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Review of the influence of *Acacia* species on establishment of Sandalwood (*Santalum spicatum*) in Western Australia

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SUMMARY

Sandalwood (*Santalum spicatum*) is a root hemi-parasitic tree that produces valuable fragrant oils. Harvesting of *S. spicatum* timber occurs mainly from natural stands in the semi-arid pastoral regions of the Goldfields and Midwest, Western Australia. These natural stands consist mainly of mature trees, with very little successful recruitment. Recruitment failure is most likely due to grazing and poor seed dispersal. Trials show that the most dramatic way to improve recruitment in natural stands is by removing grazing and planting *S. spicatum* seeds near suitable host plants, especially *Acacia* species.

Sandalwood tree farm systems are also being established in the 400-600 mm mean annual rainfall areas of the Wheatbelt and Midwest. A successful establishment technique involves planting *S. spicatum* seeds near 1-2 year old *Acacia acuminata* seedlings. *S. spicatum* growth rates have been relatively fast, with mean stem diameters (at 150 mm) increasing up to 7-9 mm yr^{-1}. Current research is determining methods to further improve *S. spicatum* performance by studying the influence of host species, parasite-to-host ratio and provenance.

In a host trial near Katanning, *S. spicatum* stem diameter was higher near *A. acuminata* (47 mm) than near *Allocasuarina huegeliana* (21 mm), at age five years. All *S. spicatum* seedlings died near *Eucalyptus loxophleba* subsp. *loxophleba* within two years. Foliar concentrations of N and K, and the K:Ca ratio were significantly greater in *S. spicatum* growing near *A. acuminata* than near *A. huegeliana*. Mean stem water potentials (Ψ_{stem}) of *S. spicatum* were significantly lower near *A. acuminata* than *A. huegeliana* in February-March 1999.

The performance of *S. spicatum* near four separate *Acacia* species is being examined at two sites, near Narrogin and Dandaragan. At age two years, *S. spicatum* mean stem diameter near *A. saligna* (28-33 mm) was 2-4 times greater than near *A. microbotrya* and *A. hemiteles*.

Recently, the *A. acuminata* group was divided into seven taxa. Seedlings from these different taxa have been planted together at two locations as hosts for *S. spicatum*. These trials will examine the influence of *A. acuminata* provenance on *S. spicatum* performance.

INTRODUCTION

Oils of sandalwood (*Santalum spicatum* (R.Br.) A.DC.) are a valuable ingredient in many products, such as incense sticks, perfumes, cosmetics and body-care lotions. Sesquiterpene oils accumulate within the heartwood of mature trees and give the timber its distinctive fragrance (Adams *et al.* 1975). *S. spicatum* occurs over the southern half of Western Australia and into South Australia (Loneragan 1990). Since 1845, export of its timber has provided a valuable industry for Western Australia (Talbot 1983). Today, the annual harvest is approximately 2000 tonnes (Jones 2001), with a value of up to $10 per kilogram. Harvesting occurs from natural stands, mainly on pastoral leases and vacant Crown land in central areas of Western Australia (Sawyer and Jones 2001).

Santalum spicatum is a root hemi-parasitic tree (Hewson and George 1984) that commonly grows with *Acacia* species (Loneragan 1990). Most natural stands occur in pastoral areas (Kealley 1991), where the annual average rainfall is below 250 mm. Natural recruitment in these stands is generally low, partly due to grazing by domestic and feral herbivores and poor seed dispersal (Loneragan 1990; Brand 1999; Brand 2000). There are concerns for the conservation of *S. spicatum* in these regions (Havel 1993). Current research is examining the effects of grazing, seed dispersal and host species on *S. spicatum* recruitment (Brand, 2000). In trials, seeds have been planted near a range of *Acacia* and other plant species to determine suitable hosts for these regions. *Santalum* species generally perform well when attached to N_2-fixing host plants, especially from the genus *Acacia* (Barrett *et al.* 1996; Radomiljac *et al.* 1999; Brand *et al.* 2000).

In Western Australia, sandalwood farm systems are being established in the Wheatbelt and Midwest, where the mean annual rainfall is 400-600 mm (Shea *et al.* 1998). A practical method of establishing *S. spicatum* is to plant seedlings of *Acacia acuminata* in rows and then sow *S.*

spicatum seeds near the hosts when the latter are 1-2 years old (Fox and Wijesuriya 1985; Brand *et al.* 1999). Using this technique, *S. spicatum* growth has been relatively fast, with mean stem diameters (at 150 mm) increasing up to 7-9 mm per year in the first five years (Brand *et al.* 1999; Brand *et al.* 2000). The predicted returns are 2-3 tonnes of commercial wood per hectare, at age 20 years (Brand and Jones 1999). Although this establishment technique is successful, current research is examining methods to improve *S. spicatum* performance through host selection, parasite-to-host ratios, and provenance trials of both host and *S. spicatum*.

This paper reviews the influence of *Acacia* species on *S. spicatum* establishment in conservation trials in semi-arid areas and in tree farm systems in the Wheatbelt and Midwest.

CONSERVATION

Ninghan Station

In 1996, a *S. spicatum* recruitment trial was established in natural vegetation on an alluvial plain at Ninghan station, near Paynes Find (Brand 2000). Sheep graze on this station and the mean annual rainfall is 293 mm. Recruitment of *S. spicatum* in the Paynes Find region is currently low (Brand 1999), and occurs mainly beneath parent trees, where survival is also low. Seeds tend to remain near the parent due to their large diameter, sometimes over 2 cm. Moving *S. spicatum* seeds away from parent trees and planting them near host species protected from grazing had a significant effect on seedling survival at Ninghan. *S. spicatum* seeds were planted near *Acacia burkittii*, *A. ramulosa*, *A. tetragonophylla* and *Hakea recurva*. A total of 6400 *S. spicatum* seeds were planted near 640 host trees.

At age three years, mean survival of seedlings raised near host trees was significantly greater (25%) than natural recruitment (0%). Seedling survival was also greater when fenced (30%) than unfenced (20%). Within the fenced treatment, *S. spicatum* survival was significantly higher near *A. burkittii* (41%) than *A. tetragonophylla* (23%, Fig. 1).

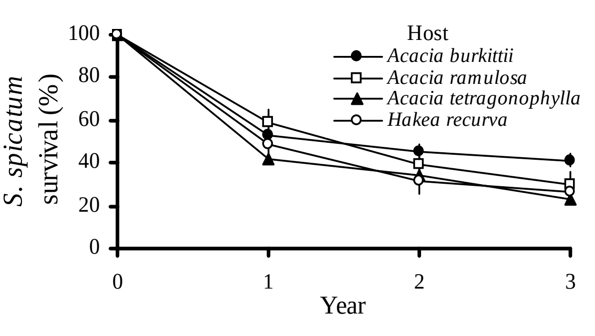

Figure 1. Mean seedling survival of S. spicatum *(± standard error) near four separate host species within the fenced treatment at Ninghan station (source: Brand 2000).*

Mean height increased only 10-20 cm per year and was similar between host treatments. At age three years, mean stem diameter (at 150 mm above the ground) was only 3-4 mm.

Goongarrie station

In the north-eastern Goldfields, a host trial for *S. spicatum* was established in natural vegetation on Goongarrie pastoral station, near Menzies. Goongarrie has been destocked of sheep since 1994 and has a mean annual rainfall of 252 mm. In March 1997, *S. spicatum* seeds were planted near seven host species: *Acacia aneura*, *A. burkittii*, *A. coolgardiensis* subsp. *coolgardiensis*, *A. hemiteles*, *A. ramulosa*, *A. tetragonophylla* and *Senna artemisioides* subsp. *filifolia*. A total of 3840 seeds were planted near 480 host plants, on four landforms: hills and ridges, granite, calcareous red earths and red sand plains.

At age three years, mean survival of *S. spicatum* seedlings was highest near *A. burkittii* (56%), and lowest near *A. ramulosa* (10%) and *A. tetragonophylla* (10%). Mean survival in the other treatments was 24-44%. At the same age, mean seedling heights were 70-110 cm, and seedling diameters (at 150 mm) were only 5-10 mm.

TREE FARM SYSTEMS

Northampton trial

Sowing *S. spicatum* seeds near young *A. acuminata* seedlings is a successful establishment technique. In 1988 and 1989, seeds were planted near one- and two-year-old *A. acuminata* seedlings in a plantation near Northampton, Western Australia (Brand *et al.* 1999). In both years, 3-6 *S. spicatum* seeds were planted near each host tree, with an aim to have a parasite-to-host ratio of 1 : 1. In 1997, mean survival of *S. spicatum* was 87% from 1988 plantings (age 9 years) and 50% from 1989 plantings (age 8 years). Initial growth was encouraging, with mean stem diameters (at 150 mm) increasing 6-7 mm per year between age 4.5 and 7 years. Growth then decreased to 4-5 mm per year between age 7 and 9 years. This decrease in growth may be related to the low host survival, especially when *S. spicatum* was introduced when the host was only one year old. In 1997 (host age 10 years), mean survival of *A. acuminata* with *S. spicatum* introduced at year one (37%), was significantly lower than when introduced at year two (84%). Therefore, the extra year without a parasite may have increased survival of *A. acuminata*.

Besides the stress of a root hemi-parasite, the *A. acuminata* seedlings planted at Northampton showed signs of wind-burn from the southerly sea breeze, whereas the natural stands of *A. acuminata* near the site were less affected. The *A. acuminata* seedlings were from a provenance south-east of Perth and may not have been suited to the local conditions. It may be possible to select superior types or provenances of *A. acuminata* that improve *S. spicatum* growth. The effects of host age, host-to-parasite ratio and provenance on *S. spicatum* performance requires further investigation. To address these research needs, a series of trials have been established on farmland in south-western Australia.

Kwobrup host trial

The influence of two N_2-fixing woody hosts (*A. acuminata* and *Allocasuarina huegeliana*) and a non N_2-fixing woody host (*Eucalyptus loxophleba* subsp. *loxophleba*) on *S. spicatum* establishment and growth was investigated at Kwobrup, near Katanning (Brand *et al.* 2000). In June 1991, the host seedlings, age six months, were planted in separate species blocks. Within each block, the seedlings were planted at 4 m intervals along 21-25 rows, spaced 4 m apart. At host age five years (June 1996), four *S. spicatum* seeds were buried 2-3 cm below the surface near each host stem.

Germination of *S. spicatum* was relatively good, with 60-86 % of sowing spots having at least one germinant near each host. At age five years, mean survival of *S. spicatum* near *A. acuminata* was 85%, significantly greater than near *A. huegeliana* (28%, Fig. 2). All *S. spicatum* seedlings near *E. loxophleba* subsp. *loxophleba* died within two years. At age five years, the *S. spicatum* had a mean height of 205 cm near *A. acuminata* and 177 cm near *A. huegeliana*. At the same age, mean stem diameter (at 150 mm) of *S. spicatum* was 47 mm near *A. acuminata*, far greater than near *A. huegeliana* (21 mm, Fig. 3). Growth of *S. spicatum* near *A. acuminata* at Kwobrup was relatively good compared to that at Northampton where the mean stem diameter was 40-44 mm at age 5.5 years (Brand *et al.* 1999).

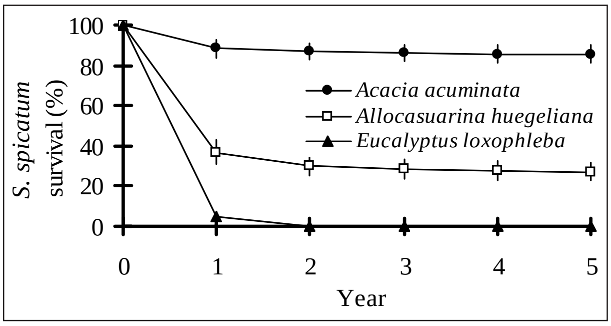

Figure 2. Mean survival (± standard error) of S. spicatum *near three host species, planted at Kwobrup.*

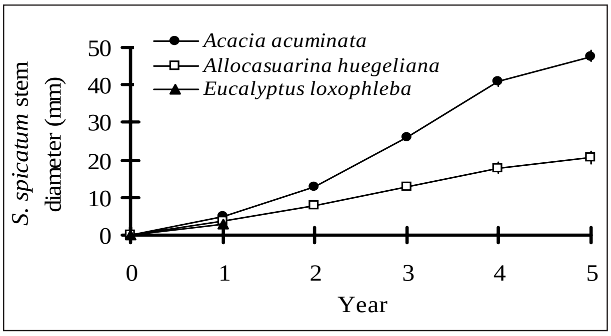

Figure 3. Mean stem diameter (± standard error) of S. spicatum *near three host species, at Kwobrup.*

Possible reasons why *S. spicatum* performed better near *A. acuminata* than *A. huegeliana* may be due to nutrition or water movement. At age three years, the foliar N and K concentrations, and the K:Ca ratio were significantly higher in *S. spicatum* near *A. acuminata* than those near *A. huegeliana*. *S. spicatum* growing near *A. acuminata* had a mean K:Ca ratio of 4.9, almost five times greater than those near *A. huegeliana* (1.0). Parasitic angiosperms typically have a high K:Ca ratio when attached to suitable host plants, which aids in nutrient movement from host to parasite (Tsivion 1978).

During the dry months of February and March 1999, stem water potentials (Ψ_{stem}) of *S. spicatum* (age 3 years) were also compared between host species treatments (Table 1). Mean stem water potential of *S. spicatum* at pre-dawn was -4.0 MPa near *A. acuminata*, significantly lower than *S. spicatum* (-2.8 MPa) near *A. huegeliana*. A lower water potential implies that there is less water available to the plant (Turner 1981). This indicates that water was more readily available to the *S. spicatum* parasitising *A. huegeliana* than those on *A. acuminata*. It appears that improved *S. spicatum* performance near *A. acuminata* was not related to greater water availability but more likely due to the host plant's ability to provide high concentrations of key elements such as N and K.

TABLE 1

Pre-dawn and midday mean leaf and stem water potentials (± std. errors) of *S. spicatum* and host (control & parasitised) trees (*n* = 6-8). Measurements were recorded in February-March 1999 (source: Brand *et al.*, 2000)

Species	Ψ_{leaf} and Ψ_{stem} (MPa), Pre-dawn (18/3/1999)	Feb-March 99 Midday (24/2/1999)
(a) Jam/sandal.		
A. acuminata (control)*	- 3.5 ±0.2 b	-
A. acuminata (parasitised)*	- 3.7 ±0.2 ab	- 4.4 ±0.4 ab
S. spicatum #	- 4.0 ±0.3 a	- 5.1 ±0.4 a
(b) Sheoak/sandal.		
A. huegeliana (control)*	- 2.4 ±0.2 c	-
A. huegeliana (parasitised)*	- 2.6 ±0.2 c	- 2.2 ±0.1 d
S. spicatum #	- 2.8 ±0.1 c	- 3.8 ±0.1 bc
(c) York gum		
E. loxophleba (control)*	- 2.8 ±0.2 c	- 3.4 ±0.1 c
p-value	< 0.001	< 0.001

Values with the same letter are not significantly different, using Fisher's LSD test (p > 0.05).
*Ψ_{leaf} ; # Ψ_{stem}

Acacia host trials

In June-July 1998, seedlings of *A. acuminata*, *A. microbotrya*, *A. saligna* and *A. hemiteles* were planted as initial hosts for *S. spicatum* at two sites, Dandaragan and Narrogin. *A. microbotrya* and *A. saligna* were selected as initial hosts because they are fast growing, though they may live for only 10 years. *A. acuminata* was also planted as the secondary or long-term host. Before planting, each site was ripped to a depth of 0.5 m, in rows spaced 4 m apart. Initial host seedlings were planted at 3 m intervals along alternate rows, with the long-term hosts planted at 3 m intervals on every other row. Initial hosts were planted in separate species plots, and each plot contained 24 initial hosts and 24 long-term hosts. Each treatment was replicated four times, at both sites.

In April 1999, six *S. spicatum* seeds were sown near each initial host plant, at both sites. Germination was relatively high, with 76-98% near each host. At age two years, mean survival of *S. spicatum* was highest near *A. saligna* (91-92%) and lowest near *A. hemiteles* (48-58%), for both sites. Survival for the other two hosts was 62-84%. At the same age, *S. spicatum* planted near *A. saligna* were 144-170 cm in height and had stem diameters of 29-33 mm (Fig. 4). In contrast, *S. spicatum* growing near *A. hemiteles* and *A. microbotrya* were only 66-76 cm tall and had stem diameters of only 6-10 mm.

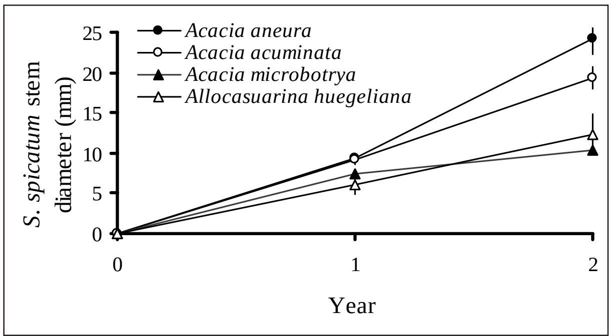

Figure 4. Mean stem diameter of S. spicatum *(at 150 mm) at age two years, planted near four different Acacia species at Dandaragan and Narrogin.*

Parasite-to-host ratio

The effects of different ratios of *S. spicatum* to host species is being trialed on farmland near Narrogin, Western Australia. In July 1997, six hectares were planted with four potential host species: *Acacia aneura*, *A. acuminata*, *A. microbotrya* and *Allocasuarina huegeliana*. The seedlings were planted at 4 m intervals along rip-lines spaced 4 m apart (625 stems per hectare), in separate species plots.

At host age two years (April 1999), *S. spicatum* seeds from a plantation near Narrogin were sown near the host plants at three parasite-to-host ratios: 0 : 1, 1 : 1, and 1 : 2. At the time of sowing, the mean height of *A. aneura* (0.7 m) was much smaller than the other three species (1.8-2.7 m). Six *S. spicatum* seeds were buried 1-2 cm below the surface, approximately 1 m from the stem of each host. In 1999, *S. spicatum* germination was 92-96% per spot.

After two years (June 2001), mean survival of *S. spicatum* was 90-99% within each host species treatment. Mean stem diameter of *S. spicatum* was 24 mm near *A. aneura* and 19 mm near *A. acuminata*, far greater than near *A. microbotrya* (10 mm) and *Allocasuarina huegeliana* (10 mm, Fig. 5). Mean height of *S. spicatum* near *A. aneura* and *A. acuminata* was 113-123 cm, again, greater than near *A. microbotrya* (90 cm) and *A. huegeliana* (94 cm). At this stage, there was no difference in *S. spicatum* performance between parasite-to-host ratio treatments.

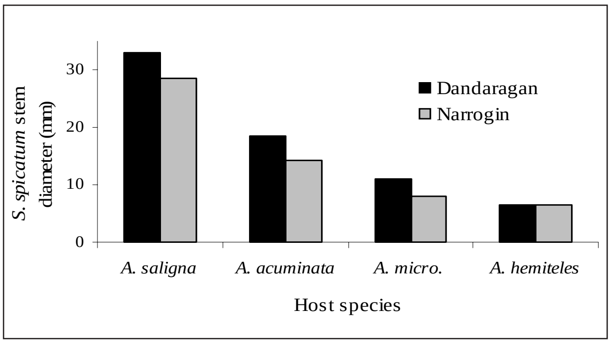

Figure 5. Mean stem diameter (± standard error) of S. spicatum *near four host species, at Narrogin.*

Provenance trials

Acacia acuminata is widely accepted as a suitable host for *S. spicatum* (Loneragan 1990; Barrett and Fox 1996; Brand *et al.* 1999). However, there is little information on the source of *A. acuminata* used in *S. spicatum* trials. *A. acuminata* and its close relatives are highly variable, and a recent taxonomic study of the group revealed seven taxa (Maslin *et al.* 1999): *A. acuminata* (typical); *A. acuminata* (narrow phyllode); *A. acuminata* (small seed); *A. acuminata / burkittii* (variant 1); *A. acuminata / burkittii* (variant 2), *A. burkittii*; and *A. oldfieldii*. Planting *S. spicatum* near these taxa may have a varying effect on *S. spicatum* performance.

In November-December 1998, seeds from these seven *A. acuminata* taxa were collected from 147 parent trees growing in 24 different provenances (Maslin *et al.* 1999). In July 2000, seedlings from 84 of these parent trees were planted at two sites: Morawa and Dowerin. At each site, the seedlings were planted at 3 m intervals along rip-lines spaced 4 m apart (833 stems per hectare), over an area of 5 ha.

At age six months (January 2001), seedling survival was 70-81% at Morawa and Dowerin. At both sites, the phyllode widths of the *Acacia* seedling types were already similar to their parent trees. More than 99% of *A. burkittii* seedlings had phyllode widths less than 2 mm, similar to their parent phyllode width of 0.7-2 mm. In contrast, over 99% of *A. acuminata* (typical variant) had phyllode widths greater than 2 mm, similar to their parent phyllode width of 3-10 mm. *S. spicatum* seeds will be direct-seeded near these host seedlings in May 2002 (host age two years) to examine the influence of *A. acuminata* type on *S. spicatum* performance.

CONCLUSIONS

Establishment of *S. spicatum* near *Acacia* species in tree farm systems has been successful in the Wheatbelt and Midwest, Western Australia. In a trial at Kwobrup, *S. spicatum* seedling survival and growth at age five years were significantly greater near *Acacia acuminata* than near *Allocasuarina huegeliana*. All *S. spicatum* seedlings died near *E. loxophleba* subsp. *loxophleba* within two years. Foliar analysis indicated that *A. acuminata* was providing more

N and K to the parasite. *S. spicatum* near *A. acuminata* also had high K:Ca ratios. These findings indicate that *A. acuminata* is a suitable host for *S. spicatum*. The *A. acuminata* group is variable and current research is examining whether certain provenances of *A. acuminata* improve *S. spicatum* performance.

In another trial, mean stem diameters of *S. spicatum* are increasing 14-16 mm per year near *A. saligna*, at Narrogin and Dandaragan. These are the fastest growth rates recorded for *S. spicatum* in a non-irrigated plantation. *A. saligna* may be short lived but it has the potential to be an excellent host for *S. spicatum* when planted in combination with a long lived host such as *A. acuminata*.

In natural stands at Ninghan and Goongarrie stations, planting *S. spicatum* seeds near established *Acacia* species has improved recruitment. At age three years, mean survival of *S. spicatum* was greater when planted near *A. burkittii* (a close relative of *A. acuminata*). In these semi-arid areas, *S. spicatum* seedlings are also growing well near some other *Acacia* species: *A. aneura*, *A. coolgardiensis* subsp. *coolgardiensis*, *A. hemiteles*, *A. ramulosa* and *A. tetragonophylla*. *S. spicatum* seedling growth is relatively slow in these regions with mean stem diameters increasing only 1-3 mm per year. This establishment method, combined with de-stocking, may help to improve *S. spicatum* recruitment in natural populations.

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