promote *S. spicatum* survival and growth, because *S. spicatum* is a root hemi-parasite (Hewson and George 1984). The *S. spicatum* was established by direct seeding near the host plants at host age 2–5 y. The method that was used to establish the plantations is similar to that described in Brand and Jones (1999). The *A. acuminata* were planted in 1992 at W1, and in 1991 at both W2 and W3 (Table 1). The *S. spicatum* were direct-seeded in 1994 at W1, in 1993 at W2, and in 1996 at W3. At each plantation, the *S. spicatum* seeds were derived from only one provenance or seed source. The seed sources, however, differed between plantations.

Curtin University trees

In March 2004, six *S. spicatum* (age 20–25 y) and five *S. album* trees (age 15 y) were sampled in a mixed plantation at Curtin

Table 1. Location and age of *Santalum spicatum* and *S. album* samples of 5–6 trees in each of two natural stands and five plantations

No.	Location	Species	Age (y)
1	Paynes Find	*S. spicatum*	Mature
2	Menzies	*S. spicatum*	Mature
3	Curtin	*S. spicatum*	20–25
4	W1	*S. spicatum*	10
5	W2	*S. spicatum*	11
6	W3	*S. spicatum*	8
7	Curtin	*S. album*	15

University of Technology, Perth, WA (Table 1). The *S. spicatum* trees were derived from different natural stands in WA and the *S. album* were progeny from a 'plus' tree in Karnataka State, India. The site consisted of deep white 'Bassendean sands' and had been irrigated using sprinklers each year during the hottest months (October–March), but less intensively during 2001–2004. Perth has a mean annual rainfall of 856 mm and a mean evaporation rate of about 1900 mm y^{-1}. The *S. spicatum* and *S. album* were planted near to one another with a variety of *Acacia* host plants, including mainly different provenances of *A. aneura* F.Muell. ex Benth. and latterly *A. saligna* (Labill.) H.Wendl. and *A. microbotrya* Benth.

Stem and heartwood dimensions

Stem diameter over bark was recorded at both 150 mm and 700 mm above ground for each of the 41 trees. At both stem heights, samples were extracted from each tree using an increment stem corer with an internal diameter of 5 mm. The increment corer was guided horizontally through the centre of the stem from one side of the bark to the other. After each core was removed, the hole in the sandalwood stem was filled with a piece of dowel and the ends were sealed with wood glue to prevent infection. The bark width, sapwood width and the internal heartwood diameter were measured on each core sample. Heartwood was defined as the central part of the core where the colour of the wood changed from pale yellow–white (sapwood) to either dark yellow–brown or red (heartwood). Under-bark diameters were used to calculate cross-sectional areas. Per cent heartwood was calculated by dividing heartwood area by the under-bark area.

Oil analysis

After collection, core samples were placed into paper bags (to help prevent fungal attack caused by sweating) and the samples were then transported for immediate analysis. Each whole core sample (heartwood + sapwood) from each tree at 150 mm and 700 mm above ground was roughly powdered using a hand-held grinder (Dremel® Multipro with a #561 bit at 15000–20000 rpm). A known mass of each powdered core was extracted with a known mass of ethanol spiked with an internal standard (Octadecane from Sigma O-1876) to produce the extract. After two or more days, the extracts were analysed using a gas chromatography flame ionisation detector (GC-FID) and a mass-selective detector (GC-MS) following standard protocols (Adams 1995) on a Varian Saturn 1. The peaks were identified using the mass spectral data from the MS and cross-correlated with the data from the FID.

The concentration of each component in the sample (C_x) was then determined from the mass of the sample analysed (powdered core, m_s), mass of ethanol and internal standard solution added (m_e), the concentration of the internal standard in the ethanol solution (C_{is}), the area count of the internal standard from the FID data (c_{is}) and the area count of the component in question from the FID data (c_x) using the equation:

$$C_x = \frac{C_{is}\, c_x\, m_e}{c_{is}\, m_5}$$

The total extractable oil concentration was derived in a similar fashion from the total area of the FID trace minus the area of the internal standard. In this study, concentration was expressed as a percentage.

Statistical analysis

The mean per cent heartwood, total extractable oil concentration and oil composition (α-santalol, β-santalol and t,t-farnesol) of sandalwood plantations and natural stands were compared using one-way analysis of variance (ANOVA). Proportions were angular-transformed before analysis and Fisher's LSD test was used to compare means. Statistical analysis was conducted using SYSTAT® version 10.2.

Although only 82 samples from 41 trees were analysed, the main objective was to place these preliminary oil production results from plantations on the record, and then incorporate the findings into later studies. The oil results from this investigation, combined with oil results from future studies, will help to determine reliable estimates of oil production in *S. spicatum* plantations.

Results

Heartwood

Values for mean percentage heartwood at 150 mm above ground (Table 2a) from Menzies (76%), Paynes Find (77%) and Curtin University (69%) sample sets were all significantly greater than in sets from the three young Wheatbelt plantations (29–48%; $F = 9.7$, $P < 0.001$). Mean percentage heartwood from *S. album* (57%) differed significantly only from W3 (29%), the youngest (8 y) of the plantations.

At 700 mm above ground (Table 2b), mean percentage heartwood in samples from Paynes Find (79%) was significantly greater than in samples from the other sites ($F = 17.3$, $P < 0.001$). Mean percentage heartwood in samples from the three Wheatbelt sites (28–38%) was significantly lower than in samples from the other sites.

Oil concentration and composition

Oil concentration

The mean total extractable oil concentration within stems varied significantly between locations at both 150 mm ($F = 9.5$, $P < 0.001$) and 700 mm ($F = 5.1$, $P = 0.001$) above ground. At 150 mm (Fig. 1a), the mean oil concentration in samples from planted trees at Curtin University (3.6 ± 0.4%), W1 (2.4 ± 0.4%) and W2 (3.3 ± 0.3%) was not significantly different from that in samples from the two natural stands: Paynes Find (3.0 ± 0.4%) and Menzies (3.1 ± 0.3%). However, the mean oil concentration in samples from W3 (0.7% ± 0.2%) was significantly lower than in samples from the other locations. The mean oil concentration in samples from *S. album* was 2.3 ± 0.5%.

At 700 mm (Fig. 1b), the mean oil concentration in samples from Curtin University (2.8 ± 0.3%), W1 (2.2 ± 0.3%) and W2 (2.8 ± 0.6%) was also not significantly different to that in samples from the two natural stands: Paynes Find (2.3 ± 0.4%) and Menzies (2.7 ± 0.4%). The mean oil concentration in samples from W3 (0.8 ± 0.2%) was also significantly lower than in samples from the other locations, except for *S. album* (1.3 ± 0.4%).

Oil composition

α-santalol

Mean α-santalol content within the extracted oil varied significantly among the sampled sandalwood plantations and natural stands at both 150 mm ($F = 17.3$, $P < 0.001$) and at 700 mm ($F = 23.7$, $P < 0.001$). At 150 mm (Fig. 2a), mean α-santalol content from *S. album* (42.8 ± 3.4%) was significantly greater than contents from all *S. spicatum* plantations and natural stands. Within *S. spicatum*, mean α-santalol contents from Curtin University (21.9 ± 5.5%) and W1 (27.3 ± 6.1%) were significantly greater than those from the other two Wheatbelt plantations (2.4–6.0%), and the two natural stands (3.8–8.0%).

Mean α-santalol content of samples at 700 mm (Fig. 2b) from *S. album* (47.3 ± 2.8%) was also significantly greater than those from all *S. spicatum* cores at this height. Mean α-santalol content of samples from W1 (18.8 ± 4.8%) was the next highest, and significantly greater than that of samples from the other *S. spicatum* plantations and natural stands. Mean α-santalol content of samples from Curtin University (5.5 ± 1.8%) and Menzies (6.3 ± 1.6%) was significantly greater than of samples from W2, which contained only a trace (0.1 ± 0.1%) of this compound.

β-santalol

Mean β-santalol content within the extracted oil varied significantly between samples from sandalwood plantations and natural stands at both 150 mm ($F = 18.7$, $P < 0.001$) and 700 mm ($F = 23.7$, $P < 0.001$). At 150 mm (Fig. 3a), mean β-santalol

Table 2. Mean (± standard error) *Santalum spicatum* and *S. album* stem diameter over bark, bark thickness, under-bark diameter, heartwood diameter and percentage heartwood (under bark), at (a) 150 mm and (b) 700 mm above ground. Means for percentage heartwood with the same letter are not significantly different, using Fisher's LSD test ($P = 0.05$).

Sample height and location	Over-bark diameter (mm)	Under-bark diameter (mm)	Heartwood diameter (mm)	Percentage heartwood
(a) 150 mm				
Paynes	148 ± 9	113 ± 11	99 ± 9	77 ± 3 a
Menzies	154 ± 10	120 ± 10	105 ± 10	76 ± 4 a
Curtin	168 ± 15	141 ± 13	117 ± 4	69 ± 4 a
W1	123 ± 6	106 ± 5	72 ± 6	48 ± 6 b
W2	111 ± 9	98 ± 9	63 ± 9	40 ± 4 bc
W3	92 ± 2	77 ± 2	39 ± 7	29 ± 10 c
S. album	162 ± 18	143 ± 14	107 ± 17	57 ± 10 ab
(b) 700 mm				
Paynes	120 ± 16	95 ± 13	85 ± 13	79 ± 4 a
Menzies	121 ± 7	91 ± 5	73 ± 5	64 ± 4 b
Curtin	123 ± 25	102 ± 23	81 ± 20	61 ± 3 b
W1	93 ± 4	81 ± 5	50 ± 6	38 ± 6 c
W2	69 ± 5	62 ± 4	33 ± 3	28 ± 4 c
W3	83 ± 3	69 ± 3	38 ± 4	32 ± 6 c
S. album	136 ± 17	117 ± 14	89 ± 8	59 ± 4 b

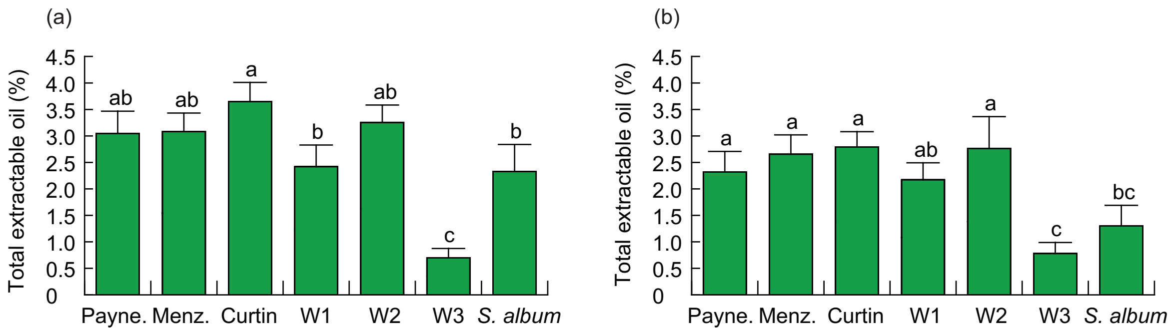

Figure 1. Mean total extractable oil concentration (% ± standard error) at (a) 150 mm and (b) 700 mm above ground, from *Santalum spicatum* and *S. album*. Within each sampling height, values with the same letter are not significantly different, using Fisher's LSD test ($P = 0.05$).

content in cores from *S. album* (22.4 ± 2.3%) was significantly greater than in all cores from *S. spicatum*. Mean β-santalol contents from W1 (10.5 ± 2.4%) and Curtin University (7.7 ± 2.1%) were significantly greater than from W2 (0.6 ± 0.2%), W3 (1.2 ± 0.5%) and Paynes Find (1.8 ± 1.2%). The mean β-santalol content of oil from Menzies was 3.0 ± 0.6%.

At 700 mm (Fig. 3b), mean β-santalol content of oil from cores of *S. album* (24.6 ± 1.5%) was also significantly greater than in samples from *S. spicatum*. Mean β-santalol contents of samples from W1 (5.5 ± 2.0%), Curtin University (2.1± 0.7%) and Menzies (2.3± 0.5%) did not differ. Mean β-santalol contents of samples were low in W3 (0.5 ± 0.5%), but not significantly different to those of samples from Paynes Find (1.3 ± 1.3%) and Menzies. W2 had no detectable β-santalol within its oil at this sampling height.

Trans, trans-farnesol

Mean t,t-farnesol contents within the extracted oil varied significantly between samples from sandalwood plantations and natural stands at both 150 mm (F = 13.7, P < 0.001) and 700 mm (F = 16.8, P < 0.001). At 150 mm (Fig. 4a), mean t,t-farnesol contents from W2 (28.4 ± 3.4%) and W3 (38.7 ± 8.3%) were significantly greater than those of samples from the other *S. spicatum* plantations and natural stands (10.1–15.0%), and *S. album*, which had less than 0.1% t,t-farnesol.

At 700 mm (Fig. 4b), mean t,t-farnesol contents of samples from W2 (28.3 ± 3.5%) and W3 (36.2 ± 4.0%) were significantly greater than those of samples from W1 (16.8 ± 2.7%), Paynes Find (16.2 ± 4.4%), Menzies (11.0 ± 2.0%) and *S. album* (0.1 ± 0.1%).

Individual trees with high-quality oil

The spread of santalol values within and between locations (Figs 5a,b) suggests there is scope for selection within both sandalwood species sampled. Within the *S. spicatum* trees, one tree from Curtin University and two trees from W1 had α-santalol contents of over 40% and β-santalol contents of 14–18%, at 150 mm above ground. The corresponding concentrations of extractable oil in these trees were 4.1% at Curtin University and 3.0% and 1.2% at W1. Samples from three of the *S. album* trees had α-santalol contents of over 46% and β-santalol contents of 24–27%, at 150 mm above ground. Their corresponding extractable oil contents were 0.9–2.6%.

Discussion

The total extractable oil concentration and oil quality from two of the four *S. spicatum* plantations (Curtin University and W1) were similar to or greater than those obtained from the natural stands at both the base (150 mm) and upper (700 mm) sampling positions. Although these results are not conclusive due to the small sample size, they do appear to indicate that *S. spicatum* plantations are capable of producing a range of marketable wood in the stems at 150–700 mm above the ground, by age 10–25 y. Brand *et al*. (2001) also reported relatively high mean oil

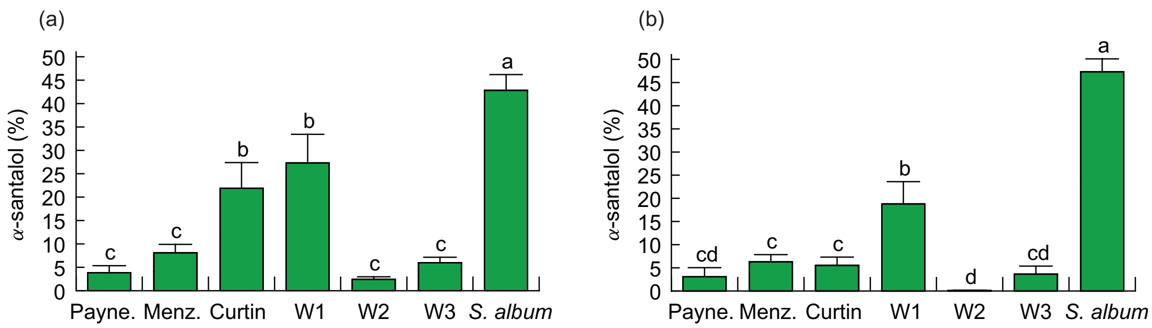

Figure 2. Mean α-santalol (% ± standard error) within the extracted oil at (a) 150 mm and (b) 700 mm above ground, from *Santalum spicatum* and *S. album*. Within each sampling height, values with the same letter are not significantly different, using Fisher's LSD test (P = 0.05).

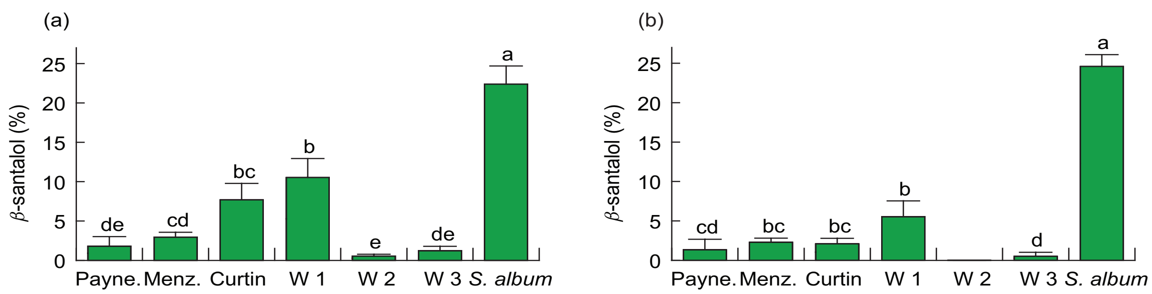

Figure 3. Mean β-santalol (% ± standard error) within the extracted oil at (a) 150 mm and (b) 700 mm above ground, from *Santalum spicatum* and *S. album*. Within each sampling height, values with the same letter are not significantly different, using Fisher's LSD test (P = 0.05).

concentrations of 2.3–2.6% in 10-y-old *S. spicatum* near Northampton, WA. Two of the plantations in this present study, however, had either a low oil concentration (W3: 0.7–0.8% oil) or a low quality oil (W2: 0.1–2.4% α-santalol; 0–0.6% β-santalol). The low oil concentration in W3 may be due to the trees in this plantation being only 8 y old, but this high variability in oil concentration between young *S. spicatum* plantations is in agreement with previous studies on young *S. album* plantations — 0.2–2.0% oil concentration in the heartwood of 10-y-old *S. album* trees growing in India (Shankaranarayana and Parthasarathi 1984), and 0.1–7.1% oil concentration in the heartwood of 14-y-old *S. album* trees growing near Kununurra, WA (Brand *et al*. 2006).

The mean oil concentration in the *S. album* trees aged 15 y that were sampled in this present study was only 1.3–2.3%. Brand *et al*. (2006) also recorded a mean oil concentration of only 1.8–2.0% in core samples (heartwood + sapwood) from 14-y-old *S. album* trees. This relatively low mean oil concentration for *S. album*, which is generally regarded as the most valuable of the sandalwood species (McKinnell 1990; Rai 1990), is not surprising because sandalwood species sometime require at least 10 y to develop both heartwood and oil. Doran *et al*. (2005) observed that four *Santalum yasi* Seeman trees, aged 10–21 y, and ten *S. album* trees, aged 10 y or more, growing in Fiji, had no detectable heartwood at 0.1–0.2 m above the ground.

The present study confirms that heartwood percentage, oil concentration and oil quality were all lower further up the tree (700 mm) than near the base (150 mm), in concordance with Piggott *et al*. (1997). This was especially evident in the young (8–11-y-old) Wheatbelt plantations, which had only 28–38% heartwood at 700 mm, compared to 69–76% heartwood in the mature natural stands. W2 had less than 0.1% α-santalol and β-santalol at 700 mm above ground. Therefore, at age 10 y, there may be only a small proportion of wood near the base (e.g. below 700 mm) of the trees with discernable commercial value. At present, there is very little information on *S. spicatum* commercial wood yields per hectare, but based on current growth rates, Brand *et al*. (2004) predicted that on suitable soils in the 400–600 mm annual rainfall zone of the Wheatbelt, *S. spicatum* could produce up to 4.4 t ha^{-1} of wood, of varying commercial grade, by age 20 y. At 10 y, the wood yield produced would be less than 2 t ha^{-1}, and the proportion of this wood with commercial value may be low. Assuming that heartwood percentage, oil concentration and oil quality will all increase with age, it appears that waiting until

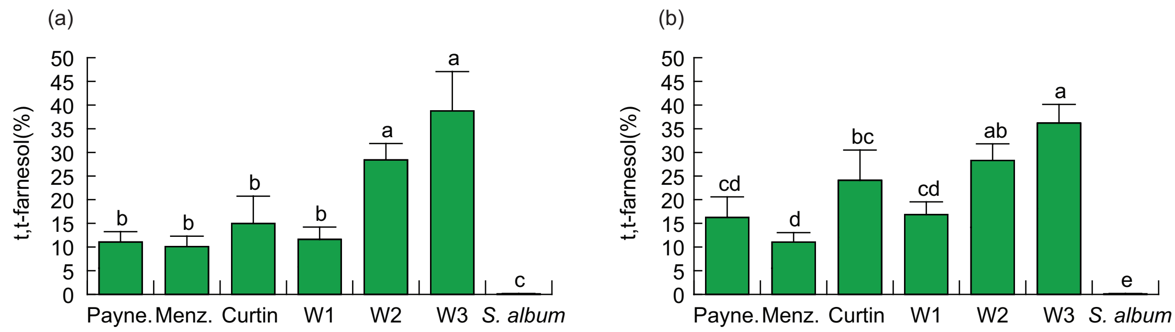

Figure 4. Mean t,t-farnesol (% ± standard error) within the extracted oil at (a) 150 mm and (b) 700 mm above ground, from *Santalum spicatum* and *S. album*. Within each sampling height, values with the same letter are not significantly different, using Fisher's LSD test (P = 0.05).

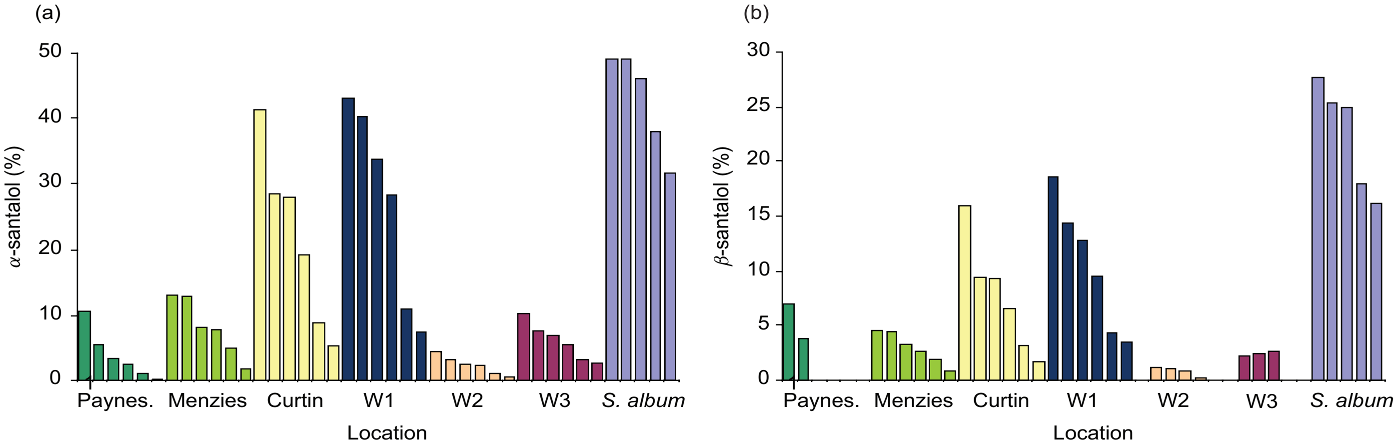

Figure 5. Percentage α-santalol (a) and β-santalol (b) within the extractable oil, at 150 mm above ground, from 36 *Santalum spicatum* trees (Paynes Find, Menzies, Curtin University, W1, W2 and W3) and from five *S. album* trees

S. spicatum plantations are age 20 y before harvesting should provide a far greater tonnage with greater mean values per tonne for the three commercial traits.

Santalum album trees consistently had significantly higher α-santalol (42.8–47.3%) and β-santalol (22.4–24.6%) contents than *S. spicatum*, concordant with the view that *S. album* oil is superior to *S. spicatum* oil (McKinnell 1990). Interestingly, at 150 mm above the ground, one *S. spicatum* tree from each of the Curtin University and W1 plantations met the current ISO standard for *S. album* oil, which requires 41–55% α-santalol and 16–24% β-santalol (ISO 3518 2002). Another W1 tree was just below the standard, with 40% α-santalol and 14% β-santalol. These results indicate that some *S. spicatum* trees appear to be able to produce oil of higher quality than previously recorded.

Currently it is unclear to what extent oil concentration and oil quality within *S. spicatum* is controlled by genetic and environmental (e.g. host species, soil type, rainfall, evaporation) factors. Because plantations and natural stands in this study were of different ages and were growing in different environments, no conclusions can be drawn on whether some trees have oil characteristics genetically superior to those of others. Until further research demonstrates otherwise, however, seeds from *S. spicatum* trees known to have both a high oil concentration and a high oil quality should be used preferentially in future plantings of the species. The Forest Products Commission (FPC) is currently establishing *S. spicatum* breeding trials in different locations in the Wheatbelt. These will help determine whether desirable plantation characteristics (e.g. high oil concentration and oil quality) can be improved by a combination of selecting superior genotypes and identifying the best environmental conditions in which to grow the trees. Real gains in *S. spicatum* yields will occur when plantations are established using this combination of best genotype and best environment.

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