



ESTIMATES AND FINANCIAL OPERATIONS COMMITTEE

2016-17 ANNUAL REPORT HEARINGS – QUESTIONS PRIOR TO HEARINGS

Forest Products Commission

Hon Diane Evers MLC asked:

1. I refer to the media statement issued on 6 October 2017 by the Hon Stephen Dawson MLC and the Hon Dave Kelly BA MLA following an assessment of the harvest coupe within the Barrabup forest, in which old growth forest had been impacted by roadworks:

- (a) what measures will the Forest Products Commission be implementing to strengthen assessment processes to ensure that old growth forests are not damaged as a result of such incidents in the future?

Answer: The Forest Products Commission (FPC) has revised its internal processes to improve the identification of unmapped old growth forest. These include:

- Use of high resolution remote imagery to further inform disturbance history and regrowth forest persistence.
- Targeted on-ground surveys to confirm disturbance status based on historical harvest data and contemporary remote sensing data.
- Dedicated staff member to identify unmapped old growth forest prior to disturbance operations commencing.
- The Department of Biodiversity, Conservation and Attractions (DBCA) will be advised of any area suspected of meeting the definition of old growth forest with a request for the completion of a formal survey.

2. I refer to Pine plantations in WA for which the Forest Products Commission is responsible for the harvest operations:

- (a) How many are under share farming agreements with the FPC;

Answer: 324

- (b) Of these, how many had harvesting operations in 2016-17;

Answer: 31

- (c) For those harvested in 2016-17, what prices did FPC pay for industrial wood, power poles and sawlogs; and

Answer: The FPC does not pay sharefarmers for individual products. Sharefarmers receive one or a combination of:

- Crop share percentage of the total net revenue from harvesting operations.

- Upfront payment.
- On-going annuity payment.

(d) How were the prices in (c) determined?

Answer: The percentage of net revenue, up-front payment or annuity payment was negotiated at the time the contracts were entered into.

3. I refer to page 109 of the Annual report which states that \$23.2 million of revenue is attributable to sandalwood:

(a) How much of the revenue is generated from wild standing sandalwood; and

Answer: 100 per cent

(b) How much of the revenue is generated from plantation sandalwood?

Answer: Nil

4. I refer to the 12,600 hectares of harvested sandalwood as detailed on page 21 of the Forest Products Commissions Annual report:

(a) please provide the breakdown between wild sandalwood and plantation sandalwood?

Answer: Wild sandalwood 12 600 hectares.

5. I refer to the Native Sandalwood Industry Strategy which notes that natural regeneration of wild sandalwood is not occurring at sufficient rates due to the extinction of small seed-dispersing marsupials and grazing from feral animals and livestock:

(a) how much is the Forest Products Commission (FPC) investing in evidence based research to improve regeneration of sandalwood as per page 4 of the document;

Answer: The FPC and its predecessors have heavily invested in evidence-based research over previous decades. I attach copies of several papers that have been published as a result of this work.

The FPC also has on-going long-term permanent sandalwood regeneration plots dating back approximately 20 years. Over the past three years, the FPC has established a new sandalwood regeneration trial (effect of seed treatment and time of sowing) near Kalgoorlie.

The FPC have spent \$50,000 per year over the last 3 years on research for this trial.

(b) who is undertaking the research and when is it expected to be completed; and

Answer: The FPC is currently working on a seed treatment and time of sowing trial, which is due to be completed by June 2019.

An FPC report on some similar seed treatment/time of sowing trials established near Kalgoorlie (during 2010-2012) was completed in 2016. This report is included in the reports tabled as part of the response for 5(a).

The FPC is currently supervising a Master of Science (MSc) student from Edith Cowan University studying the potential for stimulation of oil production in plantation Western Australian sandalwood (*Santalum spicatum*). This MSc work is due to be completed in 2018.

Research work into sandalwood is long-term and on-going.

- (c) what practices are the FPC currently undertaking to ensure the sustainability of wild sandalwood in WA?

Answer: The FPC is dedicated to ensuring the ecologically sustainable management of the wild sandalwood resource through a number of measures.

The FPC undertakes its harvesting and regeneration activities in the rangelands in a manner which is carefully planned to ensure all of the environmental values are identified and appropriately managed.

Harvesting is then conducted within the limits of the Sandalwood Order on areas identified through licencing by the DBCA as being suitable for harvest.

Current operations are being managed to achieve a full recovery of sandalwood roots to increase yield per tree, and therefore reduce the number of trees required to be harvested to meet annual tonnage quotas.

A comprehensive regeneration program has been developed to grow a replacement population of sandalwood. It contains three key strategies:

1. post-harvest seed planting where harvesting contractors plant three seeds for every tree harvested;
2. the FPC sowing sandalwood seed in areas where harvesting has previously occurred and populations are depleted; and
3. the regeneration of conservation and other lands through the Sandalwood Dreaming Project, where Aboriginal people and communities collect and plant seed on Country.

In 2018 the FPC has programmed to sow 14 tonnes of sandalwood seed (4-5 million seeds) using a mechanical seeder. It is aimed to increase seeding during the 2018-19 – 2022-23 seeding program to achieve an objective of regenerating double the area harvested each year.

The regeneration programs target areas that have suitable hosts and soil types, as well as low grazing pressures, to improve the likelihood of successful regeneration.

The FPC funds pastoralists to undertake activities such as fencing and feral animal control to protect regeneration from grazing.

The FPC funds additional enforcement resources in DBCA to help control the illegal removal of sandalwood to minimise the adverse impact on the sustainable management of the sandalwood resource.

The FPC's sandalwood program is independently audited and meets the standards of ISO 14001 Environmental Management System. The FPC is now seeking to obtain certification to the Australian Forestry Standard. Independent auditing provides external oversight and advice on the operation of the FPC's activities, including the achievement of its objectives. This assists in providing continuous improvement to this program.

6. I refer to the Minister for Forestry's response to my Question without notice No. 417 on 17 August 2017:

- (a) Will the Forest Products Commission please provide the independent assessment of employment in the forestry industry, that it commissioned on 20 February 2016?

Answer: Yes, the report is now available on the FPC's website.

7. I refer to the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) which produces quarterly reports on Australian forest and wood products statistics, including sawn wood production for hardwood and softwood for each State and Territory:

- (a) WA provided these figures for 2006-07, 2007-08, 2010-11 and 2012-13. Why has the Forest Products Commission (FPC) not provided figures to ABARES since 2013;

Answer: The FPC no longer has access to this data.

Sawn wood production as an indicator of utilisation is a legacy metric from the time when sawmills mainly produced sawn timber. In today's environment where there are a suite of products produced including engineered timbers and veneers, sawn wood production is not considered a valid metric to use to assess the use of timber recovery from sustainably sourced logs.

- (b) Will the FPC please provide these figures for each year from 2013-14 to 2016-17; and

Answer: No. The FPC no longer has access to this data.

- (c) Will the FPC agree to provide figures annually to the ABARES commencing this financial year?

Answer: No. The FPC no longer has access to this data.

8. I refer to pine plantations under share farming arrangements with the Forest Products Commission:

- (a) how is the price paid to share farmers determined for:

(i) industrial wood;

Answer: See above answer to questions 2 (c) and (d)

(ii) power poles; and

Answer: See above answer to questions 2 (c) and (d)

(iii) sawlogs;

Answer: See above answer to questions 2 (c) and (d).

(b) are prices in (a) indexed annually;

Answer: The timing of indexation depends on the provisions of each customer sales contract serviced by the sharefarm property. As a guide:

(i) industrial wood

Answer: No, indexed every six months for one contract and annually for another.

(ii) power poles

Answer: Yes.

(iii) Sawlogs

Answer: No, indexed every six months.

(c) if yes to b) on what basis is indexation calculated;

(i) industrial wood

Answer: Industrial wood is calculated both annually and six monthly based on the Consumer Price Index (CPI).

(ii) power poles

Answer: Power poles are indexed annually based on CPI.

(iii) Sawlogs

Answer: Not applicable.

- (d) will the FPC provide all relevant schedules and indexation rates for the past 10 years?

Answer: There are no relevant schedules. Indexation rates as follows:

Pine Poles

Indexation method	CPI 6 month
Jan-18	0.46
Jul-17	0.37
Jan-17	0.65
Jul-16	-0.19
Jan-16	0.93
Jul-15	0.19
Jan-15	1.23
Jul-14	1.34
Jan-14	1.76
Jul-13	0.79
Jan-13	1.6
Jul-12	0.4
Jan-12	1.53
Jul-11	1.24
Jan-11	1.36
Jul-10	1.7
Jan-10	1.62
Jul-09	-0.43
Jan-09	2.65
Jul-08	2.14
Jan-08	2.07

Note: Prior to 2014, indexation for power poles were calculated six monthly.

9. I refer to the Forest Product Commission's Annual Report, and specifically to the definition of logs unsuitable for sawmilling but suitable for other uses including manufacturing of reconstituted wood products, wood chipping, charcoal and energy generation:
- (a) Are sawmill owners required to inform the FPC of the amount of sawn timber they produce from native forest sawlogs bought from the FPC; and
- (b) What volume of (a) jarrah and (b) karri sawn timber did the sawmills that bought jarrah and karri sawlogs from the FPC produce in 2016-2017?

Answer: The FPC no longer has access to this data.

10. I refer to the Softwood Industry Strategy and the replanting of two trees for every tree harvested - is it usual practice for replanting to occur in the same location?

Answer: Yes

- (a) With reference to the recent harvest and replanting by Forest Products Commission of pine in close proximity to the Margaret River townsite, were other locations considered for replanting at the time;

Answer: No, other areas were not considered as an alternative for the Margaret Plantation.

- (b) If yes to a) what factors were considered and why was this location chosen;

Answer: Not applicable

- (c) Did the FPC consider the proximity to the Margaret River townsite and any increased fire risk to the town;

Answer: In 2016, the FPC in consultation with the DBCA, the Office of Bushfire Risk Management and the Shire of Augusta-Margaret River reviewed the fire management practices for the plantation and produced the *Margaret Plantation Management Plan 2016-26* (the Plan). Feedback was also sought from the local community and other stakeholders such as the volunteer bushfire brigades, prior to the Plan being endorsed by DBCA.

In addition to the requirements detailed in the Plan, the FPC has also established a series of buffer strips with reduced fuel within the plantation to further improve protection for the Margaret River townsite. These buffers have been strategically located as close as possible to the townsite but also to take advantage of geographic and other man-made features to maximise their potential to assist in impeding potential fire runs from the north or east.

The buffers have been established to a fire tolerant species of pine (*Pinus pinaster*) which will facilitate regular burning and will also be subject to an intensive pruning and thinning regime which will improve access and provide separation of fuels.

The FPC recognises the risk to both the townsite and plantation arising from high native fuel load across various tenures to the north and north-east of Margaret River. The FPC provides funds to DBCA to undertake fuel reduction burning on DBCA land adjoining the FPC plantations and has identified the forest areas surrounding Margaret River plantation as a priority for that program. The FPC also provides qualified and experienced staff to DBCA to assist in completing such burns.

- (d) If no to a) why not; and

Answer: It was acceptable to replant Margaret Plantation as agreed in the *Margaret Plantation Management Plan 2016-26*. As stated previously, the Plan was prepared in conjunction with the DBCA, the Office of Bushfire Risk Management and the Shire of Augusta-Margaret River. Feedback was also sought from the local community and other stakeholders such as the volunteer bushfire brigades, prior to the Plan being endorsed by DBCA.

- (e) Is it possible to find other suitable land to replant as an offset for this block?

Answer: No, this is not considered necessary due to the fire mitigation as a result of the *Margaret Plantation Management Plan 2016-26*

11. I refer to the statement in FPC's Annual Report that FORESTCHECK has shown that no species has become extinct due to forestry operations, and I ask:

- (a) Given that FORESTCHECK was not operational until 2001, and therefore was unable to generate baseline data before that date, how does the FPC justify the statement that no species has become extinct due to forestry operations?

Answer: The source of the statement is the Department of Environment and Conservation's (now DBCA) website extracted in 2012. It stated

"After 150 years of timber cutting, the South West forests retain one of the most complete suites of fauna of all the major Australian ecosystems. Animals now extinct or under threat in other parts of Australia still thrive in our forests—these include the woylie, tammar wallaby, chuditch, brushtail possum and numbat.

Over the past 30 years, the department and its predecessors have spent millions of dollars on biological surveys of flora and fauna in the forest.

There have been no recorded extinctions of any plant or animal species as a result of timber harvesting in WA."

ForestCheck has added to the depth of knowledge on the biodiversity of the forests and has helped to demonstrate that flora and fauna recover following disturbances, including timber harvesting. This has demonstrated that carefully managed harvesting is not a threat to biodiversity.

Seed pre-treatment and time of sowing effects on sandalwood (*Santalum spicatum*) regeneration in semi-arid regions, near Kalgoorlie, Western Australia

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Abstract. Sandalwood (*Santalum spicatum*) seeding trials were established in native *Acacia* shrub-land in semi-arid Western Australia, to determine methods to improve sandalwood regeneration. A total of 8,640 sandalwood seeds were sown in three separate years (2010, 2011 and 2012), at two separate sites near Kalgoorlie: Burra Rock and Gindalbie. At both sites, sandalwood germination, seedling survival and growth were compared as affected by four different seed pre-treatments (control, cracked, gibberellic acid (GA₃) and cracked + GA₃) and two separate sowing times (March and June).

In the 2010 and 2011 seeding years, first year sandalwood germination from the cracked + GA₃ treatment (22-44%) was significantly greater than the control (6-8%) and the cracked only (8-9%) treatments. However, after year one, subsequent germination was greater in the control and cracked treatments (6-16%) than both the GA₃ treatments (2-5%). The 2012 seeding had very little germination in the first year (<1%), possibly due to the low rainfall, but in subsequent years the germination again favoured the control and cracked treatments. In this study, germination appeared to favour the cracked + GA₃ treated seed in the first year (given sufficient rainfall), but in the subsequent 2-4 years, germination appeared to favour the control and cracked seed.

Sandalwood seedling survival (age 4 years) from the 2010 seeding was significantly greater in the control (15%) than both the two GA₃ treatments (6-10%). Conversely, in the 2011 seeding, seedling survival was significantly greater in the two GA₃ (20-23%) treatments than both the control and cracked treatments (8-9%). Germination pattern variation between first year and subsequent years, as well as the different survival patterns, support the use of a mixed seed pre-treatment strategy (*e.g.* sowing 75% untreated seed and 25% cracked + GA₃ treated seed) to improve germination and survival over a number of seasons.

Sandalwood seeds sown in March had significantly higher first year germination levels than those sown in June. Seedling survival from seeds sown in March was also significantly greater or the same to those sown in June, for the 2010 and 2011 seedings.

Although survival favoured the seeds sown in June for the 2012 seeding, the overall survival was very low (<2%). These results support sowing the seeds early (*i.e.* February-April), to maximize the first year germination and to also provide more time for the seedlings to establish before summer, in the semi-arid regions of WA.

Additional keywords: Seeding year, germination, survival, gibberellic acid

Introduction

Harvesting sandalwood (*Santalum spicatum* (R.Br.) A.DC) for its aromatic wood has provided a small but profitable industry in Western Australia (WA) since the 1840s (Talbot 1983). Today, the majority of sandalwood is harvested from natural stands growing in the semi-arid regions of central WA that receive a mean annual rainfall of 200-300 mm. In these dry regions, sandalwood growth is relatively slow, with trees growing near Kalgoorlie requiring 59 to 115 years to reach harvestable size (Loneragan 1990). Combined with relatively slow growth, sandalwood regeneration in these regions is also generally poor, with some populations containing mainly mature trees (Brand *et al.* 2014).

Regeneration failure within natural stands of sandalwood has been linked to factors including grazing by feral and domestic herbivores (including goats, sheep and rabbits), low rainfall and poor seed dispersal (Loneragan 1990, Brand 2000). In recent years, field studies have provided evidence to support Havel's (1993) proposal that small marsupials used to help disperse sandalwood seeds. Both the 'woylie' *Bettongia penicillata ogilbyi* and the 'boodie' *Bettongia lesueur* have been observed picking up sandalwood seeds and burying them 3-6 cm below the soil surface, up to 80 m from parent trees (Murphy *et al.*, 2005; Chapman, 2015). Unfortunately, due to predation by introduced animals including foxes, both of these small marsupials have been absent from inland Australia (apart from within fenced enclosures) for over 60 years (Burbidge *et al.* 1988).

In 2008, the Forest Products Commission (FPC) implemented a research program titled 'Operation Woylie' to trial methods to improve sandalwood regeneration and effectiveness of seeding (Sawyer 2013). Improvements identified through this program have been applied to operational procedures, whereby significant quantities of sandalwood seed are now sown annually, 10-50 mm below the soil, in mechanically ripped lines (Anon. 2011). Operation Woylie demonstrated that a 300 mm deep rip line

through the crust forming soil enables greater moisture penetration and retention in the soil after rain (Sawyer 2013). For germination to occur, the sandalwood seeds generally need to be kept moist for 4-8 weeks during the cooler months, and normally emerge during July-September (Brand 1999).

The Operation Woylie program is also targeting areas of inland WA where the grazing pressure is low and suitable vegetation types are present. Vegetation type is important because sandalwood is a root hemi-parasite (Hewson and George 1984) and requires suitable host plants to survive and grow. Within the semi-arid region of WA, sandalwood will grow with a range of vegetation types, but is generally associated with *Acacia* shrublands (Loneragan 1990, Brand 2000).

At present, the Operation Woylie program sows sandalwood seeds mainly during January to April (Anon. 2011), well before the winter rains, to allow enough time for the seeds to germinate and establish before the warmer months of spring and summer. Although sowing the sandalwood seeds in autumn is a commonly agreed sowing time in semi-arid regions (e.g. Brand 1999), there is very little information available confirming that this is the best time of year to seed. Comparing germination and survival rates between seeds sown in autumn (e.g. March) to those sown in early winter (e.g. June) would help determine the best sowing time.

Pre-treating the sandalwood seeds by cracking the seed coat (endocarp) and/or soaking in a solution of the plant hormone gibberellic acid (GA_3) may also enhance germination in the semi-arid regions. Woodall (2004) found that cracking the seed coat of *S. spicatum* enhanced germination, while Rai (1990) found that soaking Indian sandalwood (*S. album* L.) seeds in a solution of GA_3 improved germination time and percentage. However, it's important to note that sandalwood seeds can remain viable in the soil for up to 3-4 years after seeding (Brand 2000, Brand 2014), so any germination tests need to be studied over a period of at least three years to determine their effectiveness.

The main aims of this study were to plant sandalwood seeds in two separate locations in semi-arid WA and examine first year germination (%), cumulative germination (%), survival (%), seedling height (m) and stem diameter (mm) as affected by three factors: (i) site, (ii) sowing time and (iii) seed pre-treatment.

Methods

Site description

The trials were established in three consecutive years during 2010-12, at two separate sites: Burra Rock (31° 12' S, 121° 05' E) and Gindalbie (30° 14' S, 121° 41' E). Burra Rock is located approximately 50 km south-west of Kalgoorlie, and Gindalbie is located approximately 50 km north-east of Kalgoorlie (Figure 1). Kalgoorlie has a mean annual rainfall of approximately 266 mm (Australian Bureau of Meteorology).

Each site contained plots spread over an area of approximately 25 ha in area (500 m by 500 m). The Gindalbie site was fenced with ring-lock to prevent grazing by domestic and feral herbivores including goats, sheep and cattle. The Burra Rock site was unfenced, but there was no evidence of grazing by domestic or feral herbivores, during this study. Both sites contained red loamy soils, and mixed *Acacia* and *Eucalypt* shrub-land.

Soil preparation and host species

At Burra Rock and Gindalbie, a total of 36 rip-lines (18 at each site) of 8 m in length were established each year, in three separate years: 2010, 2011 and 2012. Within each rip-line, the soil was loosened using a mattock to a depth of 10-15 cm and to a width of 10 cm. The rip-lines were established in a manner similar to that achieved using a mechanical ripper, which is currently used by the FPC for re-establishing sandalwood (Sawyer pers. comm.).

All of the rip-line plots were positioned on the south-east side of existing potential host plants, and within 1-2 m of the host plant crowns. At Burra Rock, the main host species selected were *Acacia burkittii* Benth., *Eremophila dempsteri* F.Muell. *Scaevola spinescens* R.Br. and *Senna artemisioides* subsp. *filifolia* Randell. At Gindalbie, the main host species selected were *A. aneura* Benth., *A. burkittii*, *A. ramulosa* W.Fitzg. and *A. tetragonophylla* F.Muell. The height of the *Acacia* hosts were 0.5-5.0 m, while the other main host species (*Eremophila*, *Scaevola* and *Senna*) were 0.5-2.0 m in height. Each plot had between three and 16 naturally occurring host plants.

Each rip-line plot was divided into two equal lengths of 4 m, for the two separate time of year sowing treatments: early autumn (22-30 March) and early winter (7-13 June). Sowing time treatments were further divided into four 1 m sub-sections for the four different seed pre-treatments (see *Seed pre-treatment*). Within each 1 m sub-section, 10 seeds from each seed pre-treatment were planted to a depth of approximately 3-5 cm and were spaced approximately 10 cm apart.

Each seeding year, a total of 80 sandalwood seeds were sown within each 8 m plot, 1,440 seeds were sown at each site, with a total of 2,880 seeds sown. During the three seeding years, a total of 8,640 sandalwood seeds were sown in this study.

Sandalwood seed source and viability

In each of the three seeding years (2010, 2011 and 2012), the sandalwood seeds were collected fresh (within 2-3 months of ripening) in November the previous year, from three separate locations. The 2010 seeding year was derived from seed collected from approximately 40 trees growing in a plantation at the WA College of Agriculture (32° 58' S, 117° 08' E), near Narrogin. The 2011 seeding year was derived from seed collected from approximately 50 trees growing naturally on Riverina station (29° 44' S, 120° 34' E), near Menzies. The 2012 seeding year was derived from seed collected from over 100 trees growing in an FPC plantation (32° 27' S, 117° 44' E), near Mt Barker

Before the seeds were sown in each of the three seeding years (2010, 2011 and 2012), a sub-sample of 100 seeds was tested for viability. All seeds within each sub-sample were cracked and treated with GA₃ (see *Seed pre-treatment*) and then placed on a tray of vermiculite and kept moist for 42 days. Total germination rates during this period were 50 % from the WA College of Agriculture (2010), 26 % from Riverina station (2011), and 55 % from the FPC plantation (2012).

Sowing time

In each of the three seeding years, the sandalwood seeds were planted during two separate times of the year: (a) early autumn 22-30 March, and (b) early winter 7-13 June.

Seed pre-treatment

Two weeks before sowing, the sandalwood seeds (with husks removed) were subjected to four separate seed pre-treatments:

Control

No pre-treatment.

Cracked

The seeds were soaked in water for 15 hours and then drained, and then rapidly dried to promote cracking. In this study, two different methods were used for the rapid drying: silica gel in 2010, and oven heated in 2011-12. In 2010, after soaking, the freshly drained seeds were placed in a container and completely covered with dry silica gel for six hours. While in 2011-12, after soaking, the freshly drained seeds were placed in a pre-heated oven (45-50°C) for 2-3 hours.

After drying, the seeds were inspected to confirm that cracking of the seed coat had occurred. Within each seeding year, 50 seeds were inspected from both the control (no treatment) and the cracked treatments. Only 0-10 % of the seeds from the control had visible crack lines in their seed coats, while 70-94 % of the seeds from the cracked treatment had visible crack lines. The majority of the cracked seeds had only fine hair-line cracks.

GA₃

The seeds were placed in a 0.05 % solution of gibberellic acid GA₃ (50 ml of gibberellic acid in 10 L of water), then bubbled (aquarium bubbler) through for 20 hours to keep the acid aerated and suspended. The seeds were then drained and allowed to dry for 2-3 days at room temperature (20-25°C).

Cracked + GA₃

The seeds were cracked (as outlined above), and then after 24 hours they were also treated with GA₃ (as outlined above).

Germination and survival measurements

Mean germination was measured from each of the three seeding years (2010, 2011 and 2012) after the first winter in November (approximately one year). New germinants were also recorded each November, for another three years. Germination was defined as the proportion (%) of seeds that germinated out of the total number of seeds sown.

Survival in this paper was defined as the proportion (%) of seedlings alive from the total seeds sown, at age four years.

Growth measurements

Mean seedling height (m) and stem diameter (mm) at 150 mm above the ground were measured from only the seedlings that germinated in the first year and were still alive at age four years.

Rainfall

At both trial sites, a Davis WeatherLink Vantage Pro[®] weather station was established within 500 m of each plot, and recorded monthly rainfall between January 2010 and December 2012. The only exception was during 2012 at Gindalbie, in which records were obtained from the homestead, approximately 9 km south-east of the trial site. In this study, total rainfall during April-August (generally the time when germination occurs) and annual rainfall were totaled for each of the three seeding years (Table 1).



Figure 1. Locations of the two trial sites (Burra Rock and Gindalbie), near Kalgoorlie in Western Australia

Table 1. Total rainfall (mm) during the months of April-August and annually, recorded near the two trial sites (Burra Rock and Gindalbie) in each of the three sandalwood seeding years (2010, 2011 and 2012)

Seeding year	Apr-Aug (mm)		Annual (mm)	
	Burra	Gind.	Burra	Gind.
2010	95.8	114.4	233.2	186.6
2011	99.0	111.2	330.8	318.4
2012	54.2	32.5	223.8	242.6

Statistical analysis

Mean first year germination (%), cumulative germination (%), seedling survival at age four years (%), seedling height (m) and stem diameter (mm) were compared between sites, sowing times and seed pre-treatments using two-way analysis of variance (ANOVA). Proportions were angular transformed before analysis and Tukey's test was used to compare means. Statistical analysis was conducted using SYSTAT® version 11.

Results

First year germination

Site

Mean sandalwood germination in the first year from the 2010 seeding was significantly greater at Burra Rock ($19.6 \pm 2.0\%$) than at Gindalbie ($6.3 \pm 1.2\%$, $P < 0.001$). A similar result happened in the first year of the 2011 seeding, with mean germination significantly greater at Burra Rock ($29.7 \pm 2.3\%$) than at Gindalbie ($18.3 \pm 2.1\%$, $P < 0.001$). The 2012 seeding had only three seeds germinate at Burra Rock (0.2%) and only one seed germinate at Gindalbie (0.1%) in the first year, and were therefore not tested for any statistical differences between site, sowing time or seed pre-treatment.

Although not statistically tested (due to the low sample size), it appeared that < 60 mm rainfall during April-August was not enough moisture to initiate a reasonable sandalwood germination rate (*e.g.* $> 5\%$) at both sites. This was evidenced by only 0.1-0.2% germination in 2012, when the April-August rainfall was relatively low (32-54 mm)

at both sites (Table 1). In contrast, during 2010-11, the mean germination at both sites was 6.3-29.7% and the April-August rainfall was relatively high (96-114 mm).

Sowing time

Within the 2010 seeding, the mean sandalwood germination in the first year from seeds sown in March ($16.5 \pm 1.9\%$) was significantly greater than those sown in June ($9.4 \pm 1.4\%$, $P = 0.002$). Within the 2011 seeding, mean sandalwood germination in the first year was again significantly greater from seeds sown in March ($30.0 \pm 2.4\%$) than those sown in June ($18.1 \pm 2.0\%$, $P < 0.001$).

Seed pre-treatment

In the first year of the 2010 seeding, the mean germination differed significantly between the four seed pre-treatments ($P < 0.001$, Figure 1). The cracked + GA₃ treatment ($21.8 \pm 3.1\%$) was significantly greater than the control ($8.3 \pm 1.6\%$) and the cracked treatment ($8.1 \pm 2.1\%$). The GA₃ treatment was $13.6 \pm 2.3\%$, and was similar to the other treatments.

In the first year of the 2011 seeding, the mean germination also differed significantly between the four seed pre-treatments ($P < 0.001$, Figure 1). The cracked + GA₃ ($43.8 \pm 3.0\%$) and GA₃ ($36.7 \pm 3.0\%$) treatments were both significantly greater than the cracked ($9.4 \pm 2.1\%$) and the control ($6.3 \pm 1.9\%$, $P < 0.001$).

Cumulative germination after four years

Site

After four years, mean sandalwood cumulative germination from the 2010 seeding at Burra Rock ($26.0 \pm 1.9\%$) was significantly greater than at Gindalbie ($18.1 \pm 1.5\%$, $P = 0.002$). Mean sandalwood cumulative germination from the 2011 seeding at Burra Rock ($34.6 \pm 2.2\%$) was again significantly greater than at Gindalbie ($21.9 \pm 2.0\%$, $P < 0.001$). The 2012 sandalwood seeding had a similar mean cumulative germination between Burra Rock ($3.1 \pm 0.9\%$) and Gindalbie ($4.9 \pm 0.9\%$, $P = 0.070$).

It was important to note, that in the low April-August rainfall year of 2012 (32-54 mm), not only was first year germination low for the 2012 seeding, but subsequent germination for the 2010 and 2011 seedings were also low ($< 0.2\%$) for that year.

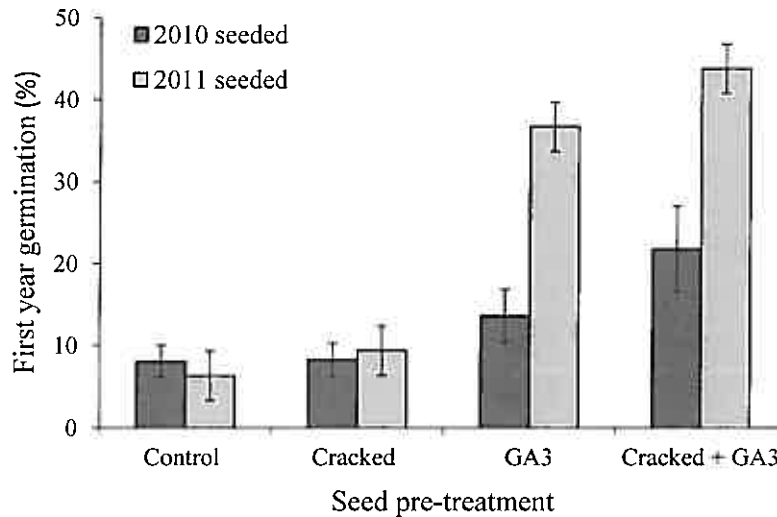


Figure 1. Mean first year germination (\pm standard error) from sandalwood seeds sown in 2010 and 2011, using four different seed pre-treatments (control, cracked, GA₃ and cracked + GA₃). The 2012 seeding is not shown in the graph, due to its low first year germination (0.1-0.2%).

Sowing time

The mean cumulative germination after four years from sandalwood seeds sown in March 2010 ($24.0 \pm 1.9\%$) was not significantly different to the seeds sown in June 2010 ($20.1 \pm 1.6\%$, $P = 0.195$). Seeds sown in March 2011 ($32.4 \pm 2.4\%$) had a significantly higher cumulative germination than those sown in June 2011 ($24.0 \pm 2.0\%$, $P < 0.001$). The mean cumulative germination levels from seeds sown in March 2012 ($2.0 \pm 0.2\%$) were significantly lower than the seeds sown in June 2012 ($6.0 \pm 0.6\%$, $P = 0.003$).

Seed pre-treatment

Mean cumulative germination after four years from seeds sown in 2010 were not significantly different between the four seed pre-treatments ($P = 0.231$, Figure 2): control ($24.3 \pm 2.5\%$), cracked ($20.0 \pm 1.8\%$), GA₃ ($18.3 \pm 2.4\%$), and cracked + GA₃ ($25.4 \pm 3.0\%$).

Mean cumulative germination from seeds sown in 2011 differed significantly between the four seed pre-treatments, after four years ($P < 0.001$, Figure 2). Mean cumulative germination from the cracked + GA₃ ($45.3 \pm 3.0\%$) and the GA₃

($39.0 \pm 2.9\%$) treatments were both significantly greater than both the cracked ($15.0 \pm 2.3\%$) and control ($13.6 \pm 2.3\%$) treatments.

Mean cumulative germination from seeds sown in 2012 also differed significantly between the four seed pre-treatments ($P = 0.004$, Figure 2), but in the opposite manner to the 2011 seeding. Mean cumulative germination from the control ($6.5 \pm 1.9\%$) and cracked ($5.0 \pm 1.2\%$) treatments were both significantly greater than the cracked + GA₃ ($0.6 \pm 0.6\%$). The GA₃ treatment was $3.9 \pm 1.1\%$, and was similar to the other treatments.

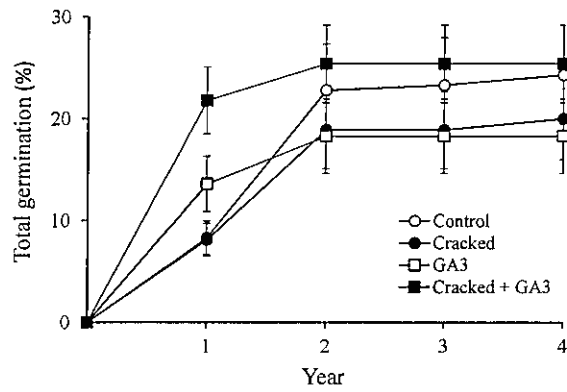
Seedling survival after four years

Site

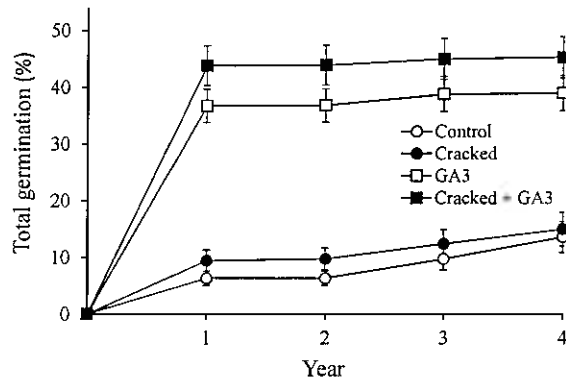
After four years, mean sandalwood seedling survival (% of seedlings alive from total seeds sown) from the 2010 seeding at Burra Rock ($10.0 \pm 1.1\%$) was not significantly different to that at Gindalbie ($10.9 \pm 1.5\%$, $P = 0.459$). Mean sandalwood seedling survival from the 2011 seeding at Burra Rock ($20.7 \pm 1.8\%$) was significantly greater than at Gindalbie ($9.1 \pm 1.2\%$, $P < 0.001$). Although survival from the 2012 seeding was low, it was significantly greater at Gindalbie ($1.7 \pm 0.4\%$) than at Burra Rock ($0.8 \pm 0.3\%$, $P = 0.040$).

Sowing time

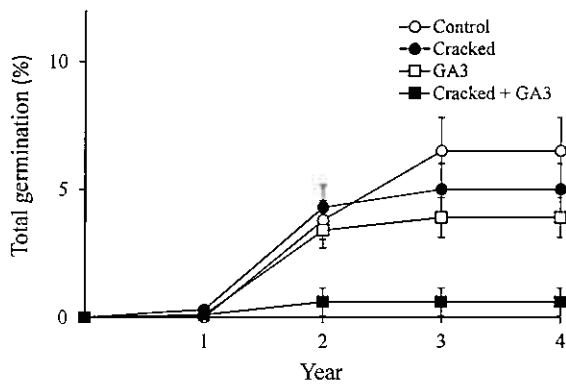
Mean seedling survival after four years from sandalwood seeds sown in March 2010 ($10.6 \pm 1.1\%$) was not significantly different to the seeds sown in June 2010 ($10.3 \pm 1.1\%$, $P = 0.788$). The mean seedling survival from seeds sown in March 2011 ($17.8 \pm 1.8\%$) was significantly greater than the seeds sown in June 2011 ($11.9 \pm 1.3\%$, $P = 0.005$). Survival from the 2012 seeding was low, but was significantly lower from seeds sown in March 2012 ($0.7 \pm 0.2\%$) than those sown in June 2012 ($1.9 \pm 0.4\%$, $P = 0.011$).



(a) 2010 seeded



(b) 2011 seeded



(c) 2012 seeded

Figure 2. Mean cumulative germination (\pm standard error) after four years from sandalwood seeds sown in (a) 2010, (b) 2011, and (c) 2012, using four different seed pre-treatments (control, cracked, GA₃ and cracked + GA₃).

Seed pre-treatment

Mean seedling survival after four years from seeds sown in 2010 differed significantly between the four seed pre-treatments ($P = 0.001$, Figure 3). Mean survival from the control ($14.9 \pm 1.8\%$) was significantly greater than both the GA₃ ($6.5 \pm 1.3\%$) and the cracked + GA₃ ($9.6 \pm 1.5\%$) treatments. The cracked treatment was $10.8 \pm 1.4\%$, and was similar to the other treatments.

Mean seedling survival from seeds sown in 2011 differed significantly between the four seed pre-treatments, after four years ($P < 0.001$, Figure 3). Mean seedling survival from the cracked + GA₃ ($22.9 \pm 2.7\%$) and the GA₃ ($19.9 \pm 2.4\%$) treatments were both significantly greater than both the cracked ($8.6 \pm 1.6\%$) and control ($8.2 \pm 1.7\%$) treatments.

Mean seedling survival between the different seed pre-treatments sown in 2012 also differed significantly ($P = 0.004$, Figure 3), but again it needs to be noted that the survival rates were all relatively low. Mean seedling survival from the cracked ($2.1 \pm 0.5\%$) treatment was significantly greater than the cracked + GA₃ (0%) treatment. Mean seedling survival from the control ($1.4 \pm 0.5\%$) and GA₃ ($1.7 \pm 0.6\%$) treatments were similar to the other treatments.

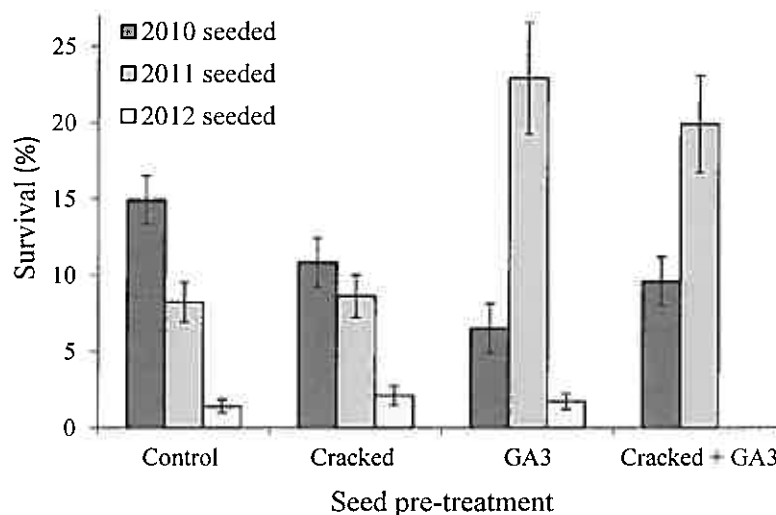


Figure 3. Mean survival (% survival of seedlings from total seeds sown \pm standard error) after four years, from sandalwood seeds sown in 2010, 2011 and 2012, using four different seed pre-treatments (control, cracked, GA₃ and cracked + GA₃).

Seedling growth after four years

Site

After four years, the sandalwood seedlings from the 2010 seeding were significantly taller at Gindalbie (1.0 ± 0.1 m) than at Burra Rock (0.6 ± 0.1 m, $P < 0.001$). The mean stem diameter (at 150 mm) was also significantly greater at Gindalbie (11 ± 1 mm) than at Burra Rock (5 ± 1 mm, $P < 0.001$).

A similar result happened from the 2011 seeding, with mean seedling height at Gindalbie (0.8 ± 0.1 m) significantly taller than those at Burra Rock (0.5 ± 0.1 m, $P < 0.001$), at age four years. Mean seedling diameter at Gindalbie (8 ± 1 mm) was also significantly greater than those at Burra Rock (4 ± 1 mm, $P < 0.001$).

The 2012 seeding was not measured due to only 0.1-0.2% of the seeds germinating in the first year.

Sowing time

Sandalwood seeds sown in March and June 2010, had a similar mean height (0.8 m, $P = 0.920$) and mean stem diameter (8 mm, $P = 0.855$), after four years. Likewise, sandalwood seeds sown in March and June 2011, had a similar mean height (0.6 m, $P = 0.500$) and mean stem diameter (5-6 mm, $P = 0.162$), after four years.

Seed pre-treatment

At age four years, the 2010 seed pre-treatment had no significant effect on mean sandalwood height (0.6-0.8 m, $P = 0.308$) or mean stem diameter (7-9 mm, $P = 0.677$). The same result happened with the 2011 seeding, with no significant differences between seed pre-treatments for both mean sandalwood height (0.5-0.6 m, $P = 0.421$) and mean stem diameter (5-7 mm, $P = 0.546$).

Discussion

This study showed that in two out of the three planting years, the cracked + GA₃ seed pre-treatment significantly enhanced sandalwood germination in the first year. In the 2010 and 2011 seeding years, mean first year germination rates from the cracked + GA₃ treatment were 22-44%, which were significantly greater than the control (6-8%) and the

cracked only (8-9%). Cromer and Woodall (2007) also found that cracked + GA₃ treated quandong (*Santalum acuminatum* (R.Br.) A.DC) seed had a significantly higher germination rate than cracked only seed.

First year sandalwood germination in the 2012 seeding year, was low (0-0.2%) across all seed pre-treatments, which appeared to be due to the low total rainfall of only 32-54 mm during April-August 2012. In contrast, during the same months during 2010 and 2011, the total rainfall (96-114 mm) was relatively good, which resulted in mean germination rates of 6-44% across the different seed pre-treatments. It appears that if the rainfall is below 60 mm during April-August, then germination is likely to be relatively low (e.g. < 5%) regardless of seed pre-treatment.

Provided that there is sufficient rainfall, it appears that using the cracked + GA₃ treated seed can enhance sandalwood germination in the first year, in the semi-arid regions of WA. However, because sandalwood seeds can remain viable in the soil for approximately 3-4 years (Brand *et al.*, 2014), subsequent germination is also important, and in this current study, subsequent germination was greater in the non GA₃ treated seed (*i.e.* control and cracked). Seeds sown in 2010, had 12-16% of the control and cracked seed pre-treatments germinate after year one, compared to only 4-5% from the two GA₃ treatments. This resulted in no significant difference in cumulative germination between the four seed pre-treatments after four years. Seeds sown in 2011, had 6-7% of the control and cracked seed pre-treatments germinate after year one, compared to only 2% from the two GA₃ treatments. Subsequent germination was also very important for the 2012 seeding, because very little seed germinated in the first year (<0.2%), most likely due to the low rainfall. However, during the next four years, 5-6% of the seeds germinated in the control and the cracked treatments, compared to <1% in the cracked + GA₃ treatment. Again, when exposed to sufficient rainfall, it appears that using a combination of untreated seed and cracked + GA₃ treated seed will increase the chances that some seed will germinate in the first year and subsequent 2-4 years.

Interestingly, the cracked only treatment displayed a similar germination rate as the control (uncracked) in the first year and also in subsequent years. In contrast, Woodall (2004) found that cracking the sandalwood seeds dramatically improved sandalwood germination, including one trial in which 100% of the seeds germinated in the cracked treatment compared to only 10% in the uncracked treatment, after 42 days. In this study, little difference in germination between the cracked and the control treatments may have

been partly due to the cracking method. Many of the sandalwood seeds in the cracked treatment generally had only fine hair-line cracks in their seed coats, which may not have been sufficient to significantly enhance germination. Perhaps a longer drying period (*e.g.* 8-12 hours, Woodall 2004), or multiple wetting and drying of the seeds (Woodall and Robinson 2002), may have increased the level of cracking and germination. Overall, soaking the seeds in the GA₃ solution appeared to have a greater effect on sandalwood germination than using cracking alone in this study.

Besides the sandalwood germination levels, the overall seedling survival (from total seeds sown) is very important in determining the success of the different seed pre-treatments. In this study, the pattern of sandalwood survival varied between seeding years. Survival from the seeds sown in 2010 was significantly greater in the control (15%) than both of the GA₃ treatments (6-10%). Conversely, survival from the 2011 seeding was significantly greater in the GA₃ treatments (20-23%) than both the control and cracked treatments (8-9%). As observed, sandalwood survival may favour the seeds that germinate early (first year) in some years, whereas in other years survival may favour the seeds that germinate later (age 2-4 years). Again, these survival results support the use of different seed pre-treatments to increase the likelihood that some sandalwood seedlings will survive either from the first year germination and/or subsequent germination events.

With regards to sowing time, first year sandalwood germination was significantly greater from seeds sown in March than those sown in June, in the relatively good rainfall years of 2010 and 2011. Survival after four years was also the same or significantly greater from seeds sown in March than those sown in June, from seeds sown in 2010 and 2011. Conversely, survival from the 2012 seeding was higher from seeds sown in June than March, but they were both relatively low at only 1-2%. Overall, these results support the early sowing time of year (*i.e.* February-April) to improve first year germination as well as providing a longer period for these seedlings to establish before the onset of the first summer.

At age four years, the sandalwood seedlings growing at Gindalbie were significantly larger than those growing at Burra Rock. This may have been related to rainfall, soil or host differences between the sites. During this study, the mean stem diameter growth (at 150 mm) was relatively slow at approximately 1-3 mm/year, which is comparable to previous sandalwood studies in semi-arid conditions (Brand, 2000; Brand *et al.*, 2014).

Interestingly, sowing time and seed pre-treatment had no significant effect on sandalwood growth after four years. Therefore, cracking the seeds and/or using GA₃ did not adversely affect the long-term growth of the sandalwood.

Overall, the findings from this study recommend sowing the sandalwood seeds in March and using a mixture of untreated seeds and cracked +GA₃ treated seeds. When there was sufficient rainfall during April-August at Burra Rock and Gindalbie, germination favoured the cracked + GA₃ treated seeds in the first year, but in subsequent years it favoured the control and cracked seeds. Since rainfall levels in semi-arid regions are not always adequate to initiate germination in the first year, and sandalwood seeds can remain viable for 3-4 years (Brand and Sawyer, 2014), these factors support using a seeding mix that contains more untreated seeds than treated seeds. A suitable sandalwood seeding mix could be 75% untreated seeds and 25% cracked + GA₃ treated seeds. Based on the results from this study, this seeding mix should help improve the likelihood of a reasonable sandalwood germination (> 5%) occurring in either the first year and/or in subsequent years, in semi-arid regions near Kalgoorlie, WA.

Acknowledgements

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References

- Anonymous (2011). *Sandalwood Operations Manual*. Forest Products Commission, Western Australia, 48pp.
- Brand, J. (1999). Conserving sandalwood (*Santalum spicatum*) in the rangelands, Western Australia. *Sandalwood Information Sheet*, Issue 2, Department of Conservation and Land Management, Western Australia, 4pp.
- Brand, J.E. (2000). The effects of management regime and host species on sandalwood (*Santalum spicatum*) recruitment near Paynes Find, Western Australia. *The Rangeland Journal* 22 (2): 243-256.

- Brand, J.E., Sawyer, B., and Evans, D.R. (2014). The benefits of seed enrichment on sandalwood (*Santalum spicatum*) populations, after 17 years, in semi-arid Western Australia. *The Rangeland Journal* **36** (5): 475-482.
- Burbidge, A.W., Johnson, K.A., Fuller, P.J. and Southgate, R.I. (1988). Aboriginal Knowledge of the Mammals of the Central Deserts of Australia. *Australian Wildlife Research* **15**: 9-39.
- Chapman, T.F. (2015). Reintroduced burrowing bettongs (*Bettongia lesueur*) scatter hoard sandalwood (*Santalum spicatum*) seed. *Australian Journal of Zoology* **63** (1): 76-79.
- Cromer, E.L. and Woodall, G. (2007). Breaking mechanical dormancy in Quandong using silica gel and enhancing germination response using Gibberellic acid. *Research Note* **28**. ALCOA World Alumina Australia.
- Havel, J. J. (1993). Review of research needs of the sandalwood industry in Western Australia. Department of Conservation and Land Management, Western Australia.
- Hewson, H.J. and George, A.S. (1984). Santalaceae. In *Flora of Australia*, Volume **22**: 29-67. Bureau of Flora and Fauna, Canberra. Australian Government Publishing Service, Canberra.
- Loneragan, O.W. (1990). Historical Review of Sandalwood (*Santalum spicatum*) Research in Western Australia. *Research Bulletin* **4**. Department of Conservation and Land Management, Western Australia.
- Murphy, M.T., Garkaklis, M.J. and Hardy, G.E.S.J. (2005). Seed caching by woylies *Bettongia penicillata* can increase sandalwood *Santalum spicatum* regeneration in Western Australia. *Australian Ecology* **30**: 747-755.
- Rai, S. N. (1990) Status and cultivation of sandalwood in India. In: Hamilton, L. and Conrad, C.E. (eds.). Proceedings of the Symposium on Sandalwood in the Pacific, USDA Forest Service General Technical Paper PSW-122, Honolulu, Hawaii, 66-71.
- Sawyer, B. (2013). Sandalwood (*Santalum spicatum*) establishment in the semi-arid and arid regions of Western Australia. *The Rangeland Journal* **35** (1): 109-115.
- Talbot, L. (1983). Wooden Gold. Early Days of the Sandalwood Industry. W.A. Forests Department. *Forest Focus* **30**: 21-31.
- Woodall, G.S. (2004). Cracking the woody endocarp of *Santalum spicatum* nuts by wetting and rapid drying improves germination. *Australian Journal of Ecology* **52**: 163-169.
- Woodall, G.S. and Robinson, C.J. (2002). Same day plantation establishment of the root hemiparasite sandalwood (*Santalum spicatum* (R BR) A DC: Santalaceae) and hosts. *Journal of the Royal Society of Western Australia* **85**: 37-42.

THE INFLUENCE OF LANDFORMS ON SANDALWOOD (*SANTALUM SPICATUM* (R.Br.) A.DC.) SIZE STRUCTURE AND DENSITY IN THE NORTH-EASTERN GOLDFIELDS, WESTERN AUSTRALIA

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Abstract

The density of *Santalum spicatum* was compared between 'land systems' and between 'land surface types' on four sheep stations in the north-eastern Goldfields: Yakabindie, Tarmoola, Glenorn and Minara. *S. spicatum* density was recorded in 4-6 ha transect plots, with a total of 14,090 ha surveyed. Within each transect plot, the *S. spicatum* were divided into five groups based on stem diameter at 150 mm: < 25 mm, 25-74 mm, 75-124 mm, 125-174 mm and > 174 mm. The proportion of *S. spicatum* in each of the five size categories was similar between land surface types and between land systems, with the majority in two groups: 75-124 mm and 125-174 mm. *S. spicatum* recruitment was low, with less than 1.5 % seedlings (< 25 mm) and 7.9 % saplings (25-74 mm).

Total density of *S. spicatum* on hills and ridges (0.65 stems/ha) was significantly higher than any other land surface type. The sandplains (0.05 stems/ha) supported the least. Within land systems, Laverton and Bevon (both hills and ridges) had the highest *S. spicatum* density. Yakabindie supported higher densities of *S. spicatum* than the other stations.

Key words: *S. spicatum*, landform, land surface type, land system, size structure, density

Introduction

Sandalwood (*Santalum spicatum* (R.Br.) A.DC.) is a root hemi-parasitic tree that occurs naturally in the southern half of Western Australia and in the western border lands of South Australia (Hewson and George 1984). *S. spicatum* is renowned for its scented wood. The wood and oil have many uses, including incense sticks, perfumes and cosmetics. In Western Australia, approximately 2000 ton of *S. spicatum* is harvested per annum and sold domestically and overseas to countries within south-east Asia (Jones 2001).

The Forest Products Commission (FPC) manages the harvesting of *S. spicatum* in Western Australia. Harvesting occurs mainly from natural stands on pastoral leases and vacant Crown land in the semi-arid Goldfields and Midwest regions. The minimum size to harvest as set by legislation is a stem diameter of 127 mm at 150 mm above the ground. Before an area is harvested, it is surveyed using the 'tally plot method' to estimate the distribution and quantity of *S. spicatum* present (Kealley 1991, Sawyer and Jones 2000). This involves travelling along roads, tracks, fence lines and mineral exploration gridlines in a vehicle and counting *S. spicatum* in transect plots. The live *S. spicatum* are classified into one of five groups, based on stem diameter at 150 mm: < 25 mm, 25-74 mm, 75-124 mm, 125-174 mm and > 174 mm. The two largest stem diameter classes are used to estimate *S. spicatum* tonnage. The mean commercial weight of *S. spicatum* in the 125-174 mm group is 16.18 kg, while the mean weight for the > 174 mm group is 28.76 kg (Kealley 1991).

Each transect plot is also matched to a landform such as a 'land system' (Pringle *et al.* 1994, Curry *et al.* 1994), or to Beard's vegetation maps (Beard 1981). Land systems are classified based on vegetation and landforms, while 'land surface types' are groups of land systems with similar geomorphology (Pringle *et al.* 1994). The north-eastern goldfields contain a total of

sixty land systems and nine land surface types (Pringle *et al.* 1994). *S. spicatum* inventory indicates that density varies between landforms, and these differences are taken into account when estimating the resource (Sawyer and Jones 2000). The estimated *S. spicatum* tonnage within a region is calculated by multiplying the average tonnage on each landform by the total area of the landform. Although the FPC use *S. spicatum* density per landform to estimate tonnage within a region, there appears to be no published information to establish that density can differ significantly between landforms.

S. spicatum is a small tree of 4 m (Hewson and George 1984) that grows slowly in pastoral regions, with stem diameters (at 150 mm) increasing only 2 mm/a near Kalgoorlie (Loneragan 1990) and Paynes Find (Brand 2000). Natural recruitment in these regions is currently low (Kealley 1991, Brand 1999) and appears to be due to poor seed dispersal (Havel 1993, Brand 2000) and grazing by feral and domestic herbivores (Loneragan 1990, Brand 2000). Landforms may also affect the success of *S. spicatum* recruitment. Surveys of *S. spicatum* age/size classes on different landforms may help show whether some landforms favour *S. spicatum* recruitment.

The aim of this study was to determine whether landforms (land surface types and land systems) affect (i) *S. spicatum* size structure; and/or (ii) *S. spicatum* density.

Methods

Inventory

Between 1995 and 1997, *S. spicatum* size structure and density were examined on four sheep stations in the north-eastern Goldfields: Yakabindie, Tarmoola, Glenom and Minara (Fig. 1). These four stations have been managed for sheep grazing since the 1930s and are between 172,000 and 219,000 ha. Mean annual rainfall on these stations is 209–224 mm. These stations were chosen because they contain a range of landforms that are representative of the region.

The *S. spicatum* individuals were counted using Kealley's (1991) 'tally plot method' from within a four-wheel drive vehicle, travelling at 10–40 km/hr along access routes. A *S. spicatum* plant was recorded if it was within 20 m of the vehicle on Yakabindie and Tarmoola, or within 30 m of the vehicle on Glenom and Minara. Each transect plot was approximately either 4 ha (40 m by 1 km) or 6 ha (60 m by 1 km). The road itself, and any disturbed area adjacent to the road or track were not included in each transect plot. On the four stations, 2894 transect plots were surveyed (Table 1), representing an area of approximately 14,090 ha. The *S. spicatum* recordings were classified into five groups based on the estimated stem diameter (at 150 mm): < 25 mm (seedling); 25–74 mm (sapling); 75–124 mm (undersize tree); 125–174 mm (mature tree); and > 174 mm (over-mature tree).

Each *S. spicatum* transect plot was on one of 37 land systems and seven corresponding land surface types (Pringle *et al.* 1994): (1) hills and ridges; (2) breakaways and lower plains; (3) erosional surfaces of low relief, < 20 m; (4) hardpan wash plains; (5) plains with deeper, coarser soils than in 4; (6) plains with saline alluvium; and (7) sandplains. There were 89–1004 transect plots surveyed on each land surface type (Table 1).

S. spicatum size structure and density were also compared between eight land systems: (1) Bevon, (2) Laverton, (3) Gransal, (4) Nubev, (5) Violet, (6) Jundee, (7) Monk and (8) Bullimore. These land systems were selected because they were well represented, with 6–274 transect plots on each station (Table 1).

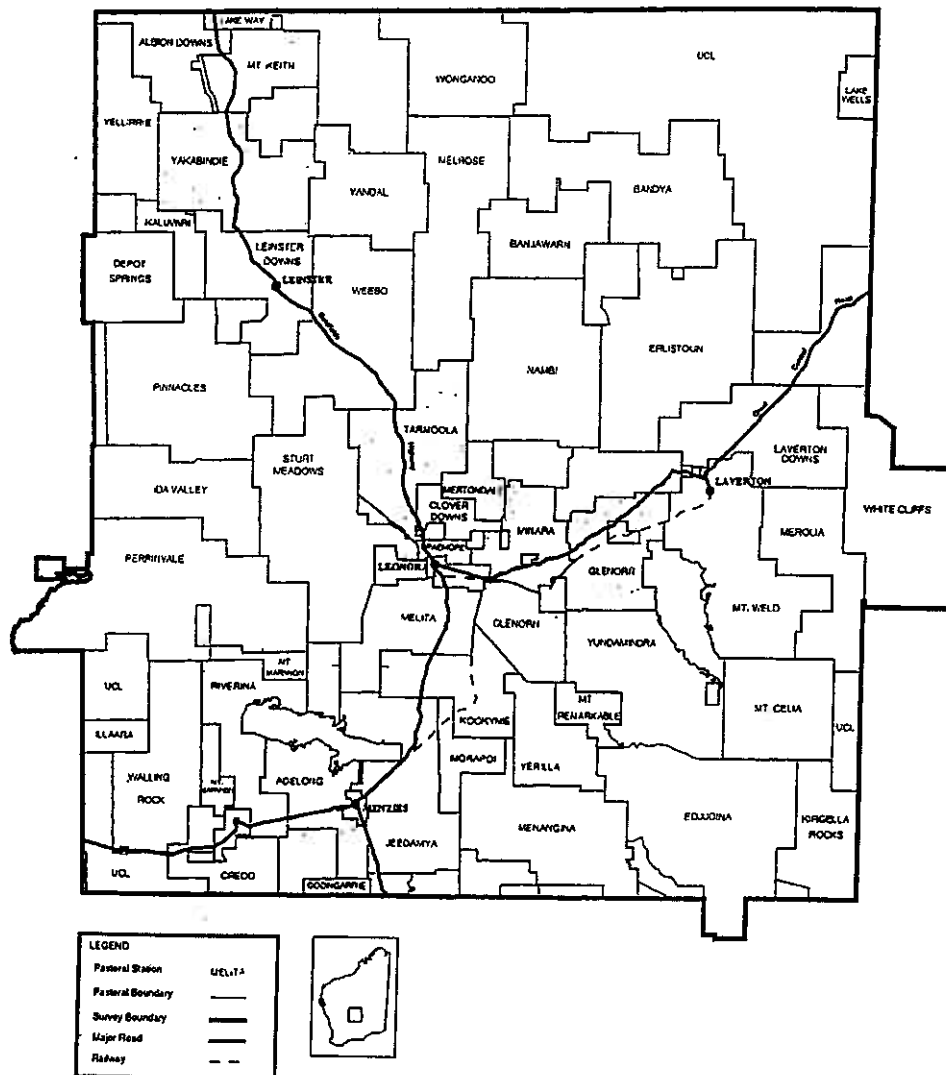


Fig. 1. The north-eastern Goldfields, showing Yakabindie, Tarmoola, Glenorn and Minara that were selected to study the influence of landforms on *S. spicatum* density.

Statistical analysis

Mean density (stems/ha) of *S. spicatum* was compared between land surface types, and between land systems using two-way analysis of variance (ANOVA). *S. spicatum* density was angular transformed and Tukey's test was used to compare means.

Results

Land surface types

The proportion of *S. spicatum* in each of the four size categories was similar between land surface types (Fig. 2). The majority of *S. spicatum* trees were 75-124 mm (23-42 %) or 125-

Table 1. Total number of *S. spicatum* transect plots assessed on each land system and land surface type, on four stations.

Land surface type	Land system	Station				Total
		Yaka.*	Tarm.*	Glenorn #	Minara #	
(1) Hills & ridges	Bevon	30	41	13	17	101
	Brookton	2	17	11	-	30
	Graves	-	-	6	-	6
	Laverton	16	64	27	30	137
	Leonora	-	24	29	42	95
	Teutonic	-	4	-	-	4
	Wyarri	-	3	-	-	3
Sub-total		48	153	86	89	376
(2) Breakaways & lower plains	Gumbreak	3	7	-	-	10
	Hootanui	-	-	17	18	34
	Sherwood	49	27	2	23	101
	Waguin	6	1	-	-	7
	Yigangi	-	-	10	-	10
Sub-total		58	35	29	41	163
(3) Erosional surfaces of low relief (< 20 m)	Challenge	-	2	-	-	2
	Felix	-	11	-	-	11
	Gransal	29	68	6	32	135
	Gundockerta	-	44	14	95	153
	Nubev	9	56	77	98	240
	Sunrise	-	5	-	4	9
	Violet	66	47	30	28	171
	Windarra	13	22	4	11	50
Sub-total		117	255	131	268	771
(4) Hardpan wash plains	Duketon	6	-	-	-	6
	Hamilton	17	53	-	1	71
	Jundee	33	42	107	38	220
	Monk	104	237	116	20	477
	Rainbow	-	13	26	2	41
	Ranch	4	-	56	11	71
	Tiger	-	2	30	29	61
	Yanganoo	57	-	-	-	57
Sub-total		221	347	335	101	1004
(5) Plains with deeper coarser soils than in (4)	Ararak	1	-	-	8	9
	Desdomena	37	19	-	-	56
	Yowie	-	-	34	-	34
	Sub-total	38	19	34	8	99
(6) Plains with saline alluvium	Cyclops	-	-	7	-	7
	Monitor	-	4	15	15	34
	Steer	-	-	2	-	2
	Wilson	6	40	-	-	46
Sub-total		6	44	24	15	89
(7) Sandplains	Bullimore	274	20	32	64	390
	Pan	2	-	-	-	2
Sub-total		276	20	32	64	392
Total		764	873	671	586	2894

Yakabindie (Yaka.), Tarmoola (Tarm.),* 4 ha plots, # 6 ha plots

174 mm (44-56 %) in diameter. The *S. spicatum* surveyed contained less than 1.5 % seedlings and 6.3 % saplings on each land surface type. Because the size class distributions were similar between land surface types, the size class data were grouped to compare total density between land surface types.

Total density of *S. spicatum* differed significantly between land surface types ($F_{6, 2866} = 38.0$, $p < 0.001$) and between stations ($F_{3, 2866} = 13.5$, $p < 0.001$). There was also a significant interaction ($F_{18, 2866} = 6.0$, $p < 0.001$) between land surface types and stations, but it was minor relative to the size of the main effects. The interaction was due to Yakabindie having the highest *S. spicatum* density on all land surface types except plains and sandplains. Yakabindie had the second highest density for plains and the lowest for sandplains. Minara had the lowest or second lowest density on all land surface types, except plains where it had the highest density.

The mean *S. spicatum* density on hills and ridges (0.65 ± 0.03 stems/ha, Fig. 3) was significantly greater than any other land surface type ($p < 0.05$). The lowest density of trees occurred on the sandplains (0.05 ± 0.05 stems/ha). The mean density of *S. spicatum* on Yakabindie (0.61 ± 0.04 stems/ha) was significantly greater than the density on Tarmoola (0.23 ± 0.04 stems/ha), Glenorn (0.17 ± 0.03 stems/ha) and Minara (0.20 ± 0.04 stems/ha, $p < 0.001$).

Land systems

S. spicatum size class distribution was also similar between land systems (Fig. 2), with the majority of *S. spicatum* in two groups: 74-124 mm (21-45 %) and 125-174 mm (41-62 %). *S. spicatum* percentages were again lowest in the seedling (0-1.4 %) and sapling (0-7.9 %) groups. The similar size class pattern between land systems also enabled the data to be grouped to compare total density between land systems.

Total density of *S. spicatum* differed significantly between the eight land systems ($F_{7, 1839} = 35.5$, $p < 0.001$) and between the four stations ($F_{3, 1839} = 15.9$, $p < 0.001$). There was also a significant interaction ($F_{21, 1839} = 4.8$, $p < 0.001$) between land systems and stations, but this was again minor relative to the size of the main effects. The interaction occurred due to Yakabindie having the highest *S. spicatum* density on Bevon, Laverton, Gransal and Nubev, but only the second or third highest on the other land systems.

The highest *S. spicatum* density occurred on Laverton (0.75 ± 0.06 stems/ha), Bevon (0.73 ± 0.06 stems/ha) and Violet (0.54 ± 0.05 stems/ha, Fig. 3). These three land systems contained significantly more *S. spicatum* than on Bullimore (0.04 ± 0.04 stems/ha), Monk (0.15 ± 0.04 stems/ha), Jundee (0.21 ± 0.04 stems/ha) and Gransal (0.24 ± 0.07 stems/ha, $p < 0.05$). The mean density of *S. spicatum* was again significantly higher on Yakabindie (0.71 ± 0.04 stems/ha) than on Tarmoola (0.27 ± 0.03 stems/ha), Glenorn (0.20 ± 0.04 stems/ha) and Minara (0.34 ± 0.04 stems/ha, $p < 0.001$).

Discussion

Land surface types and land systems have a significant influence on *S. spicatum* density in the north-eastern Goldfields. Total density of *S. spicatum* was highest on the hills and ridges (0.65 stems/ha) and lowest on the sandplains (0.05 stems/ha). The pattern was similar between land systems, with the highest total density occurring on Laverton and Bevon (both hills and ridges) and the lowest on Bullimore (sandplains). The high *S. spicatum* densities on hills and ridges in the north-eastern Goldfields may be partly due to the presence of suitable host species. Nitrogen-fixing species are generally very good hosts – especially species within the genus *Acacia* (Herbert 1925, Loneragan 1990). In particular, *A. burkittii* is a good host for *S. spicatum* near Paynes Find (Brand 2000) and it is a close relative of *A. acuminata* (Maslin *et al.* 1999), which is another good host (Barrett *et al.* 1996, Brand *et al.* 1999, Brand *et al.* 2000).

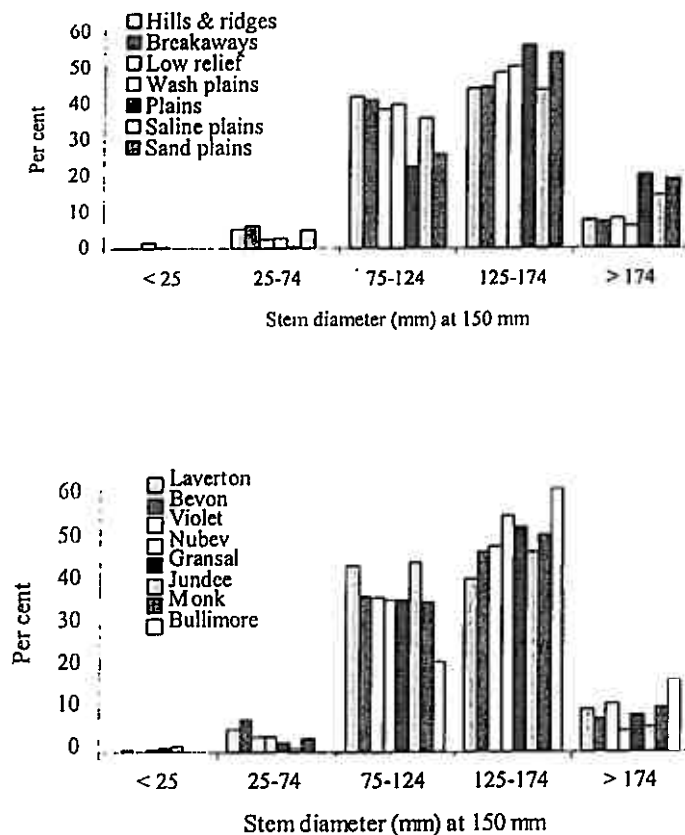


Fig. 2. Size class distribution of *S. spicatum* in the north-eastern Goldfields, growing on (a) seven land surface types, and (b) eight land systems.

In the north-eastern Goldfields, *A. burkittii* is more common on hills and ridges than on sandplains (Pringle *et al.* 1994). The higher densities of *S. spicatum* on hills and ridges may be partly due to high densities of suitable host species, such as *A. burkittii*.

Although each station had a similar pattern of variation between land surface types and between land systems, Yakabindie had significantly higher *S. spicatum* densities than the other stations. Higher densities on Yakabindie may be due to less harvesting pressure in the past. Harvesting *S. spicatum* provided an alternative source of income to many early prospectors in the Goldfields (Talbot 1983). Yakabindie is relatively isolated, compared to the other three stations, which are all close to the old mining town of Leonora. The railway line heading north from Kalgoorlie also stopped at Leonora (Fig 1), which would have increased the cost to transport timber from Yakabindie to Leonora. Therefore, *S. spicatum* trees growing at Tarmoola, Glenorn and Minara stations were probably more accessible to harvesters. Station densities also differed between land surface type and land system analyses. This was due to the analysis of land surface types containing 37 land systems, compared to only eight for the analysis of land systems.

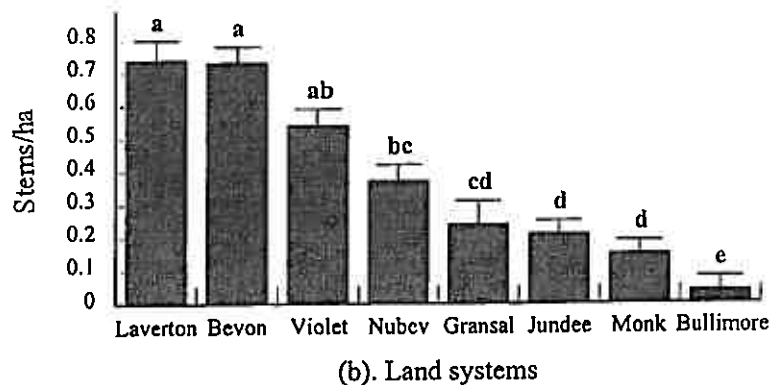
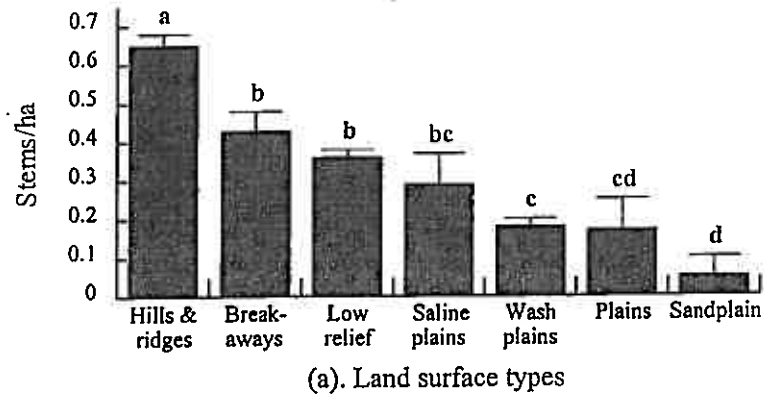


Fig. 3. Density of *S. spicatum* (stems/ha, + standard error) in the north-eastern Goldfields, growing on (a) seven land surface types, and (b) eight land systems. Values with the same letter are not significantly different, using Tukey's test ($p < 0.05$).

The proportions of *S. spicatum* seedlings ($< 1.5\%$) and saplings ($< 7.9\%$) were low on all land surface types and land systems. There would be some error in spotting small seedlings and trees from a vehicle, but these findings agree with Brand (1999) and Brand (2000) that *S. spicatum* recruitment is currently very low in the Midwest and Goldfields. An effective method to establish *S. spicatum* in natural vegetation is by direct seeding near suitable host species (Brand 2000). Further research should examine the effectiveness of direct seeding *S. spicatum* near different host species growing on different landforms. This approach may help to determine whether some landforms favour *S. spicatum* survival in the north-eastern Goldfields.

These findings support inventory reports that *S. spicatum* density and tonnage varies between landforms (Sawyer and Jones 2000). The pattern of *S. spicatum* density variation was similar between land surface types and between land systems. This indicates that either classification system is valid for *S. spicatum* resource estimates. Multiplying the mean *S. spicatum* tonnage surveyed per landform by the total area of the landform appears to be an effective method to estimate *S. spicatum* tonnage within an area, such as a station.

Acknowledgements

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References

- Barrett, D.R., Fox J.E.D. and Gentle, R. (1996). Sandalwood for saline sites. *In*: Conference proceedings on the productive use and rehabilitation of saline lands, 25-30 March 1996, Albany, Western Australia. Promaco Conventions, pp. 335-43.
- Beard, J.S. (1981). The vegetation of Western Australia at the 1:3 000 000 scale. Explanatory notes. Forests Department of Western Australia, 32 pp.
- Brand, J.E. (1999). Ecology of sandalwood (*Santalum spicatum*) near Paynes Find and Menzies, Western Australia: size structure and dry-sided stems. *Rangel. J.* 21(2): 220-8.
- Brand, J.E., Ryan, P.C. and Williams, M.R. (1999). Establishment and growth of sandalwood (*Santalum spicatum*) in south-western Australia: the Northampton pilot trial. *Aust. For.* 62 (1): 33-7.
- Brand, J.E. (2000). The effects of management regime and host species on sandalwood (*Santalum spicatum*) recruitment near Paynes Find, Western Australia. *Rangel. J.* 22(2): 243-56.
- Brand, J.E., Crombie, D.S. and Mitchell, M.D. (2000). Establishment and growth of sandalwood (*Santalum spicatum*) in south-western Australia: the influence of host species. *Aust. For.* 63 (1): 60-5.
- Curry, P.J., Payne, A.L., Leighton, K.A., Hennig, P. and Blood, D.A. (1994). An inventory and condition survey of the Murchison River catchment and surrounds, Western Australia. Department of Agriculture, Western Australia, Technical Bulletin No. 84, 430 pp.
- Havel, J. J. (1993). Review of research needs of the sandalwood industry in Western Australia. Department of Conservation and Land Management, Western Australia.
- Herbert, D.A. (1925). The root parasitism of Western Australian Santalaceae. *J. Proc. R. Soc. W.A.*, 11: 127-49.
- Hewson, H.J. and George, A.S. (1984). Santalaceae. *In*: Flora of Australia, Volume 22, pp. 29-67. Bureau of Flora and Fauna, Canberra. Australian Government Publishing Service, Canberra.
- Jones, P. (2001). Sandalwood re-visited in Western Australia. *Sandalwood Res. Newsl.* 12: 3-4.
- Kealley, I.G. (1991). The Management of Sandalwood. Wildlife Management Program 8. Department of Conservation and Land Management, Western Australia.
- Loneragan, O.W. (1990). Historical review of sandalwood (*Santalum spicatum*) Research in Western Australia. *Research Bulletin* 4. Department of Conservation and Land Management, Western Australia.
- Maslin, B., Byrne, M., Coates, D., Broadhurst, L., Coleman, H. and Macdonald, B. (1999). The *Acacia acuminata* (jam) group: an analysis of variation to aid sandalwood (*Santalum spicatum*) plantation research. Department of Conservation and Land Management, Western Australia, 60 pp.
- Pringle, H.J.R., Van Vreeswyk, A.M.E. and Gilligan, S.A. (1994). An inventory and condition survey of the north-eastern Goldfields, Western Australia. Department of Agriculture, Western Australia, Technical Bulletin No. 87, 323 pp.
- Sawyer, B. and Jones, P.J. (2000). Western Australian sandalwood Resource Statement. Department of Conservation and Land Management, Western Australia.
- Talbot, L. (1983). Wooden gold. Early days of the sandalwood industry. W.A. Forests Department. *Forest Focus* 30: 21-31.

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THE EFFECTS OF MANAGEMENT REGIME AND HOST SPECIES ON SANDALWOOD (*SANTALUM SPICATUM*) RECRUITMENT NEAR PAYNES FIND, WESTERN AUSTRALIA

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Abstract

Natural recruitment of sandalwood (*Santalum spicatum*) is generally low in pastoral regions of the Midwest and Goldfields, Western Australia. Harvesting of *S. spicatum* for the aromatic timber occurs in these regions, creating a need to develop management strategies to conserve the species. This paper examines sandalwood recruitment over three years within a natural stand of 32 ha, near Paynes Find, Western Australia. *Santalum spicatum* recruitment success was compared between three establishment treatments, and between two fencing treatments (+/-). At age three years, mean survival of *S. spicatum* seedlings planted next to host trees (25%) was significantly higher than those planted at harvesting spots (2%) and beneath parent trees (0%). In the unfenced treatment, there was evidence of grazing and *S. spicatum* survival and growth were significantly lower than in the fenced treatment. However, fencing alone did not improve *S. spicatum* recruitment because natural seed dispersal was poor and survival beneath parent trees was low. De-stocking, combined with seed enriching host trees is recommended to dramatically improve *S. spicatum* recruitment in the Paynes Find region.

Santalum spicatum seedling performance was compared growing next to three N₂-fixing species (*Acacia burkittii*, *A. tetragonophylla* and *A. ramulosa*) and one non N₂-fixing species (*Hakea recurva*). At age three years, *S. spicatum* survival was significantly higher next to *A. burkittii* (33%) than *A. tetragonophylla* (17%). *Santalum spicatum* survival next to *A. ramulosa* and *H. recurva* was 24-26%. Fencing improved *S. spicatum* survival next to *A. burkittii*, and to a lesser extent next to *A. tetragonophylla* and *A. ramulosa*. In contrast, survival of *S. spicatum* seedlings next to *H. recurva* was unaffected by fencing. *Santalum spicatum* growth next to each host species was slow and significantly higher in the fencing treatment.

Foliar concentrations of N, P, K and Ca were the same across *S. spicatum* treatments, but the concentration of Mg varied. The foliar K:Ca ratio was also similar between *S. spicatum* treatments, ranging from 1.4 to 2.0.

Key words: *Santalum spicatum*, recruitment, seed enrichment, host species, foliar nutrients

Introduction

The scented heartwood and oil from sandalwood (*Santalum spicatum* (R.Br.) AD.C.) make this species a sought after commodity throughout the world. *Santalum spicatum* is a root hemiparasitic small tree (Hewson and George 1984) that grows naturally over a large proportion of Western Australia and in the western part of South Australia (Loneragan 1990). Harvesting of the species occurs mainly in the pastoral regions of the Goldfields and Midwest, Western Australia. In these regions, recruitment is generally low (Kealley 1991, Brand 1999), which may be partly due to grazing by domestic and native herbivores (Loneragan 1990) or poor seed dispersal. *Santalum spicatum* has a relatively large nut (2 to 3 cm in diameter) which does not allow for easy dispersal. In natural stands, the majority of *S. spicatum* seedlings grow beneath parent trees (Fox 1997) where they compete with the parents for suitable host roots. Moving the *S. spicatum* seeds away from the parent trees and sowing them near suitable host plants may decrease root competition between *S. spicatum* plants and improve recruitment. Sowing *S. spicatum* seeds beneath host species with thorny branches or leaves such as sage (*Cratystylis subspinescens* S. Moore) or curara (*Acacia tetragonophylla* F. Muell.) may have the added benefit of protecting the seedlings from grazing (Havel 1993). Placing seeds in the holes created after harvesting *S. spicatum* trees may also be another suitable method to improve

recruitment - some harvesters already use this technique. Placing seeds next to host trees and at harvesting spots requires investigation to determine whether these techniques enhance recruitment.

Host studies within the *Santalum* L. genus indicate that the parasite performs better with N_2 -fixing host plants than non N_2 -fixing host plants (Radomiljac *et al.* 1999a, Brand *et al.* 2000). Radomiljac *et al.* (1999a) showed that Indian sandalwood (*S. album* Linn.) seedling growth was greater and root:shoot ratio lower when grown with N_2 -fixing woody perennials (*Acacia ampliceps* Maslin, *A. trachycarpa* (E. Pritzel) and *Sesbania formosa* (F. Muell.) N. Burb.) than a non N_2 -fixing perennial (*Eucalyptus camaldulensis* Dehnh.). Brand *et al.* (1999) also found that *S. spicatum* planted next to a non N_2 -fixing perennial (*Eucalyptus loxophleba* Benth. subsp. *loxophleba*) all died within two years, while survival next to N_2 -fixing perennials (*Acacia acuminata* Benth. and *Allocasuarina huegeliana* (Miq.) L. Johnson) was 29 to 86%. At present, *A. acuminata* appears to be the best host species for *S. spicatum* in the medium rainfall (400-600 mm/a) regions of the Wheatbelt and Midwest (Barrett *et al.* 1996, Brand *et al.* 1999, Brand *et al.* 2000). Suitable host species are also needed for the low rainfall (200-300 mm/a) pastoral regions of Western Australia.

Foliar nutrient concentration within the parasite and host can also indicate host suitability. Host trials within the *Santalum* genus reveal that host species that improve the parasite's growth can also increase the parasite's concentration of foliar nitrogen (Radomiljac *et al.* 1999b, Brand *et al.* 2000). A high K:Ca ratio is also common within parasitic angiosperms, and aids phloem movement from host to parasite (Tsivion, 1978). Brand *et al.* (2000), recorded a significantly higher K:Ca ratio within *S. spicatum* parasitising *Acacia acuminata* (4.8) than those parasitising *Allocasuarina huegeliana* (1.0).

This study compares *S. spicatum* recruitment (germination, survival and growth) success under three treatments: (i) natural; (ii) seed enrichment after harvesting; and (iii) seed enrichment of host trees. Within establishment treatments, the influence of fencing (+/-) on *S. spicatum* recruitment is examined. The effect of four different host species on *S. spicatum* recruitment and foliar nutrient concentration is also studied.

Methods

Trial site and experimental design

The sandalwood recruitment trial was established in April 1996 at Ninghan station (29°30'S, 117°11'E) near Paynes Find, Western Australia. Ninghan is a sheep grazing pastoral lease with an average annual rainfall of 293 mm. An experimental plot of 32 ha was established within a large paddock, approximately 4000 ha in area. The paddock was stocked with 200-500 sheep between 1996 and 1999.

The trial site is on an alluvial plain supporting *Eucalyptus* woodlands and classified as the Doney land system (Payne *et al.* 1998). The site also contains a large population of *S. spicatum* and is dominated by *Acacia* shrubs, including: *A. burkittii* Benth., *A. andrewsii* W. Fitzg., *A. anthochaera* Maslin, *A. oblecta* Maiden and Blakely, *A. tetragonophylla* and *A. ramulosa* W. Fitzg. Voucher specimens of each of these species were collected between 1996 and 1998 and lodged at the Western Australian Herbarium.

At the trial site, the plot was divided into two 16 ha plots (400 m by 400 m), with one fenced and the other unfenced. The fence consisted of 7-line ring-lock attached to 170 cm star pickets with a line of barbed wire along the top to exclude sheep, cattle and goats. Both of the large plots were divided into four blocks based on existing sandalwood stocking and so were discontinuous. Each block consisted of four (1 ha) sub-plots, with a total of 32 sub-plots in the

Sandalwood recruitment

trial. Sandalwood numbers in each sub-plot ranged from 3 to 31, and there was a total of 336 sandalwood within the trial. Natural recruitment was assessed within every sub-plot (16 replications), while recruitment within harvest and host enriched treatments were assessed in two sub-plots per block (8 replications).

Stem diameter (at 150 mm above the ground) of all *S. spicatum* plants at the site were measured in April 1996. These measurements were used to define seedlings (<25 mm), undersize trees (25-127 mm) and commercial size trees (> 127 mm). Before harvesting, the trial contained 168 commercial size trees, 164 undersize trees and only four seedlings (Table 1). Fenced and unfenced plots had a similar number of sandalwood in each size category. In June 1996, 86 commercial size *S. spicatum* trees were removed in the harvest treatments.

Table 1. The number of *S. spicatum* seedlings (stem diam. < 25 mm), undersize trees (25-127 mm) and commercial size trees (> 127 mm) in unfenced and fenced plots in April 1996.

Treatment	Size Category			Total
	< 25 mm	25-127 mm	> 127 mm	
Unfenced	1	89	83	173
Fenced	3	75	85	163
Total	4	164	168	336

Natural recruitment

In October 1996, inspections for new *S. spicatum* seedlings were made beneath the crown of each tree, and at least 2 m away from the crown. Each of these seedlings were tagged, and their survival and height were monitored annually for three years. In October 1999, stem diameters of these seedlings (age 3 years) were also measured.

Inspections for new seedlings were also made each October between 1997 and 1999. Survival of these seedlings were recorded annually. During the trial, *S. spicatum* seedlings were examined for evidence of grazing, including the removal of leaves and shoots.

The amount of fruit produced by *S. spicatum* trees was also recorded each October, between 1996 and 1999, by assigning trees to one of five categories: none; 1-25; 25-100; 100-500; or over 500. All 246 trees were examined, except in 1996 when only a random sample of 100 trees were surveyed.

Harvest seed enriched

In June 1996, 42 commercial size trees were removed from the unfenced plot and 44 from the fenced plot. The trees were pulled out of the ground using a vehicle, and all stem and root sections greater than 5 cm in diameter were removed. Fresh seeds from the previous season were obtained either from the harvested trees or from a group of 30 trees within 100 m of the trial site. At each harvested spot, 50 of these untreated sandalwood seeds were buried 2-3 cm below the surface. A total of 4300 *S. spicatum* seeds were sown in harvest enriched treatments. Germination, survival, growth and signs of grazing were recorded using the same techniques as for natural seedlings.

Host seed enriched

In each host seed enriched sub-plot, 10 untreated *S. spicatum* seeds were sown beneath 40 naturally occurring host plants, in June 1996. The seeds were placed next to three different N₂-fixing species (*Acacia burkittii*, *A. ramulosa* and *A. tetragonophylla*) and a non N₂-fixing species - *Hakea recurva* Meisn. In each sub-plot, between 4 and 15 plants from each species were enriched with *S. spicatum* seeds, except for two of the fenced replicates which had no *H. recurva* (Table 2). A total of 6400 *S. spicatum* seeds were sown beneath 640 host plants at Ninghan. The height of each host plant was measured in May 1996. The seeds were derived from 30 trees (see Harvest seed enriched) and each seed was buried 2-3 cm below the surface, 0.5-1.0 m from the stem. Germination, survival, growth and grazing were recorded using the same techniques as for natural seedlings.

Table 2. The number of host trees enriched with *S. spicatum* seeds in unfenced and fenced treatments at Ninghan.

Block	Unfenced		Fenced	
	reps	trees	reps	trees
<i>A. burkittii</i>	8	96	8	80
<i>A. ramulosa</i>	8	90	8	80
<i>A. tetragonophylla</i>	8	84	8	80
<i>H. recurva</i>	6	50	8	80
Total	30	320	32	320

Rainfall

Monthly rainfall records between 1996 and 1999 were obtained from Ninghan homestead (29°26'S, 117°17'E; Fig. 1), located approximately 20 km north of the trial site. In the winter of 1996, Ninghan received 245 mm rainfall – almost twice the mean winter rainfall (124 mm).

Foliar analysis

Young leaves (*S. spicatum* and *H. recurva*) and phyllodes (*A. burkittii*, *A. ramulosa* and *A. tetragonophylla*) were collected from six plants from each species within the fenced plot in October 1999. Approximately 5 g of foliage from each plant was oven-dried at 80°C and then ground. From each ground sample, a sub-sample was analysed to determine the concentration of N using the Kjeldahl method (McKenzie and Wallace 1954). Another sub-sample (0.5 g) was digested with tri-acid (HNO₃ + HClO₄ + H₂SO₄) and then distilled water was added to make 25 mL. This solution was used for further nutrient analysis: P, K, Ca and Mg. Phosphorus was determined using a colorimetric spectrophotometer (Kitson and Mellon 1944) and K was determined using a flame photometer. Calcium and Mg were determined using an atomic absorption spectrophotometer (Piper 1947).

Statistical analysis

Mean survival and seedling heights were compared between treatments, using one-way and two-way analysis of variance (ANOVA), and two-sample t-tests. Proportions were angular transformed before analysis and Tukey's test was used to compare means. SYSTAT® was used to analyse the data.

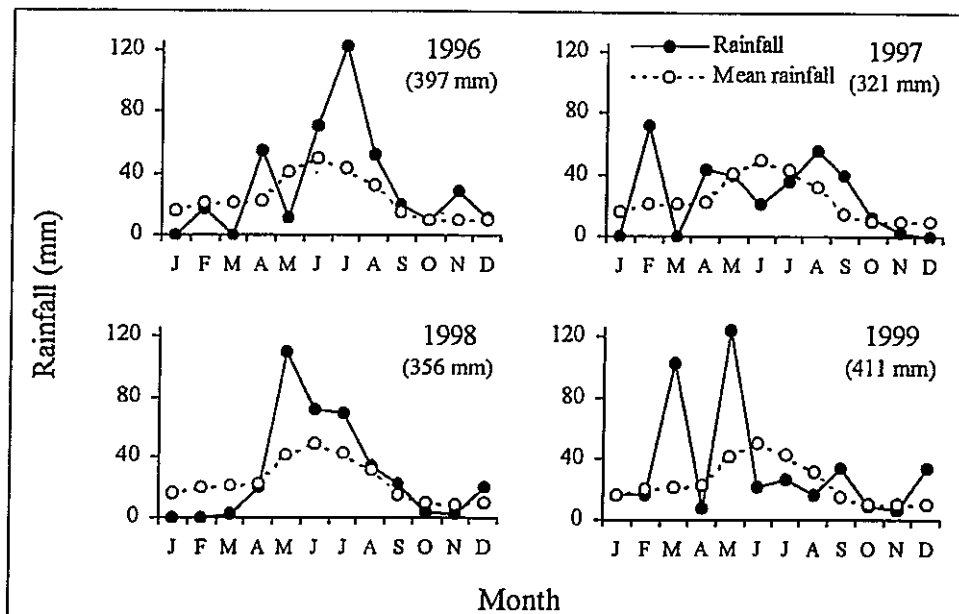


Fig. 1. Monthly rainfall at Ninghan station between 1996 and 1999. Mean monthly rainfall was determined using rainfall records between 1905 and 1996.

Although the seed enrichment treatments were replicated, the cost of fencing in a remote area precluded the possibility of replicating the fencing treatments, making the fencing design pseudoreplicated (Williams and Matheson 1994). However, by combining these results with observations on grazing may help to show whether grazing affects *S. spicatum* recruitment near Paynes Find, Western Australia.

Results

Sandalwood size structure and fruit production

Before the trial started (April 1996), over 98% of the *S. spicatum* within the Ninghan trial site had stem diameters over 60 mm (Fig. 2). There were only four seedlings and these were observed growing beneath the crowns of parent trees.

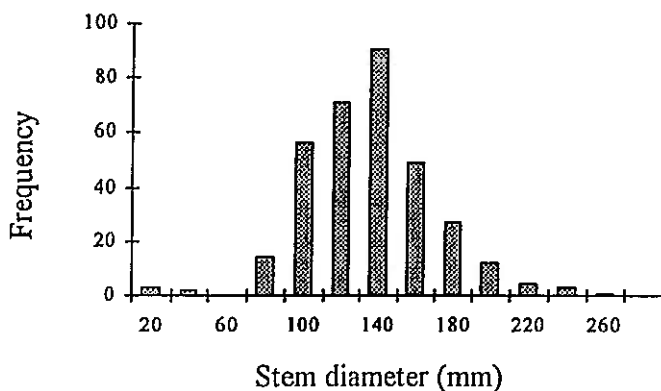


Fig. 2. The initial *S. spicatum* stem diameter (at 150 mm) distribution at the Ninghan site, before the trial started, April 1996.

Fruit production in *S. spicatum* was generally low, however, 17-23% of trees produced more than 25 mature fruit in both 1996 and 1997 (Fig. 3). In the following two years, less than 1% of trees produced over 25 mature fruit.

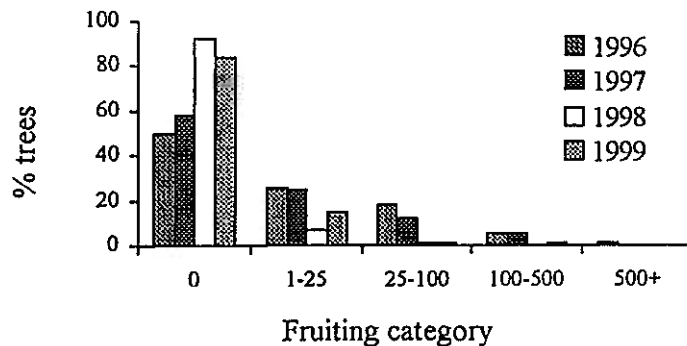


Fig. 3. Fruit production within 100-246 individual *S. spicatum* trees at Ninghan, during 1996-1999. Fruiting within trees was grouped into five categories.

Management treatments

Sandalwood germination

In October 1996, *S. spicatum* germination rate next to hosts (37-39%) was relatively high in both fencing treatments - 2461 seedlings (Table 3). Germination at harvesting spots (23-29%) was also high in both fencing treatments - 1107 seedlings. In contrast, only 48 seedlings germinated naturally beneath 246 parent trees.

Between 1997 and 1998, a further 380 seeds germinated in the host enriched treatments, 141 germinated in the harvest enriched treatments and 46 germinated in the natural treatments.

Table 3. The number of sandalwood seedlings that emerged in each management treatment at Ninghan, in 1996.

	Host	Harvest	Natural	Total
Unfenced	1199	602	22	1823
Fenced	1262	505	26	1793
Total	2461	1107	48	3616

Sandalwood survival

Mean *S. spicatum* survival in host treatments ($25.2 \pm 1.9\%$) was significantly greater than harvest ($1.8 \pm 0.8\%$) and natural (0% , $p < 0.001$), at age three years (Fig. 4). At the same age, overall mean *S. spicatum* survival in the fenced plot ($11.1 \pm 0.8\%$) was significantly greater than the unfenced plot ($6.9 \pm 0.8\%$, $p = 0.002$). The interaction between fencing and seeding treatments was not significant ($p = 0.063$).

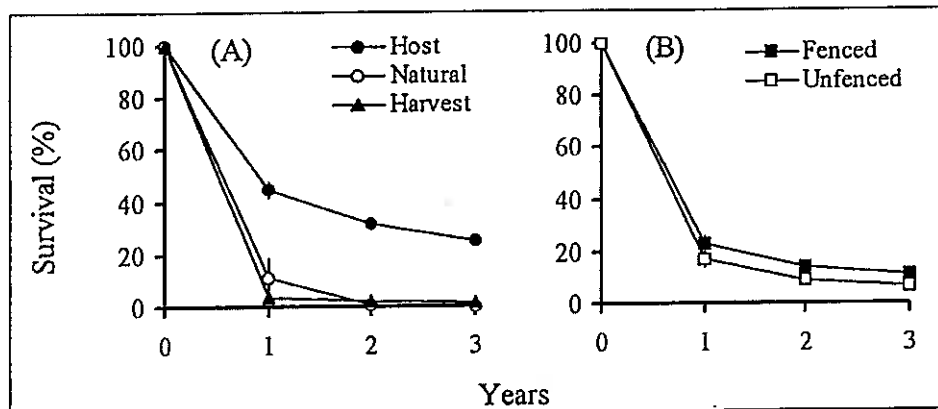


Fig. 4. Mean annual survival (\pm std. err.) of *S. spicatum* seedlings in the three establishment treatments (A), and in the two fencing treatments (B).

S. spicatum survival from 1997-98 germinants were not tested for significant differences in 1999, however, survival was again higher for host enriched (41%) than harvest (6%) or natural (27%). Survival was also higher in the fenced plot (40%) than the unfenced plot (23%).

Sandalwood growth

The mean height of *S. spicatum* seedlings in host and harvest (37-39 cm) treatments were not significantly different ($p = 0.472$), at age three years (Fig. 5). However, seedlings in the fenced plot (46 ± 3 cm) were significantly taller than seedlings in the unfenced plot (31 ± 2 cm, $p < 0.001$). There was no interaction between establishment treatment and fencing ($p = 0.581$). In 1997, 11% of the *S. spicatum* seedlings in the unfenced plot showed signs of grazing by herbivores – removal of shoots near the base of the stem. In 1998 and 1999, grazing was evident in 5-7% of the unfenced seedlings. There was no evidence of grazing in the fenced plot during the trial.

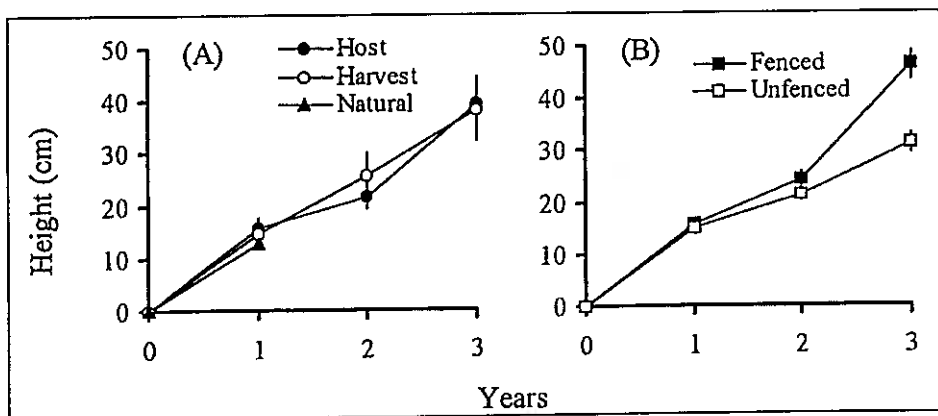


Fig. 5. Mean annual height (\pm std. err.) of *S. spicatum* seedlings in the three establishment treatments (A), and in the two fencing treatments (B).

Establishment treatments did not affect the mean stem diameter (at 150 mm) of the *S. spicatum* seedlings (stem diam. = 4 mm, $p = 0.748$). However, mean stem diameter of fenced seedlings

(5.0 ± 0.5 mm) was significantly higher than that of unfenced seedlings (3.0 ± 0.5 mm, $p = 0.001$). Establishment and fencing treatments did not interact for stem diameter ($p = 0.372$).

Host species

Host height and sandalwood germination

In April 1996, *A. burkittii* (2.5 ± 0.1 m) and *A. ramulosa* (2.4 ± 0.1 m) were both significantly taller than *A. tetragonophylla* (2.1 ± 0.1 m) and *H. recurva* (1.7 ± 0.1 m, $p < 0.001$). Host heights in fenced and unfenced plots were the same (2.1 – 2.2 m, $p = 0.489$) and there was no interaction between host species and fencing ($p = 0.874$).

Mean *S. spicatum* germination next to each host species was 36 to 41% and was not significantly different between hosts ($p = 0.173$). Germination rates in both fencing treatments (38–41%) were also the same ($p = 0.262$). The interaction between host and fencing treatments was not significant ($p = 0.268$).

Sandalwood survival

Within the host treatments, mean *S. spicatum* survival was significantly higher in the fenced plot ($30.5 \pm 2.8\%$) than the unfenced plot ($20.3 \pm 2.1\%$, $p = 0.002$). Mean survival of *S. spicatum* seedlings growing next to *A. burkittii* ($33.4 \pm 3.2\%$) was significantly greater than *A. tetragonophylla* ($16.8 \pm 3.2\%$, $p = 0.002$). Survival of *S. spicatum* seedlings next to *A. ramulosa* ($24.3 \pm 3.7\%$) and *H. recurva* ($26.4 \pm 3.4\%$) were the same as the other host treatments. There was no significant interaction between host and fencing treatments ($p = 0.475$).

Within the *A. burkittii* treatment, mean *S. spicatum* survival in the fenced plot ($41.3 \pm 3.7\%$) was significantly higher than the unfenced plot ($25.6 \pm 3.5\%$) at age three years ($p = 0.007$, Fig. 6). Fencing also improved survival in *A. tetragonophylla* (fenced: $22.9 \pm 5.4\%$; unfenced: $10.7 \pm 2.4\%$; $p = 0.057$) and *A. ramulosa* (fenced: $30.0 \pm 6.3\%$; unfenced: $18.6 \pm 3.4\%$; $p = 0.094$) but only at a significance level of 10%. Mean survival of *S. spicatum* next to *H. recurva* in the fenced plot ($26.8 \pm 4.4\%$) was very similar to the unfenced treatment ($26.2 \pm 5.1\%$, $p = 0.538$).

Sandalwood growth

The mean heights of *S. spicatum* seedlings were the same between host treatments (35 to 43 cm, $p = 0.205$) at age three years. However, mean seedling height within the fenced treatment (46 ± 2 cm) was significantly greater than in the unfenced treatment (34 ± 2 cm, $p < 0.001$). There was no interaction between host and fencing treatments ($p = 0.773$).

Fencing significantly improved mean *S. spicatum* seedling heights next to *A. ramulosa* ($p = 0.016$), *A. tetragonophylla* ($p = 0.046$) and *H. recurva* ($p = 0.020$), at age three years (Fig. 7). Mean seedling height of *S. spicatum* next to *A. burkittii* was also greater in the fenced plot, but not significantly ($p = 0.162$). Evidence of grazing (removal of shoots) on *S. spicatum* seedlings in the unfenced plot was highest in 1997, ranging from 6% next to *H. recurva* to 18% next to *A. tetragonophylla*. At the same time, grazing was also evident on 9–12% of *A. burkittii* and *A. ramulosa*. In 1998 and 1999, the proportion of seedlings with signs of grazing next to each host species was 4–9%.

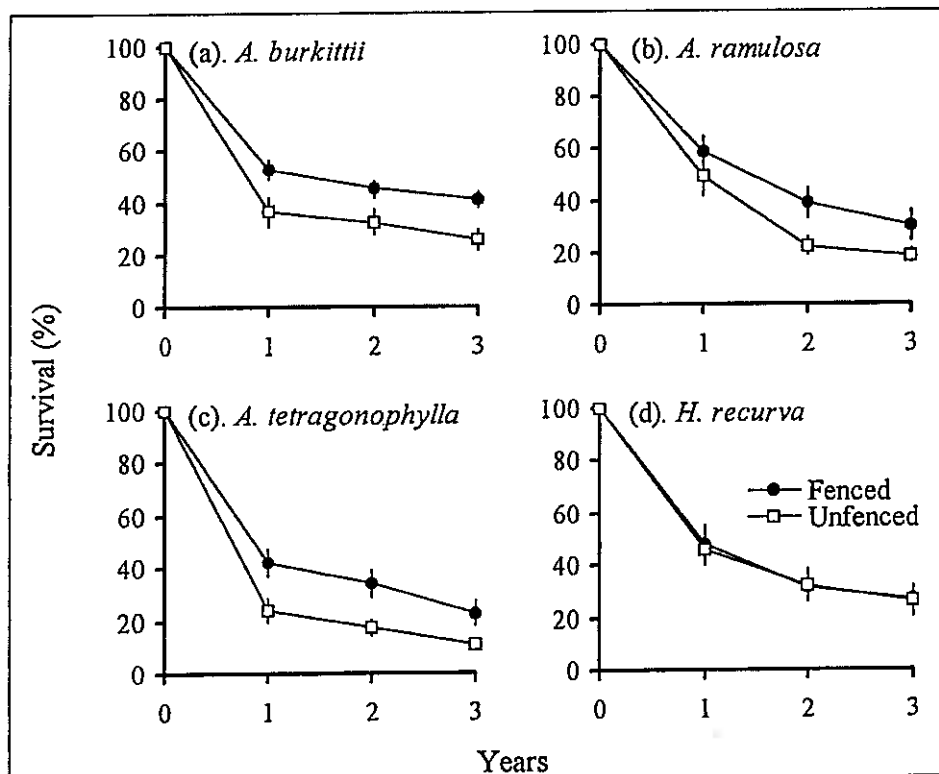


Fig. 6. Mean *S. spicatum* seedling survival (\pm std. err.) next to four separate host species within fenced and unfenced treatments.

Mean stem diameters of the *S. spicatum* seedlings did not vary between host species (3.5 to 4.0 mm, $p = 0.328$). Although the difference in stem diameter was small, the fenced seedlings (4.5 ± 0.2 mm) were significantly greater than unfenced seedlings (3.0 ± 0.2 mm, $p < 0.001$). Host and fencing treatments did not interact ($p = 0.992$).

Foliar analysis

S. spicatum seedlings next to the four host species had similar foliar concentrations of N (20.3 to 25.9 mg/g), P (0.5 to 0.7 mg/g), K (21.3 to 22.3 mg/g) and Ca (11.2 to 15.7 mg/g, Table 4). The K:Ca ratios of the *S. spicatum* treatments (1.4 to 2.0) were also similar. Magnesium was the only variable element between *S. spicatum* treatments, with those parasitising *H. recurva* (2.5 ± 0.5 mg/g) significantly higher than those parasitising *A. burkittii* (1.1 ± 0.1 mg/g, $p < 0.001$).

Between hosts, *H. recurva* had the lowest concentrations of N (7.9 ± 0.2 mg/g), P (0.1 ± 0.0 mg/g) and K (5.0 ± 0.3 mg/g, Table 4). Calcium and Mg concentrations and the K:Ca ratio were similar between hosts. The concentration of K in hosts (5.0 to 8.3 mg/g) was significantly lower than in *S. spicatum* (21.3 to 22.3 mg/g).

Table 4. Mean element concentrations (\pm std. errors) in the foliage of *S. spicatum* and host trees, in October 1999 ($n = 6$).

Species	Element					
	N (mg/g)	P (mg/g)	K (mg/g)	Ca (mg/g)	Mg (mg/g)	K:Ca ratio
<i>S. spicatum</i> parasitising:						
<i>A. burkittii</i>	25.9 \pm 2.4 a	0.5 \pm 0.1 ab	21.6 \pm 1.1 a	15.7 \pm 1.4 a	1.1 \pm 0.1 b	1.4 \pm 0.1 abcd
<i>A. ramulosa</i>	20.3 \pm 2.8 ab	0.7 \pm 0.2 a	22.3 \pm 1.9 a	14.4 \pm 1.1 ab	1.9 \pm 0.1 ab	1.6 \pm 0.2 abc
<i>A. tetragon.*</i>	21.7 \pm 1.4 ab	0.7 \pm 0.1 a	21.8 \pm 1.0 a	11.6 \pm 1.2 abc	1.8 \pm 0.2 ab	2.0 \pm 0.2 a
<i>H. recurva</i>	24.5 \pm 1.7 ab	0.7 \pm 0.1 a	21.3 \pm 1.7 a	11.2 \pm 0.7 abcd	2.5 \pm 0.5 a	1.9 \pm 0.2 ab
Hosts						
<i>A. burkittii</i>	25.5 \pm 1.0 a	0.7 \pm 0.1 a	8.3 \pm 0.5 b	9.9 \pm 0.6 bcde	1.1 \pm 0.1 b	0.9 \pm 0.1 cd
<i>A. ramulosa</i>	17.2 \pm 0.7 b	0.3 \pm 0.1 b	7.9 \pm 0.7 c	8.4 \pm 0.6 cde	1.9 \pm 0.2 ab	1.0 \pm 0.2 cd
<i>A. tetragon.*</i>	20.2 \pm 1.5 ab	0.6 \pm 0.1 a	8.2 \pm 0.5 b	7.6 \pm 1.3 de	1.8 \pm 0.2 ab	1.2 \pm 0.2 bcd
<i>H. recurva</i>	7.9 \pm 0.2 c	0.1 \pm 0.0 c	5.0 \pm 0.3 c	6.2 \pm 0.6 e	1.4 \pm 0.1 b	0.8 \pm 0.1 d
p-value	0.000	0.000	0.000	0.000	0.000	0.000

Values with the same letter are not significantly different, using Tukey's test ($p > 0.05$).

* *A. tetragonophylla*

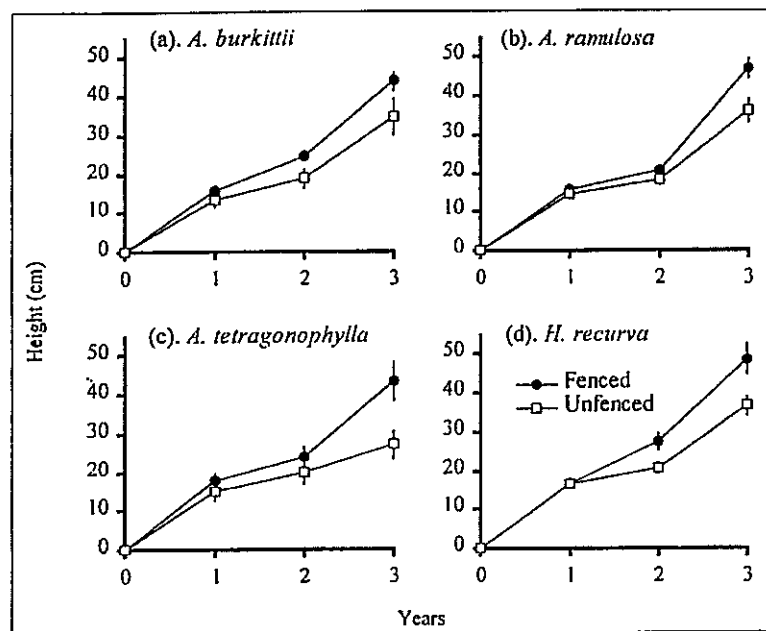


Fig. 7. Mean *S. spicatum* seedling height (\pm std. err.) next to four separate host species within fenced and unfenced treatments.

Discussion

Santalum spicatum recruitment was significantly improved by sowing seeds next to host trees and excluding livestock. At age three years, survival of *S. spicatum* seedlings next to host trees was 25%, higher than both harvest (2%) and natural (0%). Within the host treatment, survival of fenced seedlings (30%) was greater than unfenced seedlings (20%). *Santalum spicatum* seedling height and stem diameter were also greater in the fenced treatment. The two fencing treatments were pseudoreplicated, so the difference in *S. spicatum* seedling performance between fencing treatments may be due to differences between blocks. However, between 1997 and 1999, shoots were removed from 5 to 11% of the *S. spicatum* seedlings in the unfenced plot each year, while no seedlings were affected in the fenced plot. Therefore, grazing by sheep and goats may have reduced *S. spicatum* seedling survival and growth in the unfenced treatment. The unfenced plot is in a 4000 ha paddock that had 200 to 500 sheep and many feral goats during the trial.

Poor seed dispersal also contributes to the low natural recruitment rate of *S. spicatum* on Ninghan station. In 1996, there were only 48 new seedlings beneath 246 parent trees. All of these seedlings died within three years. Annual rainfall during this period was 321 to 411 mm, well above the long-term average of 293 mm. Between 1997 and 1998, only 46 more seedlings germinated naturally, with none away from parent trees. This poor germination is surprising, because 17 to 23% of the parent trees produced over 25 seeds in 1996 and 1997. Fruit production in 1995 was far greater, with over 6000 seeds collected from only 30 *S. spicatum* trees within 100 m of the trial. The majority of *S. spicatum* seeds observed were lying on the surface. Havel (1993) hypothesised that the woylie (*Beltongia penicillata*) use to disperse and cache *S. spicatum* seeds within inland Australia. The woylie disappeared from central Western Australia about 50 years ago (Burbidge *et al.* 1988). While it is difficult to test this, it may partly explain why today not many *S. spicatum* seedlings grow naturally away from parent trees in the rangelands. This study showed that de-stocking alone did not have an immediate impact on *S. spicatum* recruitment within a natural stand. Instead, enrichment of *S. spicatum* seeds near host trees is encouraged to promote recruitment.

Survival of *S. spicatum* planted in harvested tree gaps was very low and appears not to be a practical method for promoting recruitment. The poor seedling survival at harvested spots is probably due to the lack of suitable host roots. The seeds were sown in holes created by the large butt and roots of the harvested tree, which may have pushed away potential host roots. Low seedling survival may have also been due to competition between *S. spicatum* seedlings at each spot.

Within host species, overall *S. spicatum* survival next to *A. burkittii* (33%) was significantly greater than *A. tetragonophylla* (17%), at age three years. Survival of *S. spicatum* next to *A. ramulosa* and *H. recurva* were the same as the other two hosts. The slightly higher *S. spicatum* survival next to *A. burkittii* is not surprising because this species is very similar to *A. acuminata* (Maslin *et al.* 1999), which is an excellent host in the wheatbelt (Barrett *et al.* 1996, Brand *et al.* 1999, Brand *et al.* 2000). Growth of the *S. spicatum* seedlings (height 35–43 cm; stem diam. 3 to 4 mm) was very slow, and similar between host species. These slow growth rates are typical of *S. spicatum* in semi-arid environments. At Kalgoorlie, *S. spicatum* stem diameters (at 150 mm) increase only 1 to 2 mm per annum (Loneragan 1990). The results from this study show that the three N₂-fixing species (*A. burkittii*, *A. ramulosa* and *A. tetragonophylla*) and the non N₂-fixing species (*H. recurva*) are all suitable hosts for *S. spicatum* in semi-arid Western Australia.

Fencing appeared to improve survival of *S. spicatum* seedlings next to *A. burkittii*, at age three years. Survival of *S. spicatum* seedlings next to *A. tetragonophylla* and *A. ramulosa* were also higher in the fenced plot, but at a significance level of only 10%. In contrast, fencing had no

effect on the survival of *S. spicatum* seedlings next to *H. recurva*, which indicates that this species may protect *S. spicatum* from grazing. In 1997, grazing was less apparent on *S. spicatum* seedlings growing next to *H. recurva* than the other host species. The spiny leaves of *H. recurva* may deter herbivores grazing beneath the tree. Although *A. tetragonophylla* has spiny phyllodes, goats and livestock readily graze the foliage of this species (Mitchell and Wilcox 1988).

Within the *S. spicatum* foliage, the concentration of each element was the same between host treatments, except Mg. This indicates that the *S. spicatum* seedlings are gaining similar nutrients from each host treatment, which may be due to the trial being in mixed vegetation. Besides the immediate host, the seedlings are probably also attached to some other species. The K:Ca ratio in each *S. spicatum* treatment was relatively high (1.4 to 2.0), consistent with previous *Santalum* studies (Struthers *et al.* 1986, Radomiljac *et al.* 1998, Brand *et al.* 2000). Parasitic angiosperms typically absorb K in preference to Ca (Lamont 1983) which implies that the *S. spicatum* treatments at Ninghan are successfully parasitising each of the four host species.

The lack of natural recruitment of *S. spicatum* at Ninghan and other regions in Western Australia is a concern for the conservation of this species. Poor seed dispersal and grazing appear to be important factors limiting recruitment. The results from this study indicate that de-stocking combined with planting seeds next to suitable host species will dramatically improve *S. spicatum* recruitment. *Acacia burkittii*, *A. ramulosa*, *A. tetragonophylla* and *H. recurva* are all suitable host species for *S. spicatum* in semi-arid regions of Western Australia.

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References

- Barrett, D.R., Fox J.E.D. and Gentle, R. (1996). Sandalwood for saline sites. In: Conference proceedings on the Productive Use and Rehabilitation of Saline Lands, 25-30 March 1996, Albany, Western Australia pp. 335-43. Promaco Conventions.
- Brand, J.E. (1999). Ecology of sandalwood (*Santalum spicatum*) near Paynes Find and Menzies, Western Australia: size structure and dry-sided stems. *Rangel. J.* 21(2): 220-8.
- Brand, J.E., Ryan, P.C. and Williams, M.R. (1999). Establishment and growth of sandalwood (*Santalum spicatum*) in south-western Australia: the Northampton pilot trial. *Aust. For.* 62(1): 33-7.
- Brand, J.E., Crombie, D.S. and Mitchell, M.D. (2000). Establishment and growth of sandalwood (*Santalum spicatum*) in south-western Australia: the influence of host species. *Aust. For.* 63(1): 60-5.
- Burbidge, A.W., Johnson, K.A., Fuller, P.J. and Southgate, R.I. (1988). Aboriginal knowledge of the mammals of the central deserts of Australia. *Aust. Wildl. Res.* 15: 9-39.
- Fox, J.E.D. (1997). Why is *Santalum spicatum* common near granite rocks? *J. R. Soc. West. Aust.* 80: 209-20.
- Havel, J.J. (1993). Review of research needs of the sandalwood industry in Western Australia. Department of Conservation and Land Management, Western Australia.
- Hewson, H.J. and George, A.S. (1984). Santalaceae. In: Flora of Australia, Volume 22, pp. 29-67. Bureau of Flora and Fauna, Canberra. Australian Government Publishing Service, Canberra.
- Kearley, I.G. (1991). The management of sandalwood. Wildlife Management Program 8. Department of Conservation and Land Management, Western Australia.
- Kitson, R.E. and Mellon, M.G. (1944). Colorimetric estimation of phosphorus as molybdo-vanadophosphoric acid. *Indust. Eng. Chem., Anal. Ed.* 16: 379.

- Lamont, B. (1983). Mineral nutrition of mistletoes. *In: The biology of mistletoes* (Eds M. Calder and P. Bernhardt) pp. 185-204. Academic Press, University of Melbourne, Victoria.
- Loneragan, O.W. (1990). Historical review of sandalwood (*Santalum spicatum*) research in Western Australia. Research Bulletin 4. Department of Conservation and Land Management, Western Australia.
- Maslin, B., Byrne, M., Coates, D., Broadhurst, L., Coleman, H. and Macdonald, B. (1999). The *Acacia acuminata* (jam) group: an analysis of variation to aid sandalwood (*Santalum spicatum*) plantation research. Department of Conservation and Land Management, Western Australia. 60 pp.
- McKenzie, H.A. and Wallace, H.S. (1954). The Kjeldahl determination of nitrogen: a critical study of digestion conditions - temperature, catalyst and oxidising agent. *Aust. J. Chem.* 7: 55-70.
- Mitchell, A.A. and Wilcox, D.G. (1988). 'Plants of the arid shrublands of Western Australia.' University of Western Australia Press, Nedlands. 325 pp.
- Payne, A.L., Van Vreeswyk, A.M.E., Pringle, H.J.R., Leighton, K.A. and Hennig, P. (1998). An inventory and condition survey of the Sandstone-Yalgoo-Paynes Find area, Western Australia. Agriculture Western Australia, Technical Bulletin No. 90.
- Piper, C.S. (1947). 'Soil and plant analysis.' The WAITE Agricultural Research Institute, University of Adelaide. 368 pp.
- Radomiljac, A.M., McComb, J.A. and Shea, S.R. (1998). Field establishment of *Santalum album* L. - the effect of the time of introduction of a pot host (*Alternanthera nana* R.Br.). *For. Ecol. Manage.* 111: 107-18.
- Radomiljac, A.M., McComb, J.A. and McGrath, J.F. (1999a). Intermediate host influences on the root hemi-parasite *Santalum album* L. biomass partitioning. *For. Ecol. Manage.* 113: 143-53.
- Radomiljac, A.M., McComb, J.A. and Pate, J.S. (1999b). Heterotrophic carbon gain and mineral nutrition of the root hemi-parasite *Santalum album* L. in pot culture with different hosts. *Aust. For.* 62(2): 128-38.
- Struthers, R., Lamont, B.B., Fox, J.E.D., Wijesuriya, S. and Crossland, T. (1986). Mineral nutrition of sandalwood (*Santalum spicatum*). *J. Exp. Bot.* 37: 1274-84.
- Tsivion, Y. (1978). Physiological concepts of the association between parasitic angiosperms and their hosts - a review. *Isr. J. Bot.* 27: 103-21.
- Williams, E.R. and Matheson, A.C. (1994). 'Experimental design and analysis for use in tree improvement.' CSIRO, Melbourne, Victoria. 174 pp.

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ECOLOGY OF SANDALWOOD (*SANTALUM SPICATUM*) NEAR PAYNES FIND AND MENZIES, WESTERN AUSTRALIA: SIZE STRUCTURE AND DRY-SIDED STEMS

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Abstract

Population size structure of sandalwood (*Santalum spicatum*) was studied on four pastoral leases near Paynes Find and Menzies, in semi-arid Western Australia. Stem diameter, height, height to crown and the orientation of dry-sided stems were recorded for 1017 individual sandalwood. Populations of *S. spicatum* at Paynes Find contained only mature trees, indicating no successful recruitment for at least 30 years. In contrast, populations of *S. spicatum* at Menzies had a high proportion of seedlings and saplings. Crown measurements of mature *S. spicatum* trees indicated high grazing intensity at Paynes Find: mean height to crown at Paynes Find (147-148 cm) was significantly higher than Menzies (92-94 cm).

Dry-side percentage differed significantly between directional faces, consistent with sun damage. Highest mean dry-side percentages were on stem sides facing the sun between midday and late afternoon: west, north-west, south-west and north. This directional pattern was the same between pastoral leases, and there was no interaction between pastoral lease and dry-side direction. Mean percentage of mature trees with a dry-sided stem was also significantly higher at Paynes Find (76-82%) than at Menzies (42-46%). Significantly less foliage low to the ground on mature trees at Paynes Find may have exposed the stems to more sun damage. Land systems did not significantly influence dry-side direction on Burnerbinmah or Goongarrie. No *S. spicatum* seedlings or saplings had a dry-sided stem.

Key words: *Santalum spicatum*, size structure, dry-sided stems

Introduction

Fragrant timber from sandalwood (*Santalum spicatum* (R.Br.) A.DC.) is a valuable product in south-east Asia, and is commonly used to make incense sticks (Richmond 1977). *Santalum spicatum* is a root hemi-parasitic tree (Hewson and George 1984) and occurs naturally in south-western and central Western Australia, and on the western border of South Australia (Loneragan 1990). The distinct 'sandalwood' fragrance comes from sesquiterpenes contained in the heartwood (Adams *et al.* 1975). The fragrance of *S. spicatum* heartwood is similar to Indian sandalwood (*S. album*) which has been valued for over two thousand years (Rai 1990). *S. spicatum* was first exported from Western Australia in 1845, and extensive harvesting during early settlement largely removed the species from the Western Australian Wheatbelt (Talbot 1983). Today, natural stands are harvested on pastoral leases and vacant crown land in the Goldfields and Midwest, Western Australia. Harvesting *S. spicatum* is still an important industry, with approximately 1800 tonnes exported per annum (Kealley 1991).

The growth rate of *S. spicatum* is very slow, requiring 50-90 years to reach a stem diameter of 127 mm (at 150 mm above the ground) at Kalgoorlie, and 30-50 years at Narrogin (Loneragan 1990). Mature trees may attain a height of 4 m (Hewson and George 1984). Natural regeneration occurs at a very low rate on pastoral leases due to grazing by sheep, goats and rabbits (Loneragan 1990). Since 1987, the Department of Conservation and Land Management (CALM) has purchased and de-stocked three pastoral leases in the Goldfields (Jaurdi, Mt. Elvire and Goongarrie) and one in the Midwest (Burnerbinmah), a total area of over 600,000 ha. Together with 4.6 million ha of statutory reserves containing *S. spicatum* (Kealley 1991), the aim is to conserve the species throughout its range.

Inventory reports show that *S. spicatum* regeneration levels are low (Kealley 1991), and detailed size structure within and between populations needs further study. Established trees

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appear to be heavily grazed and bark is absent on stem sides of some trees in the Goldfields and Midwest (P. Ryan, pers. comm.). Absence of cambium on dry-sided trees may greatly reduce the amount of water and nutrients transported to the crown. Decreased water movement may reduce growth and ultimately cause death. Therefore the occurrence of dry-sided stems is an important consideration when re-establishing *S. spicatum* in arid environments. Why some *S. spicatum* have a dry-sided stem is unknown, but this may be linked to sun scald. The cambium tissue on stem sides exposed to the sun during the hottest part of the day may have been damaged.

The specific aims of this study were to: (i) compare *S. spicatum* size structure on pastoral leases near Paynes Find and Menzies; and (ii) examine the level of dry-sided stems in *S. spicatum* and determine whether this is due to sun scald.

Methods

Location and land systems

Measurements were recorded from *S. spicatum* populations growing at Burnerbinmah and Thundelarra near Paynes Find in March 1996, and Goongarrie and Jeedamya near Menzies, in March 1997 (Fig. 1). All four study sites were sheep grazing properties: Burnerbinmah from the 1890s until de-stocked by CALM in 1995; Thundelarra from the 1890s to present; Goongarrie from the 1920s until de-stocked in 1994; and Jeedamya from the 1920s to present. All pastoral leases have arid climates, with mean annual rainfall of 230-290 mm near Paynes Find, and 229-238 mm near Menzies. Between 1980 and 1994 the mean annual rainfall was 251 mm at Burnerbinmah and 243 mm at Goongarrie (Fig. 2). In February 1995, cyclonic storms brought heavy rains to Goongarrie (350 mm) and Burnerbinmah (249 mm). The annual rainfall for 1995 was 721 mm at Goongarrie and 451 mm at Burnerbinmah.

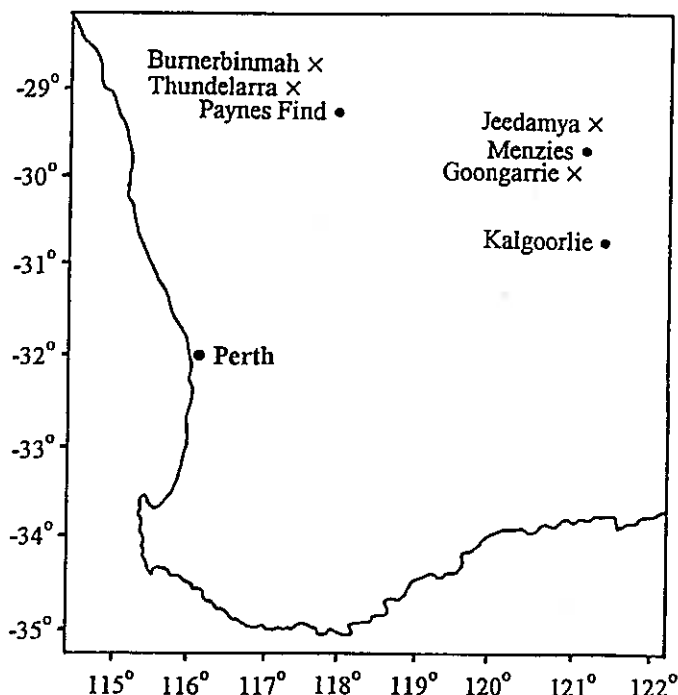


Fig. 1. Location of the four pastoral leases (x) used to examine *S. spicatum* ecology, in Western Australia.

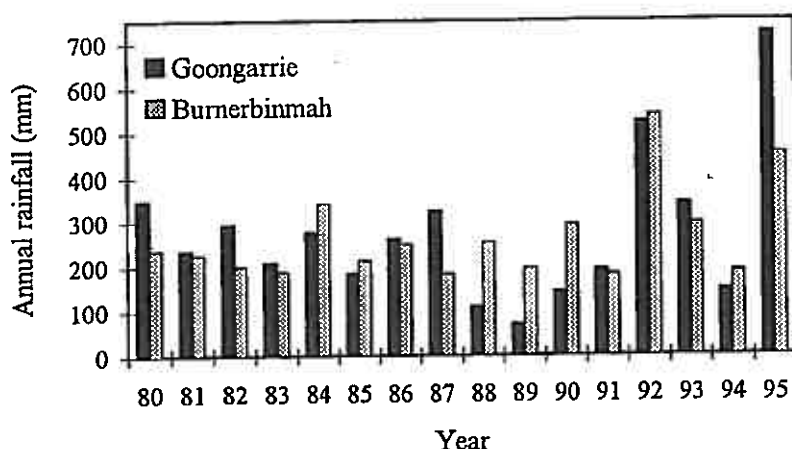


Fig. 2. Annual rainfall at Burnerbinmah and Goongarrie between 1980 and 1995.

S. spicatum populations selected on Burnerbinmah and Thundelarra were growing on five different land systems: Sherwood, Kalli, Woodline, Ero and Roderick, described by Curry *et al.* (1994). Sherwood has breakaways, kaolinised footslopes and extensive gently sloping plains on granite with mulga and halophytic shrublands. Kalli consists of level to gently undulating plains of red sand over laterite, with grassy *Acacia* shrublands. Woodline has nearly level sandy surfaced plains over a siliceous hardpan, with mulga shrubland. Ero and Roderick are similar land systems and both contain alluvial plains, with saline soils and predominantly halophytic shrublands.

Goongarrie and Jeedamya *S. spicatum* populations were growing on four separate land systems: Laverton, Bandy, Marmion and Deadman, described by Pringle *et al.* (1994). Laverton consists mainly of hills and ridges on greenstone and basalt, with *Acacia* shrublands. Bandy has low outcrops of granite and fringing plains, with *Acacia* shrublands. Marmion has gently undulating sandplains, with mixed spinifex, *Acacia*, heath and mallees. Deadman contains level to gently undulating plains, with *Casuarina* woodlands and *Acacia* shrublands.

Size class structure and dry-sided stems

On each pastoral lease, between four and eight *S. spicatum* populations growing on separate land systems were selected (Table 1). Within each population, 10–128 *S. spicatum* were measured for stem diameter, height and height to crown. Stem diameter was measured over the bark at 150 mm from the ground. Height to crown was measured from the base of the stem to the lowest green leaf. Stem diameter (at 150 mm) was used to group *S. spicatum* into three size categories: seedlings (< 10 mm), saplings (10–50 mm) and trees (> 50 mm).

The presence of dry-sided stems was also recorded. This was defined as *S. spicatum* stems without live bark from the ground to 40 cm, on one or more directional faces: north (337.5°–22.5°), north-east (22.5°–67.5°), east (67.5°–112.5°), south-east (112.5°–157.5°), south (157.5°–202.5°), south-west (202.5°–247.5°), west (247.5°–292.5°) and north-west (292.5°–337.5°).

Mean tree dimensions and the proportion of dry-sides of mature trees (> 100 mm stem diam.) were compared between pastoral leases, using one-way Analysis of Variance (ANOVA). The proportion of trees with dry-sides was compared between directions, and between pastoral leases, using two-way ANOVA. Within Burnerbinmah and Goongarrie, the proportion of trees

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with dry-sides were compared between directions, and between land systems, using two-way ANOVA. Proportions were angular transformed and Tukey's test was used to compare means.

A Unidata starlogger (Model 6004-11) weather station recorded hourly air temperature ($^{\circ}\text{C}$) and radiation (W/m^2) at Burnerbinmah for 28 consecutive days, in February 1997.

Table 1. Number of populations and *S. spicatum* sampled on each land system at (a) Burnerbinmah and Thundelarra near Paynes Find, and (b) Goongarrie and Jeedamya near Menzies.

(a). Paynes Find				
Land system	Burnerbinmah		Thundelarra	
	Pop.	Sandal.	Pop.	Sandal.
1. Sherwood	2	72	2	25
2. Kalli	2	85	-	-
3. Woodline	2	77	3	60
4. Ero/Roderick	2	84	1	15
Total	8	318	6	100

(b). Menzies				
Land system	Goongarrie		Jeedamya	
	Pop.	Sandal.	Pop.	Sandal.
5. Laverton	2	142	1	49
6. Bandy	2	123	1	30
7. Marmion	2	102	1	28
8. Deadman	2	149	1	30
Total	8	516	4	137

Results

Size structure

The size distribution of *S. spicatum* on Burnerbinmah was similar to that on Thundelarra, with 85-90% of plants having stems between 100 mm and 200 mm in diameter (at 150 mm), in March 1996 (Fig. 3). No seedlings or saplings were present, and the smallest stem diameter was 64 mm. In contrast, regeneration was high in Goongarrie and Jeedamya populations, with 17-25% seedlings and 9-10% saplings, in March 1997. Each Goongarrie land system contained regeneration, especially Laverton and Deadman (Fig. 4). These two land systems had 24-33% seedlings and 13-14% saplings. Most of the larger trees were growing on granite outcrops of Bandy with 35% of stem diameters above 150 mm. *Santalum spicatum* growing on greenstone ridges of Laverton were generally smaller with only 5% above 150 mm.

Dry-sided stems

Dry-sided stems only occurred in *S. spicatum* trees with stem diameters (at 150 mm) above 60 mm, and were common in mature trees with stem diameters greater than 100 mm. The proportion of mature trees with dry-sided stems was significantly different between pastoral leases (Table 2), with Paynes Find stations (75.6-82.4%) much higher than Menzies stations (42.2-45.5%, $p < 0.001$). Mean height to crown on Paynes Find stations (147-148 cm) was also significantly higher than Menzies stations (92-94 cm, $p < 0.001$). Mature trees at Paynes Find and Menzies stations had similar mean heights (290-308 cm, $p = 0.350$) and mean stem diameters (140-153 mm, $p = 0.118$).

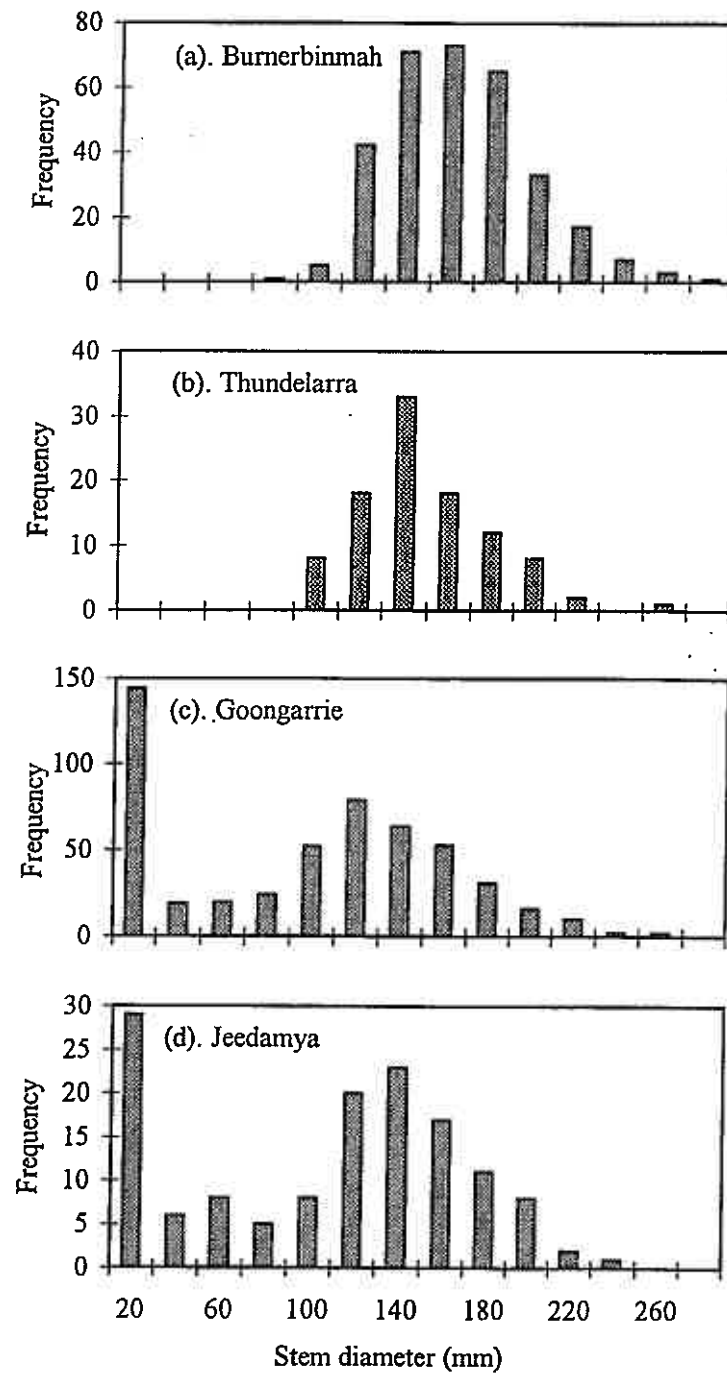


Fig. 3. *S. spicatum* stem diameter (at 150 mm) distributions at Burnerbinmah, Thundelarra, Goongarrie and Jeedamya, in 1996-97.

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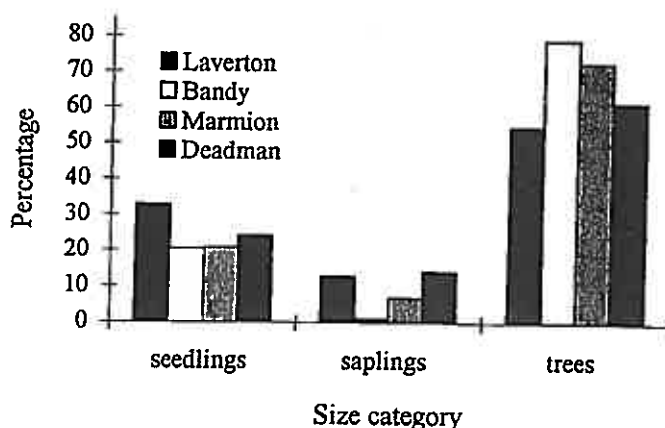


Fig. 4. *S. spicatum* size structure on four separate land systems, at Goongarrie.

Table 2. *S. spicatum* mean dry-side percentage, height to crown, tree height and stem diameter, on each pastoral lease. Measurements recorded from mature trees with stem diameters greater than 100 mm (at 150 mm).

Pastoral lease	Dry-side (%)	Height to crown (cm)	Tree height (cm)	Stem diam (mm)
Burnerbinmah	75.6 ± 4.4 a	148 ± 5 a	307 ± 8	153 ± 4
Thundelarra	82.4 ± 5.1 a	147 ± 6 a	290 ± 7	141 ± 5
Goongarrie	45.5 ± 4.4 b	94 ± 5 b	302 ± 8	140 ± 4
Jeedamya	42.2 ± 6.3 b	92 ± 8 b	308 ± 9	142 ± 6
p-value	<0.001	<0.001	0.350	0.118

Values with the same letter are not significantly different, using Tukey's test ($p < 0.01$).

The percentage of stems with a dry-side on the west face ($75.3 \pm 2.5\%$) was significantly higher than any other face (Table 3). North-west ($46.4 \pm 3.0\%$), south-west ($37.5 \pm 2.4\%$) and north ($16.7 \pm 2.2\%$) faces all had significantly more dry-sides than the south ($7.4 \pm 1.7\%$), north-east ($3.7 \pm 0.9\%$), south-east ($2.7 \pm 0.8\%$) and east ($1.4 \pm 0.9\%$) faces. Dry-side direction was similar between pastoral leases ($p = 0.115$), and there was no interaction between pastoral lease and dry-side direction ($p = 0.865$).

Table 3. *S. spicatum* mean dry-side direction percentage, on each pastoral lease.

Pastoral lease	Direction							
	W	NW	SW	N	S	NE	SE	E
Burnerbinmah	75.6	45.8	29.3	18.9	4.4	2.3	1.2	0
Thundelarra	74.7	48.0	43.5	13.8	6.9	1.2	1.2	0
Goongarrie	77.5	49.6	42.9	15.2	9.0	4.2	5.3	2.0
Jeedamya	71.1	38.7	34.2	19.4	11.5	9.4	2.8	5.0
Total mean	75.3a	46.4b	37.5b	16.7c	7.4d	3.7de	2.7de	1.4e
Std. err.	±2.5	±3.0	±2.4	±2.2	±1.7	±0.9	±0.8	±0.9

Values with the same letter are not significantly different, using Tukey's test ($p < 0.01$).

Land systems did not significantly influence dry-side direction on Burnerbinmah ($p = 0.409$), or Goongarrie ($p = 0.687$). There was no significant interaction between land system and dry-side direction on Burnerbinmah ($p = 0.996$), or Goongarrie ($p = 0.484$).

Hourly temperature levels in February 1997 at Burnerbinmah (Fig. 5) reveal that air temperature was greatest between 12 p.m. and 6 p.m. (35.0 – 37.5°C). Mean radiation level peaked between 11 a.m. and 3 p.m. (643 – 757 W/m^2).

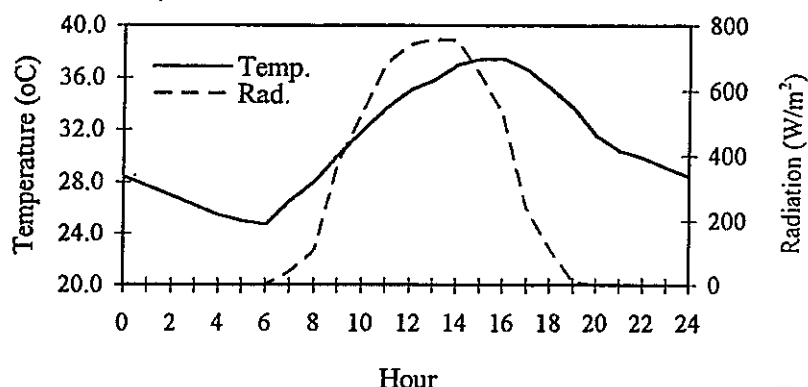


Fig. 5. Mean hourly temperature ($^\circ\text{C}$) and radiation (W/m^2) at Burnerbinmah, during February 1997.

Discussion

Populations sampled near Paynes Find contained only mature *S. spicatum* trees; no stem diameter (at 150 mm) was less than 64 mm. The estimated stem diameter growth of *S. spicatum* in the Goldfields and Murchison is only 1–2 mm (at 150 mm) per annum (Loneragan 1990). This suggests that there has been no successful recruitment at Burnerbinmah and Thundelarra for at least 30 years. In contrast, *S. spicatum* populations near Menzies had a high proportion of seedlings and saplings, on each land system studied. The high proportion of seedlings at Goongarrie (25%) compared to none at Burnerbinmah may be partly due to the difference in recent rainfall. In 1995, Goongarrie received an unusually high annual rainfall of 721 mm, while Burnerbinmah received 451 mm. However, Goongarrie also contained 10% saplings (age 5–20 years) and received less rain between 1980 and 1994 than Burnerbinmah. Recruitment failure near Paynes Find may instead be due to heavy grazing by domestic and feral herbivores, including sheep, goats and rabbits. Although this study did not examine the impact of grazing on seedlings, crown measurements of mature trees indicate high grazing activity near Paynes Find. Mean height to crown of Paynes Find populations (147–148 cm) was significantly higher than Menzies populations (92–94 cm, $p < 0.001$). The absence of *S. spicatum* foliage at 1–1.5 m, near Paynes Find, is probably due mainly to feral goats. A grazing study by Wilson *et al.* (1976) showed feral goats were capable of stripping foliage to a height of 2 m. During this study, hundreds of feral goats were observed near Paynes Find, whereas only three feral goats were counted near Menzies.

The Paynes Find stations can support a high numbers of herbivores because of available fresh water. Herbivore grazing pressure is directly related to access to watering points, especially in arid environments (Andrew 1988). Historically, grazing would have been high on Burnerbinmah because it has five semi-permanent fresh water holes, and had 24 operational bores between 1960 and 1995, over only 59,000 ha. Conversely, grazing on Goongarrie would have been lower because there was no permanent fresh water, and only six bores, over 100,000 ha. This study provides evidence that grazing intensity is higher at Paynes Find than

Menzies, but further research is required to determine if grazing is the main reason for recruitment failure at Paynes Find. The reduced grazing pressure on de-stocked pastoral leases in these regions should provide excellent field sites to conduct *S. spicatum* regeneration trials.

Dry-sided stems were not present in *S. spicatum* seedlings or saplings, but were common in mature trees, at a significantly higher rate at Paynes Find (75.6-82.4%) than Menzies (42.2-45.5%, $p < 0.001$). The high proportion of dry-sided stems in Paynes Find populations is most likely due to greater sun exposure. Paynes Find populations had less foliage low to the ground, thus reducing shade to the stem. High temperatures for prolonged periods can damage cambium tissue (Martin 1963), and direct sun exposure may have killed the *S. spicatum* cambium layer from the ground to the shaded area. Significant differences in mean dry-side percentage between directional faces is also consistent with sun damage. On each pastoral lease the highest mean dry-side percentages were on the west (75.3%), north-west (46.4%), south-west (37.5%) and north (16.7%). This pattern of dry-sided stems occurring mainly on western and northern stem sides was also the same between land systems. These stem sides face the sun when temperatures and radiation levels are most severe - between midday and late afternoon. This was confirmed at Burnerbinmah, where the mean air temperature was hottest between 12 p.m. and 6 p.m. and mean radiation level peaked between 11 a.m. and 3 p.m. in February 1997. This suggests that a high proportion of dry-sided *S. spicatum* stems on northern and western faces is due to sun scald. Selkirk (1971) also concluded that sun scald caused dry-sides on the northern stem side of mature *Pinus radiata*. The absence of cambium tissue on *S. spicatum* stems will reduce water and nutrient transport to the leaves and may thus reduce growth rate. Future plantings of *S. spicatum* in arid environments should endeavour to shade tree stems from afternoon sun in order to prevent sun scald.

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References

- Adams, D.R., Bhatnagar, S.P. and Cookson, R.C. (1975). Sesquiterpenes of *Santalum album* and *Santalum spicatum*. *Phytochemistry* 14: 1459-60.
- Andrew, M.H. (1988). Grazing impact in relation to livestock watering points. *Trends Ecol. Evol.* 3: 336-9.
- Curry, P.J., Payne, A.L., Leighton, K.A., Hennig, P. and Blood, D.A. (1994). An inventory and condition survey of the Murchison River catchment and surrounds, Western Australia. Department of Agriculture, Western Australia, Technical Bulletin No. 84.
- Hewson, H.J. and George, A.S. (1984). Santalaceae. In: *Flora of Australia*, Vol. 22: 29-67. Bureau of Flora and Fauna, Canberra. Australian Government Publishing Service, Canberra.
- Kealley, I. (1991). The management of sandalwood. Department of Conservation and Land Management, Western Australia, Wildlife Management Program 8.
- Loneragan, O.W. (1990). Historical review of sandalwood (*Santalum spicatum*) research in Western Australia. Department of Conservation and Land Management, Western Australia, Research Bulletin 4.
- Martin, R. E. (1963). A basic approach to fire injury of tree stems. In: *Proceedings of the second annual Tall Timbers Fire Ecology Conference*, Tallahassee, Florida, pp 151-62.
- Pringle, H.J.R., Van Vreeswyk, A.M.E. and Gilligan, S.A. (1994). An inventory and condition survey of rangelands in the north-eastern Goldfields, Western Australia. Department of Agriculture, Western Australia, Technical Bulletin No. 87.
- Raj, S.N. (1990). Status and cultivation of sandalwood in India. In: *Proceedings of the Symposium on Sandalwood in the Pacific*, 9-11 April 1990, Honolulu, Hawaii (Eds L. Hamilton and C.E. Conrad). USDA Forest Service General Technical Report PSW-122, pp. 66-71.
- Richmond, P.C. (1977). The Sandalwood Trade. Western Australian Forests Department, Information Sheet 26.

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- Selkirk, A.B. (1971). Notes on the history of sun scald in *Pinus radiata* at Mundaring Weir. Forests Department, Perth, Western Australia. *Forest Notes* 9(1): 6-8.
- Talbot, L. (1983). Wooden gold. Early days of the sandalwood Industry. W.A. Forests Department. *Forest Focus* 30: 21-31.
- Wilson, A.D., Mulham, W.E. and Leigh, J.H. (1976). A note on the effects of browsing by feral goats on a Belah (*Casuarina cristata*) - Rosewood (*Heterodendrum oleifolium*) woodland. *Aust. Rangel. J.* 1: 7-12.

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The benefits of seed enrichment on sandalwood (*Santalum spicatum*) populations, after 17 years, in semi-arid Western Australia

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Abstract. Initially, the size-class structure of 1067 natural sandalwood (*Santalum spicatum*) trees and seedlings, growing in populations at three semi-arid sites (Burnerbinmah, Ninghan and Goongarrie) in Western Australia, was measured during 1996–97. These same populations, and any new sandalwood seedlings and small trees that had established after 1996–97, were measured again after 17 years (2013). Size-class structure was assessed by measuring over-bark stem diameter at 150 mm above the ground. Populations of sandalwood trees at the Burnerbinmah and Ninghan sites failed to regenerate and, after 17 years, they contained only 0–3% small trees and 0–2% seedlings. Their overall population size declined by 21–24% and, combined with recruitment failure, these natural stands of sandalwood may largely disappear within 50–60 years. At the Goongarrie site, the proportion of large trees within the natural population increased from 58% to 82%. The proportion of small trees was constant at 13–16%, while seedlings declined from 29% to 2%. The population reduced by 35%, mainly due to high seedling mortality. Although the population was in decline, there appeared to be enough small trees and seedlings to maintain the population longer than at both the Burnerbinmah and Ninghan sites.

In a second study, 16 640 sandalwood seeds were sown at the same three sites during 1996–97, and then assessed for germination, survival, growth and fruit production over 17 years. Sandalwood germination and growth were compared between locations, fencing treatments and land systems. Seed enrichment was successful at each site with 27–45% germination and 6–20% survival (from germinated seeds) after 17 years. The overall seedling survival rates (from total seeds sown) ranged from 2.1% to 5.2%. Mean stem diameter of seedlings was significantly larger at Goongarrie (37 mm) than at both Burnerbinmah and Ninghan (20–22 mm) sites. Grazing significantly affected the performance of sandalwood seedlings at an age of 17 years at the Ninghan site. At this site, seedling survival (from germinated seeds) was 16% in the fenced plots compared with only 6% in the unfenced plots. Mean stem diameter in the fenced plots (24 mm) was also significantly greater than in the unfenced plots (11 mm). Land systems did not affect survival of sandalwood seedlings at the Burnerbinmah site but had a significant impact at the Goongarrie site after 17 years. Seedling survival was significantly greater on the hills and ridges than those growing on the plains with granite and red sand plains. Seed-enrichment programs are recommended to improve long-term regeneration and sustainability of sandalwood trees.

Additional keywords: grazing, land system, population, regeneration, sandalwood, size-class structure.

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Introduction

Sandalwood [*Santalum spicatum* (R.Br.) A.DC.] is a small hemiparasitic tree (Hewson and George 1984), which grows naturally over a wide geographical range in the southern half of Western Australia (WA) (Loneragan 1990). This species produces valuable aromatic oils within its heartwood and has been commercially harvested in WA since the 1840s (Talbot 1982). At present, the majority of natural populations of sandalwood trees occur in the semi-arid inland regions of WA where the average annual rainfall is 200–300 mm. Surveys of natural populations of sandalwood trees in the semi-arid areas of WA

indicate that natural regeneration is low (Kealley 1991; Brand 1999), possibly due to low seed dispersal and grazing (Brand 2000).

Seeds of sandalwood trees are relatively large (15–25 mm in diameter) and, unless near a watercourse, tend to remain below parent trees (Fox 1997) where germination and survival rates are low (Brand 2000). Moving sandalwood seeds away from parent trees and planting them near suitable host plants (e.g. *Acacia burkittii* Benth.) has shown to dramatically increase regeneration (Loneragan 1990; Brand 1999). Small marsupials, such as the woylie (*Bettongia penicillata*), may have previously played a role

in dispersing sandalwood seeds (Havel 1993) but this species disappeared from central WA over 60 years ago (Burbidge *et al.* 1988). Murphy *et al.* (2005) confirmed that woylies will pick up sandalwood seeds and cache them up to 80 m from the parent tree, resulting in increased regeneration.

Grazing by feral and domestic herbivores, including sheep and goats, has also been shown to have a significant impact on the survival and growth of sandalwood seedlings (Loneragan 1990; Brand 2000). Besides being preferred by herbivores, the sandalwood tree is also very slow-growing in the semi-arid regions of WA, with trees requiring 50–90 years to reach a stem diameter size of 127 mm at 150 mm above the ground, which is required for commercial harvesting (Loneragan 1990). This means that, for successful regeneration to occur, the seedlings need to grow in areas where grazing pressure is low for an extended period, perhaps as long as 25–50 years.

In 2008, the State Government of WA developed a specialised sandalwood seeding program in semi-arid regions, near to where mature sandalwood trees were being harvested for their aromatic wood. This project was titled 'Operation Woylie' and incorporated sowing sandalwood seeds in mechanically ripped lines near suitable host plants and in areas where grazing pressure was low (Sawyer 2013). The added benefit of using mechanically ripped lines is that it breaks the crust of the soil surface, which enhances moisture retention around the seeds, resulting in increased germination.

Although broad-scale programs of sandalwood seeding are currently being implemented in semi-arid regions of WA (Sawyer 2013), there is only limited information on long-term regeneration and survival. To address these long-term regeneration questions, the opportunity arose to re-visit some relatively old sandalwood trials, which were established during 1996–97 (Brand 1999, 2000), and re-measure them after 17 years (2013).

The first part of the study examines changes in the size-class structure of natural populations of sandalwood trees growing in semi-arid regions of WA over a 17-year period. This study will help determine long-term mortality, levels of regeneration and the sustainability of natural populations of sandalwood. The second part of the study determines the long-term benefits of using seed-enrichment programs in the same locations and over the same time period. Within these seed-enrichment experiments, seedling survival and stem diameter were measured as affected by (i) location, (ii) land system/host species and (iii) grazing.

Materials and methods

Size-class structure

Size-class structure in natural stands of sandalwood was assessed at three sites in WA: Burnerbinmah, Ninghan and Goongarrie (Fig. 1). Burnerbinmah (28°47'S, 117°22'E) is located ~260 km east of Geraldton, Ninghan (29°30'S, 117°11'E) is located ~270 km south-east of Geraldton, while Goongarrie (29°59'S, 121°03'E) is located ~100 km north-west of Kalgoorlie.

The Burnerbinmah site was managed for sheep grazing from the 1890s until it was destocked in 1995. The Ninghan site has been grazed by sheep since the 1890s, while the Goongarrie site was managed for sheep grazing between the 1920s until it was de-stocked in 1994. At each site, the trees used in the study

had previously been measured during 1996–97, which was documented by Brand (1999, 2000).

Burnerbinmah site

In March 1996, a total of 309 sandalwood trees growing on the Burnerbinmah site were measured for their over-bark stem diameter (mm) at 150 mm above the ground. Between 69 and 85 sandalwood trees were present on each of four different 'land systems', as described by Payne *et al.* (1998): 'Sherwood', 'Kalli', 'Woodline' and 'Ero'. Sherwood consists of breakaways, kaolinised foot-slopes and extensive gently sloping plains on granite with mulga and halophytic shrublands. Kalli contains level to gently undulating plains of red sand over laterite, with grassy *Acacia* shrublands. Woodline has nearly level sandy-surfaced plains over hardpan, with mulga shrubland. Ero contains alluvial plains, with saline soils and predominantly halophytic shrublands. The sandalwood trees were surveyed in transect lines along roads/tracks, with a total area surveyed of ~5 km × 200 m (100 ha). Every effort was made to include all the sandalwood trees within the transect lines.

Ninghan site

On the Ninghan site, a total of 247 sandalwood trees and seedlings were measured for stem diameter (mm) at 150 mm above the ground in June 1996. The sandalwood trees and seedlings were recorded growing on only one land system: 'Doney', which is described as alluvial plains supporting *Eucalyptus* woodlands (Payne *et al.* 1998). The sandalwood were all enclosed within an area of ~400 m × 800 m (32 ha). Within half of this area, a fenced plot was established with an area of 400 m × 400 m (16 ha) to exclude grazing by feral and domestic herbivores including sheep, goats and cattle (Brand 2000). In June 1996, the fenced area contained 120 sandalwood and the unfenced area contained 127 sandalwood.

Goongarrie site

In March 1997, a total of 511 sandalwood trees and seedlings growing on Goongarrie were measured for stem diameter (mm) at 150 mm above the ground. Between 102 and 151 sandalwood were measured on each of four different land systems: 'Laverton', 'Bandy', 'Marmion' and 'Deadman' (Pringle *et al.* 1994). Laverton consists mainly of hills and ridges on greenstone and basalt, with *Acacia* shrublands. Bandy has low outcrops of granite and fringing plains, with *Acacia* shrublands. Marmion has gently undulating red sand plains, with mixed spinifex, *Acacia*, heath and mallees. Deadman contains level to gently undulating plains, with *Casuarina* woodlands and *Acacia* shrublands. The sandalwood were surveyed in transect lines covering an area of ~100 ha, using a similar process to that described at Burnerbinmah.

Size-class structure comparisons after 16–17 years

During September–November 2013, all of the sandalwood trees and seedlings that were measured in 1996–97 at the three sites were re-measured for stem diameter (mm) at 150 mm above ground. Any sandalwood trees or seedlings that had died since 1996 were recorded. At the same time, any new seedlings or small trees, observed within the experimental area, were also measured and included in the new size-class structure. Each of



Fig. 1. Location of the three sites (Burnerbinmah, Ninghan and Goongarrie) used to study size-class structure and recruitment of sandalwood in Western Australia from 1996 to 2013.

the study areas were carefully walked through to try and capture any new seedlings or small trees which had established within the populations after 1996. All of the sandalwood trees and seedlings were grouped into one of three different stem diameter (at 150 mm) categories: large trees (diameter >80 mm), small trees (20–80 mm) and seedlings (<20 mm).

Seed enrichment

At the same three sites and within the same land systems that the size-class structure of natural populations of sandalwood was examined, seed-enrichment experiments were also established during 1996–97.

Burnerbinmah site

On the Burnerbinmah site, four seed-enrichment plots (replicates) were established on each of the four different land systems (Woodline, Kalli, Sherwood and Ero) in March 1996 and then another four seed-enrichment plots were established again in February 1997, making a total of 32 seed-enrichment plots (Table 1). Each enrichment plot was spaced at least 100 m apart and the plots were spread across the same area as that of the size-class structure study (~100 ha). Within each seed-enrichment plot, sandalwood seeds were planted in 20–30 different 'sowing

Table 1. The number of sandalwood seeds sown, enrichment plots and the associated host species for each land system, on the Burnerbinmah site during 1996–97

Land system	Host species	Enrichment plots	Seeds sown
Woodline	<i>A. aneura</i> , <i>A. grasbyi</i> , <i>A. ramulosa</i>	8	1600
Kalli	<i>A. aneura</i> , <i>E. forrestii</i> , <i>S. spinescens</i>	8	1600
Sherwood	<i>A. aneura</i> , <i>A. tetragonophylla</i>	8	1600
Ero	<i>A. aneura</i> , <i>A. burkittii</i> , <i>E. forrestii</i>	8	1600
Total	—	32	6400

spots', spaced at least 5 m apart. At each sowing spot, eight seeds were sown 2–3 cm below the soil surface, within an area of 1 m². The sandalwood seeds were collected fresh from natural populations growing near Kalgoorlie for the 1996 seeding, and near the Ninghan site for the 1997 seeding. On each of the four different land systems, a total of 200 sowing spots and 1600 seeds were established. A total of 6400 seeds were sown on the Burnerbinmah site during 1996–97.

The seeds were planted in mixed vegetation, but to increase the chances of the seeds connecting to host roots, each sowing spot

was established beneath the crown of a potential host plant. On each land system, 2–3 different plant species were selected, with a total of seven different host species used on the Burnerbinmah site (Table 1): *Acacia aneura* Benth., *A. burkittii*, *A. grasbyi* Maiden, *A. ramulosa* W. Fitzg., *A. tetragonophylla* F. Muell., *Eremophila forrestii* F. Muell. and *Scaevola spinescens* R.Br. At the time of sowing the sandalwood seeds beneath the potential host plants, each of the five *Acacia* species were ~0.5–6.0 m in height, while both *E. forrestii* and *S. spinescens* were ~0.3–2.0 m in height.

Ninghan site

On the Ninghan site, eight seed-enrichment plots (replicates) were established within both the unfenced plot (16 ha) and the fenced plot (16 ha), on the Doney land system, in June 1996, as described by Brand (2000). Within each enrichment plot, 10 sandalwood seeds were planted in 40 different sowing spots, spaced 5–10 m apart. In both the unfenced and fenced plot, a total of 320 sowing spots and 3200 seeds were established. A total of 6400 seeds were sown on the Ninghan site in 1996.

The sandalwood seeds were collected fresh in March 1996 from natural trees growing within 100 m of the Ninghan experimental site. The seeds were sown using similar methods to the Burnerbinmah site, in mixed vegetation and beneath the crown of potential host plants. Within each seed-enrichment plot, sandalwood seeds were sown beneath four different host species: *A. burkittii*, *A. ramulosa*, *A. tetragonophylla* and *Hakea recurva* Meisn. The heights of the *Acacia* hosts were ~0.5–5.0 m, while *H. recurva* was ~0.3–3.0 m at the time of sowing the sandalwood seeds.

Goongarrie site

On the Goongarrie site, four seed-enrichment plots (replicates) were established on each of the four land systems (Laverton, Bandy, Marmion and Deadman) in March 1997, making a total of 16 seed-enrichment plots (Table 2). Each seed-enrichment plot was spaced at least 500 m apart and the plots were spread across the same area as the natural sandalwood tree size-class structure study (~100 ha). Within each enrichment plot, eight sandalwood seeds were planted in 30 different sowing spots, spaced at least 5 m apart. On each of the four land systems, a total of 120 sowing spots and 960 seeds were established. A total of 3840 seeds were sown at Goongarrie in 1997.

The sandalwood seeds were collected fresh from natural populations growing near Kalgoorlie in March 1997 and were sown using similar methods as previously described, in mixed vegetation and beneath the crown of potential host plants. On

each land system, two different plant species were selected, with a total of seven different host species used (Table 2): *A. aneura*, *A. burkittii*, *A. coolgardiensis* Maiden subsp. *coolgardiensis*, *A. hemiteles* Benth., *A. ramulosa*, *A. tetragonophylla*, and *Senna artemisioides* subsp. *filifolia*. In March 1997, the heights of *A. aneura*, *A. burkittii*, *A. coolgardiensis* subsp. *coolgardiensis*, *A. ramulosa*, and *A. tetragonophylla* were 0.5–5.0 m. The approximate height of *A. hemiteles* was 0.5–3.0 m and of *S. artemisioides* subsp. *filifolia* was 0.3–1.5 m.

Germination, survival and growth

At each site, sandalwood germination (%) was recorded in October (soon after germination) each year for the first 5 years. Germination normally occurs during June–August, so most of the new seedlings should have been captured. Total germination (%) was defined as the total proportion of seeds sown that germinated during the first 5 years of the experiment. Sandalwood seedling survival (%) was measured at 5 years, 10 years and 16–17 years after sowing. Survival (%) is defined within this paper as either (i) the proportion of seedlings alive from the seeds that germinated, or (ii) the proportion of seedlings alive from total seeds sown. Stem diameter (mm) at 150 mm above the ground and height (m) were measured on each seedling, which established after 16–17 years, in September–November 2013. The percentage of seedlings with mature fruit set (%), which could be either on the plant or on the ground below the plant, was recorded at 5, 10 and 16–17 years.

Rainfall

The long-term mean annual rainfall (1896–2013) was relatively low at the three sites: Burnerbinmah – 238 mm, Ninghan – 295 mm and Goongarrie (recorded ~40 km away at Menzies) – 254 mm. During the course of the study (1996–2013), mean annual rainfall was above the long-term means for both the Burnerbinmah (294 mm) and Ninghan (321 mm) sites. Near Goongarrie (Menzies), annual rainfall data was not available for each year during the experiment but was available for Kalgoorlie (~100 km away). At Kalgoorlie, the mean annual rainfall during 1996–2013 was 265 mm, which was slightly above the long-term average at Menzies. Mean annual rainfall data was obtained from the Australian Government Bureau of Meteorology (www.bom.gov.au, accessed 16 July 2014).

Statistical analysis

Germination (%), seedling mean survival (%), mature fruit set (%), stem diameter (mm) and height (m) measurements were compared between locations, land systems and grazing treatments, using a one-way ANOVA. Proportions were angular transformed before analysis and Tukey's test was used to compare means. Statistical analysis was conducted using SYSTAT version 10.2.

Results

Size-class structure

Burnerbinmah site

In 1996, the Burnerbinmah sandalwood population contained 309 trees, consisting of 99% large trees (>80 mm diameter),

Table 2. The number of sandalwood seeds sown, enrichment plots and the associated host species for each land system, on the Goongarrie site in 1997

Land system	Host species	Enrichment plots	Seeds sown
Laverton	<i>A. burkittii</i> , <i>S. artemisioides</i>	4	960
Bandy	<i>A. ramulosa</i> , <i>A. tetragonophylla</i>	4	960
Marmion	<i>A. aneura</i> , <i>A. coolgardiensis</i>	4	960
Deadman	<i>A. hemiteles</i> , <i>S. artemisioides</i>	4	960
Total	–	16	3840

with only one small tree (20–80 mm) and no seedlings (Fig. 2). Between 1996 and 2013, 75 of the large trees and one small tree died. When re-assessed in 2013, two new seedlings, which appeared to be less than 1 year old, were added to the population. After 17 years, the population had shrunk by 24% and was still dominated by large trees (99%). The mean stem diameter (and standard error of mean) (at 150 mm) of large trees on Burnerbinmah was 158.9 ± 2.1 mm in 1996 and 173.9 ± 2.2 mm

in 2013, which is a mean growth in stem diameter of ~ 0.9 mm year⁻¹.

Ninghan site

The Ninghan population contained 247 sandalwood in 1996 (Fig. 2) and consisted of 223 large trees (90%), 20 small trees (8%) and four seedlings (2%). Between 1996 and 2013, 45 of the large trees, six of the small trees and all four of the seedlings

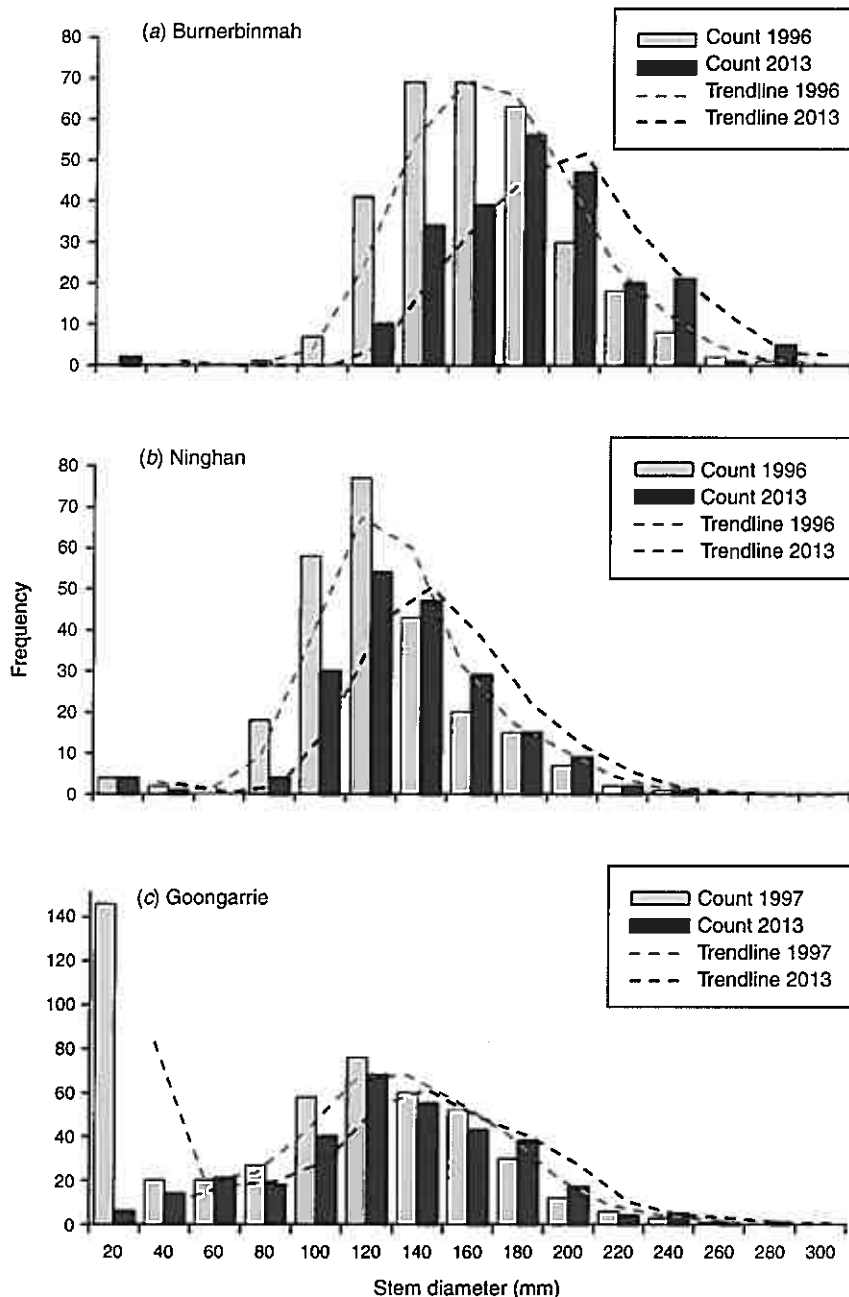


Fig. 2. Comparisons of distribution of stem diameters (at 150 mm above the ground) of sandalwood trees and seedlings between 1996–97 and 2013 for (a) Burnerbinmah, (b) Ninghan and (c) Goongarrie sites. Moving average (average of two adjacent stem diameter size-classes) trend lines are also shown for each site.

died. During the same period, nine of the small trees from the 1996 survey moved into the large tree-size category.

In 2013, only four new seedlings, which all appeared less than 1 year of age, were added to the population. After 17 years (Fig. 2), the population size had decreased by 21%, and consisted of 187 large trees (95%), five small trees (3%) and four seedlings (2%). The mean stem diameter (at 150 mm) of large trees on Ninghan was 123.5 ± 2.1 mm in 1996 and 131.9 ± 2.2 mm in 2013, with a growth rate of 0.5 mm year⁻¹.

Goongarrie site

In 1997, the Goongarrie population contained 511 sandalwood (Fig. 2), consisting of 298 large trees (58%), 67 small trees (13%) and 146 seedlings (29%). Between 1997 and 2013, 188 of the trees and seedlings died within each of the three size-classes: 44 large trees, 14 small trees and 130 seedlings. During this same period, recruitment occurred into different size categories, with 18 of the small trees growing into large trees, and 12 of the seedlings growing into small trees.

When the population was re-assessed in 2013 (Fig. 2), it had gained six new small trees and two new seedlings since the previous survey (1997). However, due to the high mortality rate, the overall population size had decreased by 35%, and consisted of 272 large trees (82%), 53 small trees (16%) and six seedlings (2%). The mean stem diameter (at 150 mm) of large trees on Goongarrie was 123.0 ± 2.1 mm in 1997 and 132.7 ± 2.2 mm in 2013, with a growth rate of 0.6 mm year⁻¹.

Seed enrichment

Site

Mean germination rates at each of the three sites (Burnerbinmah, Ninghan and Goongarrie) were highest in the first year and then decreased thereafter: range 21.9–38.5% (Year 1), 0.5–9.5% (Year 2), 1.1–5.5% (Year 3), 0–1.7% (Year 4) and 0% (Year 5). After 5 years, the mean total germination rate was relatively high at each site, and was significantly higher on the Ninghan ($44.6 \pm 1.5\%$) and Burnerbinmah ($38.3 \pm 2.4\%$) sites than on the Goongarrie site ($26.9 \pm 1.2\%$, $P < 0.001$).

Survival of seedlings (from germinated seeds) was similar between sites after 5 years (25.5–30.1%, Fig. 3). However, by 16–17 years, survival of seedlings was significantly higher on the Goongarrie ($19.5 \pm 3.0\%$) site than the Burnerbinmah ($6.2 \pm 1.1\%$, $P < 0.001$) site. Survival on the Ninghan site was $11.1 \pm 1.7\%$, and was not significantly different from the other two sites. The overall survival rates of seedlings (from total seeds sown) after 16–17 years were $2.1 \pm 0.4\%$, $4.9 \pm 0.5\%$ and $5.2 \pm 0.9\%$ on the Burnerbinmah, Ninghan and Goongarrie sites, respectively.

At 16–17 years, mean seedling diameter (at 150 mm) was significantly greater on the Goongarrie (36.7 ± 1.1 mm) site than on both the Burnerbinmah (21.6 ± 1.1 mm) and Ninghan (19.9 ± 0.8 mm, $P < 0.001$) sites. This equates to a growth in mean stem diameter of only 1.2 – 2.3 mm year⁻¹. At the same age, mean seedling height was also significantly greater on the Goongarrie (1.9 ± 0.1 m) site than on both the Burnerbinmah (1.2 ± 0.1 m) and Ninghan (1.1 ± 0.1 m, $P < 0.001$) sites. At each of the three sites, no fruit set was observed at 5 years of age and only 1.0–1.5% of the seedlings had produced fruit by 10 years

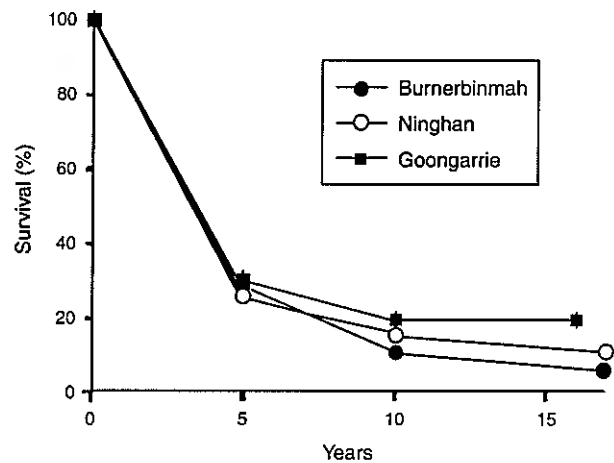


Fig. 3. Mean survival rate (s.e. of mean as bars) from germinated sandalwood seeds at the three different sites (Burnerbinmah, Ninghan and Goongarrie) at 5, 10 and 16–17 years.

of age. After 16–17 years of age, the proportion of seedlings that had produced fruit rose dramatically, and was significantly higher on the Goongarrie ($58.9 \pm 7.1\%$) site than on the Ninghan ($24.5 \pm 5.9\%$) and Burnerbinmah ($4.9 \pm 2.2\%$, $P < 0.001$) sites.

Land systems

On the Burnerbinmah site, mean total germination (during 1996–99) was similar between each of the four land systems (Woodline, Kalli, Sherwood and Ero), ranging from 33.9% to 44.0% ($P = 0.515$). After 17 years (2013), mean survival (from germinated seeds) was also similar between land systems (4.4 – 7.1% , $P = 0.941$).

At 17 years of age, the mean stem diameter at 150 mm of sandalwood seedlings on the Burnerbinmah site was significantly greater on the Kalli (32 ± 2 mm) land system than on the other three land systems ($P < 0.001$). Mean stem diameter on the Sherwood (23 ± 2 mm) land system was also significantly greater than on the Ero (14 ± 2 mm) land system, with the Woodline land system intermediate (18 ± 2 mm). This pattern of variation between land systems was also similar for seedling height at 17 years of age. Mean seedling height was significantly greater on the Kalli (1.7 ± 0.1 m) land system than on the other three land systems (0.9 – 1.1 m, $P < 0.001$).

On the Goongarrie site, mean total germination rate (during 1997–2000) on each of the four land systems (Laverton, Bandy, Marmion and Deadman) ranged from 22.5% to 30.5%, and was not significantly different from one another ($P = 0.162$). At 16 years of age (2013), mean survival rate of seedlings (from germinated seeds) was significantly higher on the Laverton ($34.0 \pm 7.2\%$) land system than on the Marmion ($13.9 \pm 4.2\%$) and Bandy ($3.8 \pm 1.4\%$, $P < 0.001$) land systems. Mean survival rate of seedlings on the Deadman ($26.1 \pm 3.8\%$) land system was similar to the Laverton and Marmion land systems, but was significantly greater than on the Bandy land system.

Mean seedling stem diameter (at 150 mm) on Goongarrie at 16 years of age was significantly greater on the Bandy (58 ± 4 mm) and Marmion (48 ± 2 mm) land systems than on

the Deadman (33 ± 2 mm) and Laverton (31 ± 2 mm, $P < 0.001$) land systems. Mean seedling height was also significantly greater on the Bandy (2.5 ± 0.1 m) and Marmion (2.4 ± 0.1 m) land systems than on the Deadman (1.7 ± 0.1 m) and Laverton (1.7 ± 0.1 m, $P < 0.001$) land systems.

Grazing

On the Ninghan site, mean total germination (during 1996–99) was similar between the fenced (ungrazed) plots ($45.1 \pm 2.8\%$) and the unfenced (grazed) plots ($44.1 \pm 1.4\%$, $P = 0.792$). Survival rate of seedlings (from germinated seeds) after 5 years was significantly greater within the fenced plots ($30.7 \pm 2.5\%$) than the unfenced plots ($20.4 \pm 2.3\%$, $P = 0.008$). This pattern continued over the next 12 years (Fig. 4), and by 17 years of age, mean survival rate in the fenced plots ($15.7 \pm 2.0\%$) was more than twice that of the unfenced plots ($6.5 \pm 1.5\%$, $P = 0.002$).

At an age of 17 years, mean stem diameter at 150 mm in the fenced plots (24 ± 1 mm) was significantly greater than in the unfenced plots (11 ± 1 mm, $P < 0.001$). Similarly, mean seedling height in the fenced plots (1.2 ± 0.1 m) was significantly greater than in the unfenced plots (0.7 ± 0.1 m, $P < 0.001$).

Discussion

Natural populations of sandalwood trees on the Burnerbinmah and Ninghan sites failed to regenerate during this 17-year study and, by 2013, they consisted mainly of large trees (95–99%), with only 0–3% small trees and 0–2% seedlings. Mortality of sandalwood trees was also high at both locations, and their overall population sizes decreased by 21–24%. The high mortality rate, combined with a lack of natural replacement of small trees and seedlings, indicates that, unless intervention is taken, the majority of natural sandalwood trees on the Burnerbinmah and Ninghan sites will largely disappear within 50–60 years. These findings support previous concerns over the sustainability of natural stands of sandalwood trees in semi-arid regions of WA (Kealley 1991).

Regeneration of sandalwood trees on the Goongarrie site was relatively high in 1997, with the natural population containing

58% large trees, 13% small trees and 29% seedlings in 1997. However, 16 years later (2013), the size-class structure of the population had changed to become predominantly large trees (82%), with 16% small trees and only 2% seedlings. During this same period, the overall population size also shrank by 35%, largely due to a high mortality rate of seedlings of ~90%. Besides the high mortality of seedlings, the number of large sandalwood trees that died was over twice the number of replacement large trees (i.e. recruitment of small trees into large trees). Therefore, the size of the sandalwood population on the Goongarrie site is also currently decreasing. However, it has some successful recruitment, which should enable this species to persist at this site.

In contrast to the low regeneration observed in the natural populations, the seed-enrichment experiments at each of the sites showed that regeneration was relatively successful, especially on the Goongarrie site. Mean germination rates of sandalwood ranged from 27% to 45% across sites and, after 16–17 years, mean survival rates of seedlings (from germinated seeds) ranged from 6% to 20%. The overall survival rates of seedlings (from total seeds sown) ranged from 2.1% to 5.2%, which indicates that ~20–50 sandalwood seeds were required to produce one live seedling at an age of 16–17 years. This information on long-term seeding rates will aid planning for future regeneration programs, including 'Operation Woylie' (Sawyer 2013).

At 16–17 years of age, survival and growth of sandalwood seedlings were highest on the Goongarrie site. This did not appear to be related to rainfall because this site had a lower mean annual rainfall during the period from 1997 to 2013 (265 mm) than both Burnerbinmah and Ninghan (294–321 mm) sites. Genetics may have affected seedling performance between sites because the seeds were derived from different locations in this study. However, the observed differences in seedling survival and growth between locations appeared to be mainly due to grazing. This was evidenced by significantly greater seedling survival (from germinated seeds) on the Ninghan site within the fenced plots (16%) than the unfenced plots (6%), at 17 years of age. Seedling diameter within the fenced plots (24 mm) was also double that of the unfenced plots (11 mm) on the Ninghan site. Although the effects of grazing were not tested at the other two sites, goats were frequently observed on the Burnerbinmah site, whereas no goats were observed on the Goongarrie site. Therefore, lower grazing pressure on the Goongarrie site appeared to be an important reason why survival and growth of sandalwood seedlings were significantly higher at this location. These findings concur with previous studies about the importance of selecting areas where grazing pressure is low to provide a greater chance for regeneration of sandalwood trees (Loneragan 1990; Brand 2000).

Land systems did not affect survival of sandalwood seedlings from germinated seeds on the Burnerbinmah site but had a greater impact on the Goongarrie site where survival was highest on the hills and ridges. A previous study of sandalwood trees growing on four pastoral stations in the north-eastern Goldfields area of WA, also found a significantly higher concentration of sandalwood trees growing on hills and ridges than on six other land surface types (Brand and Jones 2002). In this present study, higher survival rates of sandalwood seedlings on the hills and ridges may have been partly due to the host plants present,

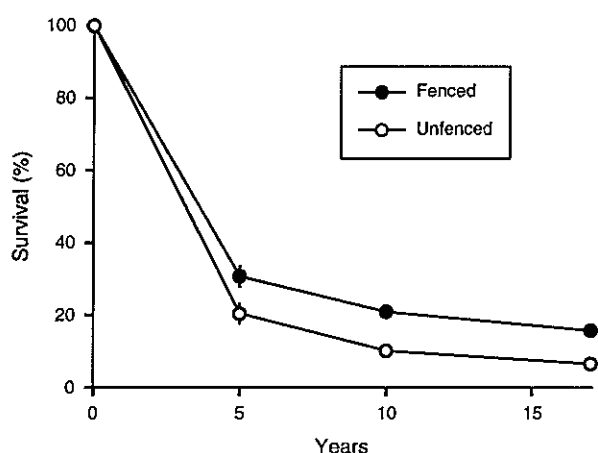


Fig. 4. Mean survival rate (s.e. of mean as bars) from germinated sandalwood seeds within the fenced and unfenced plots on the Ninghan site at 5, 10 and 17 years of age.

including *A. burkittii* (jam wattle). *Acacia burkittii* is a close relative of *A. acuminata* Benth. (Maslin *et al.* 1999), which is a recommended host for plantations of sandalwood trees in the medium annual rainfall (400–600 mm) regions of WA (Loneragan 1990; Brand *et al.* 2000). Although survival of sandalwood may be more favoured on some land systems than others, overall, this study showed that sandalwood can be successfully established on a range of land systems.

Mean stem diameters of sandalwood seedlings were variable between land systems at 16–17 years of age. On both Burnerbinmah and Goongarie sites, growth of sandalwood seedlings was relatively high on the red sand plains (Kalli and Marmion land systems). Although the red sand plains did not favour greater seedling survival from germinated seeds in this study, once established they did appear to favour faster growth of the seedlings.

This study confirms that there is a critical absence of regeneration of sandalwood trees in natural stands in some of the semi-arid regions of WA. In contrast, the seed-enrichment program was relatively successful in each location, especially where grazing pressure was low. At 16–17 years of age, 5–59% of the seedlings at each location were also producing mature fruit, which may support future regeneration. Therefore, seed-enrichment programs are recommended to improve long-term regeneration and sustainability of this species.

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References

- Brand, J. E. (1999). Ecology of sandalwood (*Santalum spicatum*) near Paynes Find and Menzies, Western Australia: size structure and dry-sided stems. *The Rangeland Journal* 21, 220–228. doi:10.1071/RJ9990220
- Brand, J. E. (2000). The effects of management regime and host species on sandalwood (*Santalum spicatum*) recruitment near Paynes Find, Western Australia. *The Rangeland Journal* 22, 243–256. doi:10.1071/RJ0000243
- Brand, J. E., and Jones, P. J. (2002). The influence of landforms on sandalwood (*Santalum spicatum*) size structure and density in the north-eastern Goldfields, Western Australia. *The Rangeland Journal* 24, 219–226. doi:10.1071/RJ02012
- Brand, J. E., Crombie, D. S., and Mitchell, M. D. (2000). Establishment and growth of sandalwood (*Santalum spicatum*) in south-western Australia: the influence of host species. *Australian Forestry* 63, 60–65. doi:10.1080/00049158.2000.10674814
- Burbidge, A. W., Johnson, K. A., Fuller, P. J., and Southgate, R. I. (1988). Aboriginal knowledge of the mammals of the Central Deserts of Australia. *Australian Wildlife Research* 15, 9–39. doi:10.1071/WR9880009
- Fox, J. E. D. (1997). Why is *Santalum spicatum* common near granite rocks? *Journal of the Royal Society of Western Australia* 80, 209–220.
- Havel, J. J. (1993). 'Review of Research Needs of the Sandalwood Industry in Western Australia.' (Department of Conservation and Land Management: Perth, WA.)
- Hewson, H. J., and George, A. S. (1984). Santalaceae. In: 'Flora of Australia, Volume 22'. (Ed. A. S. George.) pp. 29–67. (Australian Government Publishing Service: Canberra, ACT.)
- Kealley, I. G. (1991). 'The Management of Sandalwood. Wildlife Management Program 8.' (Department of Conservation and Land Management: Perth, WA.)
- Loneragan, O. W. (1990). 'Historical review of sandalwood (*Santalum spicatum*) research in Western Australia.' Research Bulletin 4. (Department of Conservation and Land Management: Perth, WA.)
- Maslin, B., Byrne, M., Coates, D., Broadhurst, L., Coleman, H., and Macdonald, B. (1999). 'The *Acacia acuminata* (jam) Group: an Analysis of Variation to Aid Sandalwood (*Santalum spicatum*) Plantation Research.' (Department of Conservation and Land Management: Perth, WA.)
- Murphy, M. T., Garkaklis, M. J., and Hardy, G. E. S. J. (2005). Seed caching by woylies *Bettongia penicillata* can increase sandalwood *Santalum spicatum* regeneration in Western Australia. *Austral Ecology* 30, 747–755. doi:10.1111/j.1442-9993.2005.01515.x
- Payne, A. L., Van Vreeswyk, A. M. E., Pringle, H. J. R., Leighton, K. A., and Hennig, P. (1998). 'An inventory and condition survey of the Sandstone-Yalgoo-Paynes Find area, Western Australia.' Technical Bulletin No. 90. (Department of Agriculture: Perth, WA.)
- Pringle, H. J. R., Van Vreeswyk, A. M. E., and Gilligan, S. A. (1994). 'An inventory and condition survey of the north-eastern Goldfields, Western Australia.' Technical Bulletin No. 87. (Department of Agriculture: Perth, WA.)
- Sawyer, B. (2013). Sandalwood (*Santalum spicatum*) establishment in the semi-arid and arid regions of Western Australia. *The Rangeland Journal* 35, 109–115. doi:10.1071/RJ12088
- Talbot, L. (1982). Wooden gold. Early days of the sandalwood industry. *Forest Focus* 30, 21–31.