Sandalwood in the Pacific: A State-of-Knowledge Synthesis and Summary from the April 1990 Symposium[1]

Abstract: The economic and cultural values of sandalwood (*Santalum* spp.) are attributed to the fragrant oil found mainly in the heartwood. Sandalwoods grow naturally in a variety of climates from warm desert in Australia to subtropical regions with almost uniform rainfall in Hawai'i and New Caledonia. Growth habit varies from large shrubs to tall trees. Species that grow in relatively favorable environments appear to readily regenerate naturally. Guidelines for propagation include these: pretreating seed before sowing, treating the potting medium with fungicide, providing primary and secondary host species, and preparing the site before outplanting. Propagation from cuttings generally is not successful; direct sowing or enrichment planting can be used in some cases. All species are fire-sensitive and palatable to livestock. Spike disease afflicts sandalwood in India and Hawai'i, and a moth attacks *S. album* in Western Australia. Much of the sandalwood harvested is dead wood. Live trees are harvested selectively on the basis of size, which is related to heartwood content. The three major uses for sandalwood are carvings, incense, and oil. About 10 countries produce sandalwood for markets in France, Hong Kong, Nepal, Singapore, and Taiwan. Research is needed to fill gaps in information on various aspects of sandalwood in many of the countries where it grows.

Sandalwood is economically and culturally important to many countries around the Pacific. Some countries that were exploited for their sandalwood in the past are now looking to replant sandalwood forests or to manage natural stands as part of their forestry operations.

The symposium on Sandalwood in the Pacific highlighted the known information on sandalwood in some of the countries where there is an established industry or where sufficient interest exists to establish or revitalize such an industry.

This synthesis paper, produced by a small group of the participants at the April 1990 Symposium on Sandalwood in the Pacific, summarizes the state-of-knowledge on sandalwood. Topics covered are occurrence of sandalwood, ecology, propagation, management, harvesting, marketing, and utilization. In addition, high-priority research needs are outlined.

DISTRIBUTION

The present global distribution of *Santalum* species is listed below, with their approximate rainfall and elevational ranges (Fosberg and Sachet 1985, George 1984, Skottsberg 1930, Smith 1985, Sykes 1980, Tuyama 1939, Yuncker 1971, and Wagner and others 1990). Species reported in the cited references but absent from this list are now considered to be included within the taxa in this list. Additional information is needed to clarify the distribution of this genus.

Taxon and Authority	Rainfall Range (*mm*)	Elevation Range *(m)*	Distribution
Santalum acuminatum (R. Br.) A. DC.	—	0-500	S. Australia
Santalum album L.	300-3000[1]	0-700	India
	800-1500	0-2000	Indonesia: Timor, Sumba, Flores, and now planted in Java, Bali, and elsewhere in Asia and the Pacific
	1400-1800	0-250	Australia
Santalum austrocaledonicum Vieillard			New Caledonia[2]
var. *austrocaledonicum*	—	—	New Caledonia and Isles Loyalty[2]
	1000-1500	0-300	Vanuatu
var. *minutum* Halle	800	100-200	New Caledonia, Northest part of island[2]
var. *pilosulum* Halle	1000-2500	0-800	New Caledonia[2]
Santalum boninense (Nakai) Tuyama	1000	50-100	Ogasawara Island
Santalum ellipticum Gaudichaud	50-1300	0-1390	Hawaiian Islands
Santalum fernandezianum F. Philippi	—	—	Juan Fernandez (extinct)
Santalum freycinetianum Gaudichaud			
var. *freycinetianum*	760-3800	150-980	Moloka'i, O'ahu
var. *lanaiense* Rock	500-1000	90-900	Lana'i, Maui
var. *pyrularium* (Gray) Stemmermarm	900-3800	15-1150	Kaua'i
Santalum haleakalae Hillebrand	850-1900	1800-2590	Maui
Santalum insulare Bertero			
var. *insulare*	—	<1000	Tahiti
var. *alticola* Fosberg & Sachet	—	2000-2066	Tahiti
var. *deckeri* Fosberg & Sachet	—	250-940	Marquesas
var. *hendersonense* (F. Brown) Fosb. & Sachet	—	—	Henderson Island
var. *marchionense* (Skoots.) Skottsberg	—	300-940	Marquesas
var. *Margaretae* (F. Brown) Skottsberg	—	c.250	Austral Islands
var. *mitiaro* Sykes	—	0-10	Cook Islands

[1]Synthesized by Grahame B. Applegate, Queensland Forest Service, Atherton, Australia; James Chamberlain, Nitrogen Fixing Tree Association; Godfrey Daruhi, Department of Forestry, Port Vila, Vanuatu; Joseph L. Feigelson, Exotic Maui Woods, Inc., Haiku, Maui, Hawai'i; Lawrence Hamilton, East-West Center, Honolulu, Hawai'i; Francis H. McKinnell, Department of Conservation and Land Management, Como, West Australia; Peter E. Neil, Nepal-United Kingdom Forestry Research Project, Kathmandu, Nepal; Shobha Nath Rai, Government of Kamataka, Khawad, India; Bo Rodehn, Paia, Hawaii; Pamela C. Statham, University of Western Australia, Nedlands; and Lani Stemmermann, University of Hawai'i at Hilo, Volcano.

Taxon and Authority	Rainfall Range *(mm)*	Elevation Range *(m)*	Distribution
Santalum insulare Bertero var. *raiateense* (J. W. Moore) Fosberg & Sachet	—	200-500	Society Island (Raiatea)
var. *raiavanse* F. Brown		c.60	Austral Islands
Santalum lanceolatum R. Br.[3]	300-1300	0-700	Australia
Santalum macgregorii F. v. Mueller	1000-1500	200-1800	New Guinea
Santalum murrayanum (Mitchell) C. Gardn.	—	0-500	S.W. Australia
Santalum obtusifolium R. Br.	1400-2000	100-700	Australia
Santalum paniculatum A. Gray			
var. paniculatum	380-2550	38-2100	Hawai‘i
var. *pilgeri* (Rock) Stemmermann	760-1350	730-1970	Hawai‘i
Santalum spicatum (R. Br.) A. DC.	200-600	0-300	Australia
Santalum yasi Seeman	—	0-200	Fiji
	—	0-100	Tonga

[1]These ranges are for India. Shobha Nath Rai has suggested that these are extreme values, with most of the cultivated stands occurring between 500 and 2000 mm rainfall, and 300-600 m elevation. While there is some question whether *Santalum is* truly native to India, the conference participants consider it to be. No *Santalum is* native to Nepal, but *S. album* has been planted in Makwanpur (2000 mm rainfall and 450 m elevation) and Gorkha. It is also planted in China and elsewhere.

[2]Dr.J.F. Cherrierof Centre Technique Forestier Tropical in New Caledonia provided information through correspondence to Lawrence Hamilton in May 1990.

[3]This is the most widespread of the Australian species, found from Cape York to W. Australia and S. Australia.

ECOLOGY

Climate

Sandalwoods grow naturally in a variety of climates from warm desert in Australia, through seasonally dry monsoon climate in India, Eastern Indonesia, and Vanuatu, to subtropical climate with almost uniform rainfall in Hawai‘i and New Caledonia.

In Australia, *S. spicatum* grows where rainfall is as low as 200 mm, but is usually found only on water-gaining sites on the lower slopes and drainage lines. In India, *S. album* can be found in rainfall zones from 300 mm to 3000 mm, again generally on the lower slopes. In Vanuatu, *S. austrocaledonicum* is found in areas which have rainfall ranging from 1000 mm to 1500 mm. The Hawaiian species of *Santalum* vary markedly in their occurrence. *S. haleakalae* is found in higher elevations with cool, dry to moist climates and a rainfall of 850-1900 mm. *S.freycinetianum* grows in intermediate elevations and rainfall from 1000-3000 mm, while *S. paniculatum* and *S. ellipticum* are found in generally drier sites at lower elevations. However, these comments are tentative as there seems little definitive information on the Hawaiian species. One interesting feature of *S. paniculatum* var. *pilgeri* is that it appears to have morphological features such as thick leaves which would seem to be an adaption to drier conditions.

We have little information on the conditions under which *S. yasi* grows in Fiji, but it grows in coastal areas on some islands, predominantly in secondary forests and old village gardens.

The range of climatic conditions under which many sandalwood species grow is unknown. A particular species may be very adaptive and can tolerate and grow over a range of site conditions. However, many of these areas may not provide suitable conditions for heartwood development, the most commercially valuable part of the tree.

Soils

In India, sandalwood usually grows on free-draining red loams with a pH range of 6-6.5. Occasionally it is found on sandy textures associated with lateritic soils. It is not found on waterlogged soils. The same species in Timor grows on grey clay and red loam soils formed on coral parent material, often extremely stony, and having a pH of 8-9.

S. spicatum in Western Australia is found growing on red soils which have a high proportion of calcrete nodules where the pH is 7.5 and also on lateritic soils with a pH of 6.0. In Queensland *S. lanceolatum* grows over a wide area on "gilgai" soils, which are sandy clays with a high content of calcium carbonate and where the pH is 7.5-8.0.

In Vanuatu *S. austrocaledonicum* grows on volcanic soils on Tanna, on humic ferralitic red loams on Erromango, and on Efate and the Cumberland Peninsula (on Espiritu Santo) on shallow soils formed on raised coral reef. In New Caledonia, the same species grows on lateritic soils with a high iron content on La Grande Terre. On Isle de Pins and the Loyalty Islands, the soils are said to be derived from coral parent material.

In Hawai‘i, all species of *Santalum* grow on volcanic soils.

It would appear, then, that the genus is quite adaptable as to soil conditions under which it will grow. The only common thread is that all soils are free-draining.

Environmental Factors

Fire

All species are fire-sensitive, which is is a major problem in maintaining the species in some countries, especially Indonesia and India. In Western Australia it is less of a problem for *S. spicatum* because wildfires in the desert are infrequent, depending on a large accumulation of fuel over three or four seasons. Nevertheless, fires have occurred there and killed large areas of the species. In Queensland, fire may be a major factor affecting the local distribution of *S. lanceolatum*. In Vanuatu on the island of Aneityum, fire has played a major role in reducing the natural cover. This and overexploitation may have led to the

extinction of *S. austrocaledonicum* on the island.

Grazing

All species seem to be quite palatable to livestock—horses, sheep, rabbits, pigs, goats, and cattle—and grazing is thus another critical factor in successful establishment of sandalwood. Under some circumstances, such as in parts of Queensland, where there is no particular threat to the species, *Santalum* is reported to have been used as livestock fodder on a limited scale in times of drought.

Pests and Diseases

The spike disease, well known and very destructive in India, is also suspected to afflict the Hawaiian species. This disease shortens the internodes, reduces leaf size, kills the haustoria connections, and blocks the vascular bundles in the phloem. It also causes tip dieback, in which leaves fall and give the tree a spiked appearance. In some districts in India, spike disease affects about 2 percent of the population of sandalwood. *S. album* has also been attacked in Western Australia by a moth that girdles the stem to the depth of the cambium.

Growth Habit

Sandalwoods vary from large shrubs or small trees (*S. spicatum*) to tall trees 20 m or more in height (*S. album* in India and *S. paniculatum* in Hawai‘i).

In New Caledonia, trees of *S. austrocaledonicum* on LaGrande Terre can be twisted and deformed on exposed sites, but on more sheltered sites their form is good, with strong apical dominance and a height of about 15 m. On Vanuatu, the same species is commonly forked close to the ground and often has a shrubby habit.

S. lanceolatum in Queensland is generally an erect single-stemmed small tree, but on harsh sites it is reduced to a more shrubby form with crown break at about 1.5 m.

Sandalwoods show marked variations in morphological features such as leaf size, bark appearance and fruit size, and this variation has probably led to the confusion that existed in the taxonomy of the genus in the past and which plagues us even today.

The kernels of most species are edible. In *S. acuminatum,* the fleshy exocarp of the fruit is also edible and has been grown commercially for this purpose to some extent.

Coppicing ability varies widely among species. In Australia, *S. spicatum* does not coppice in the desert zone, but does so readily when close to the sea at Shark Bay, where the climate is much milder. *S. lanceolatum* also coppices freely, as does *S. album* in India but the latter only in the juvenile stage. *S. austrocaledonicum* in Vanuatu does not coppice at all. *S. paniculatum* on the Island of Hawaii also coppices from cut stumps.

Root suckers are found on the Australian species *S. lanceolatum, S. album* in India, and *S. paniculatum* from Hawai‘i. They are not observed in the other species. Presence of root suckers has a bearing on the ease with which one may propagate the species by vegetative means.

Host Species

In India, several species of each of the following genera may act as host species for sandalwood: *Acacia, Paraserianthes, Terminalia,* and *Pterocarpus.* Associated understory species also parasitized are *Carissa, Lantana,* and *Randia.*

In Western Australia, several species of *Acacia, Eucalyptus, Cassia, Casuarina, Eremophila, Dodonea, Mariana, Atriplex,* and *Cratystylis* are recorded as hosts. The last five genera are shrubs.

In north Queensland, *S. lanceolatum,* which is thought to be parasitic, grows in association with *Melaleuca, Eucalyptus, Acacia,* and *Excoecaria parvifolia* (gutta-percha).

An interesting difference occurs in Vanuatu, where grasses may act as hosts, along with *Acacia spirorbis* and *Hibiscus tiliaceus.* In Indonesia, a wide variety of species are recognized as sandalwood hosts, including *Pterocarpus, Acacia, Cassia, Paraserianthes, Casuarina, Sesbania,* and many more.

In New Caledonia, common hosts are *Acacia, Paraserianthes,* and *Casuarina.* Very little seems to be known of host species for the Hawaiian sandalwood species. In Fiji, *S. yasi* is associated with *H. tiliaceus, Cocos nucifera,* and *Alyx amoena.*

The opinion expressed by some, that sandalwood does not need a host at all, is usually based on observations of trees growing alone in the open. This does not necessarily indicate lack of a host. Sandalwood may be parasitizing grasses, as in Vanuatu, or other herbaceous plants. However, it is possible that older sandalwood plants may benefit from the presence of a host but may not require one.

Careful studies on several species— *S. spicatum* in Australia, *S. album* in India, and *S. austrocaledonicum* in New Caledonia—have demonstrated the absolute need for a host during the juvenile stage. It seems unlikely that the other species in the genus would differ in such a fundamental feature.

What is the value of parasitism to the *Santalum*? It can photosynthesize by itself but for some reason has developed special structures on its roots called "haustoria," which penetrate the roots of other plants, even other sandalwood plants. Research on *S. spicatum* has shown that there is direct xylem to xylem union between parasite and host. The parasite can therefore draw moisture from the host if needed. Other research on this species and on *S. album* indicates that N, P, and K may be transferred from the host to the sandalwood.

Plants in the nursery often develop a chlorosis which is cured by the application of iron chelates. In the field this chlorosis is not normally seen so it is likely that the sandalwood can also obtain iron also from its host.

Heartwood and Oil

The main reason for the economic and cultural values of sandalwood is the oil contained in its timber, mainly in the heartwood. Heartwood oil content varies widely between species and, to some degree [in chemical composition], even within

species.

S. album has the highest quality oil content, with about 6-7 percent; *S. yasi* from Fiji has about 5 percent; *S. austrocaledonicum* has 3-5 percent, depending on the source; and *S. spicatum,* 2 percent. As far as is known, only *S. album, S. yasi,* and *S. austrocaledonicum* are distilled for their oil. *S. spicatum* is now used only for incense (joss-stick) manufacture, although it has been distilled in the past. No figures are available for the heartwood oil content of *S. lanceolatum* or the Hawaiian species. *S. murrayanum* and *S. acuminatum* from Australia have no or very little oil in their heartwood and have never been exploited for this purpose. Some species such as *S. austrocaledonicum, S. album,* and *S. spicatum* also have low oil content in their sapwood.

Within the commercially used species, a considerable amount of variation in heartwood content exists from tree to tree and from stand to stand. Although much research remains to be done in this area, we can make some generalizations: (a) in relation to rainfall, heartwood contents tend to be higher for a given size tree in lower rainfall conditions (or any other situations where the tree moisture is often under stress); (b) in relation to genetic variation, evidence on *S. album* and *S. spicatum* indicates that oil content varies. There is, in fact, a tree selection program for this feature. There may also be genetic variation in the age at which heartwood development commences; (c) in relation to site quality, generally the faster the growth, the lower the heartwood content of a given size individual is, although it is difficult to separate the effect of growth rate and the indirect effect of other factors. On an individual tree basis, faster growth may well produce a lower proportion of heartwood, but on a per hectare basis faster growth may produce greater total heartwood biomass.

Oil from *S. spicatum* has an optical rotation of -8° to -3°, *S. lanceolatum* from -30° to -40°, and for *S. album* -15° to -21°. The oil of the two Australian species was formerly mixed to simulate *S. album* oil for some medicinal purposes, where the optical rotation of the oil was strongly correlated with the particular medicinal property being sought.

There is no known published information on the oil produced from *S. austrocaledonicum* or *S. yasi* nor from the Hawaiian species.

Flowering and Seeding

S. album starts flowering at age 3 years but does not produce viable seeds until age 5. It has two flowering periods each year, March and September in both India and Indonesia, and seeds mature in April and October. Both seed crops are of similar size. The seed is 6-7 mm in diameter with a thin fleshy exocarp of about 1 mm.

S. spicatum also commences flowering at age 3, with good seed from about 5 years. In the desert, however, flowering is dependent on the right combination of rainfall, so it is extremely irregular in both time and space. In the same year it is possible to find abundant seed in one area but none at all in another, due to chance rainfall events. The seed in the species is 1.3 -1.5 cm in diameter with a leathery brown exocarp which hardens with time and becomes woody.

S. austrocaledonicum flowers twice a year in April and October, with seed maturing in May and November. The November crop is generally heavier; however, any crop can be adversely affected by cyclones, which are frequent in this part of the Pacific. For *S. yasi* there is a similar flowering cycle. Detailed information on S. *lanceolatum* or any of the Hawaiian species was not available when this paper was written.

Birds apparently are the principal method of dispersal of the seed. They are attracted to the fleshy fruit and pass the kernels intact through their alimentary tract. This is certainly so for *S. album* in India and Indonesia, for *S. spicatum* in Australia, and for *S. yasi* in Fiji.

In the natural regeneration of *S. spicatum* in Western Australia, the percentage of seed which actually develops into trees is normally about 1 percent. In a very good season it can be as high as 16 percent.

Growth Rates

Detailed information on growth rates is available for the two most studied species, *S. spicatum* and *S. album*. For *S. spicatum,* the forthcoming Department of Conservation and Land Management publication "An Historical Review of Sandalwood Research in Western Australia" gives details of volume growth rates in two climatic zones—the wheatbelt and desert of Western Australia—and gives estimates of heartwood production from trees of various sizes. In the desert zone where the rainfall is 200-250 mm annually, it generally takes 100 years to grow a tree of merchantable size (127 mm diameter at 150 mm above the ground), while. in the wheatbelt, where the winter rainfall is 300-600 mm, 50 years are required to grow the same sized tree.

For *S. album* in India, under natural conditions, girth increments of 1.0-1.3 cm per year can be expected. This rate can go up to 5 cm per year in the case of cultivated trees. In terms of heartwood the rule of thumb is that after the age of 15 years, on average, every tree adds 1 kg of heartwood to its weight per year. There is a parabolic relationship between tree diameter and rate of increment. Increment is lower in young trees and old trees, while it is comparatively higher in the middle diameter classes.

According to a number trials on Erromango (Vanuatu), *S. austrocaledonicum* had a mean height increment of 1.1 m per year. The buffer rows in these trials were tended and there was no "formally" associated secondary host. Naturally growing stands have a low increment unless they are associated with a good secondary host. In New Caledonia, the same species was found to have a girth increment of 1.2-1.3 cm per year.

PROPAGATION

A reasonable amount of knowledge about the propagation of sandalwood has been accumulated for *S. album,* the Indian sandalwood, *S. spicatum* from Western Australia, and *S. austrocaledonium* from New Caledonia and Vanuatu. In the judgment of those having experience with other sandalwood species, this accumulated information seems generally applicable. What follows is more or less a set of guidelines for

propagating sandalwood. These guidelines express in general what is known, though there are still serious gaps in knowledge.

Seed Source

Seed should be obtained only a reputable source of high quality seed, (e.g., genetically selected *S. album* seed from seed production areas in southern India or recognized stands of the various species in other locations such as Hawai'i, Australia, Fiji, Indonesia, Papua New Guinea, Vanuatu.

Seed Collection and Handling

Preferably, all seed should be collected directly from trees, or if this is not possible, from below the trees soon after seed fall. This should be the case for all species of sandalwood. Seed should be depulped immediately by washing in water. Depulped seed should be treated with a disinfectant to reduce fungal and bacterial problems. The leathery exocarp of *S. spicatum* does not encourage the development of fungi, so fungicides are not required for this species. The exocarp must be removed or damaged, however, to enable the seed to germinate. Seed should then be dried under shade and stored in a cool place. Alternately, seed should be dried in an oven to 8 percent moisture content and stored in a refrigerator at about 5°C. If these storage methods are followed, germination percentage should remain good for a number of years. In New Caledonia, the Centre Technique Forestier Tropical (CTFT) specifies that seed of *S. austrocaledonicum* must be picked from the tree when mature, then depulped by rubbing against a steel mesh the same day, washed thoroughly, treated with 1 percent calcium hypochlorite for 1 minute, and dried for storage.

There is a seed domancy period of two months for *S. album* and perhaps one month for *S. austrocaledonicum.* There is no known dormancy period for *S. spicatum.*

Seed longevity appears to vary between species. In *S. album* and *S. austrocaledonicum,* it declines rapidly in the first 6 months and, if stored at ambient temperatures, declines to a very low level by 18 months. Seed life is prolonged by cold storage, although precise data are lacking.

The effect of time on seed viability has been studied in *S. spicatum.* Fresh seed has a germination percentage of 84 percent and this declines steadily to as low as 20 percent after 9 years at ambient temperatures. The optimum storage method for this species is cold storage at 4°C over silica gel. Seed in this environment maintains a germination rate of 52 percent after 9 years.

Nursery Techniques

Germination and Propagation

Seed germination is affected by temperature. At CTFT it has been shown that the optimum temperature for germination of *S. austrocaledonicum* is 25° -27°C. This temperature range was also optimum for *S. album* in research at Curtin University in Perth, Western Australia. Seed of all sandalwood species should be pre-treated before sowing. Germination of most species is slow and erratic, but can be speeded up by presoaking in water or, better still, in 0.05 percent gibberellic acid (GA). Some interesting work in India has indicated that sandalwood leaves themselves have high levels of GA during the flowering cycle, and an infusion of sandalwood leaves contains sufficient GA to have a stimulating effect on seed germination. Another method of enhancing germination is manual scarification with a file or saw to remove the seed coat or to nick it, and then soaking the seed in water at ambient temperature before sowing. This pretreatment should speed up germination rates, increase germination percentage, and ensure that seed germination is more uniform.

Germination generally does not begin for 2 weeks after sowing and may be spread over several months. A very efficient technique has been developed by CTFT which involves presoaking with GA, then germinating in vermiculite beds bottom heated to maintain a temperature of 25°C, transferring out the germinated seeds into plastic tubes, to which a primary host is later added. In India and Australia, *S. album* seedlings have been shown to be very susceptible to fungal attack, and regular treatment of seedlings with fungicide is necessary. In India, nematodes are also a problem, and a nematicide must be used in the seed b: d and the potting mix.

The aim is to produce strong and vigorous seedlings of 30-45 cm, which have some lignification of the lower stem. Experience has shown that such stock survives best in the generally harsh environments where they are planted. This should be considered when planning the nursery program so that sufficient time is available to raise seedlings of appropriate size.

The following mediums have been successfully used for germination:

- Beds of a 1:3 sand to soil mixture that have been treated with nematicides and fungicides.
- A mix of sterile peat moss, vermiculite, and fine cinders. However, vermiculite alone or a similar medium might be preferable.

Beds should be kept at an optimum temperature of 28°-30°C. Germinants should be shaded (50 percent) and protected from extremes of temperature, frost, and wind. They should not be over- or under-watered. The sandalwood seedlings should be transferred into large plastic pots (e.g., 13 x 30 cm) at the four-leaf stage. Fertilizer should not be required if a good potting mixture is used.

Chelated iron has sometimes been found to be a useful additive to the potting mix. The mixture also should be treated with fungicides and nematicides. Again, the transplants should be protected from extremes of weather, not over- or under-watered, and kept in partial shade (30-50 percent).

Primary Host Species

When sandalwood seedlings are transplanted into plastic pots, seed or seedlings of a primary host plant should also be transplanted into the pots. Such host plants could include these: *Acacia* spp., *Alternathera* spp., *Amaranthus* spp., *Breynia cerrua, Cajanus cajan,* and *Capsicum* spp. The criterion for

selecting a host plant should be that the host should "assist" the sandalwood and not compete with it or physically obstruct it from normal growth. Species that develop a thick, fibrous, and succulent root system with a low growth habit are preferable. These primary host species should be able to take pruning to control competition and be easy to propagate.

Vegetative Propagation

Cuttings generally are not a successful method of propagating sandalwood, but tissue culturing *S. album* has been successful in India and Western Australia. After a considerable amount of research carried out in Western Australia, it was concluded that it is not possible to use tissue culture techniques to propagate *S. spicatum.* Cleft grafting of *S. album* has had up to a 60 percent success rate.

Planting

Site Selection

Seedlings should be outplanted at the start of the rainy season. For *S. album,* the ideal planting site would be at an elevation of 700-1200 mm, with an annual rainfall of 600-1600 mm. Temperatures should be in the range of an annual minimum of 10°C and a maximum of 35°C. For best growth, soils should be fairly moist, fertile iron-rich clays. Plantations have been successfully established on more adverse sites. Waterlogged or saline soils should be avoided. For many other sandalwood species, site requirements still need to be defined.

Site Preparation

General forestry practices involving site cultivation are recommended for plantations of sandalwood. No specific site preparation requirements for *S. album* are apparent to date.

The planting site should be fenced to reduce the possibility of grazing damage. Precautions should be taken against fire.

Regular weeding should be carried out in the first few months following establishment, particularly in areas of vigorous grass competition.

Secondary Host Species and Plantation Layout

Secondary hosts should be established on the plantation site before to planting the sandalwood. In New Caledonia, secondary host species are planted in the year before outplanting *S. austrocalendonicum.* This year allows the roots of the host species to develop sufficiently to allow good host-parasite contact.

The hosts could be of a very wide range of species, with large enough crowns to afford some protection, and preferably would be indigenous. Sandalwood seedlings are occasionally planted very close to their host; otherwise, hosts are planted in alternate or adjacent rows. Hosts should not be further than 2.2 m from the sandalwood, or its growth is significantly reduced.

Desirable features of a secondary host are moderate vigor or tolerance to lopping (e.g., *Paraserianthes falcataria*), a thin canopy, and some other use for local communities (e.g., fuelwood, fodder, or fruit). Sandalwood growth appears to be better with a nitrogen-fixing legume host than with non-legumes. The secondary host should also be reasonably long-lived. In places where grazing animals are a problem, host species with thorns are an advantage. In the desert regions of Western Australia, *Mariana polystyrgia*, a thorny legume which grows to a meter in height, effectively protects *S. spicatum* from sheep grazing. *S. album* is given the same protection by *Acacia nilotica* in India.

Combinations of sandalwood and secondary hosts that have proven successful in the past include these:

- *S. album* with *Casuarina equisetifolia, Melia dubia, Pongamia pinnata*, *Terminalia* spp., and *Wrightia tinctoria*.
- *S. austrocaledonicum* with *Acacia spirorbis* and *Paraserianthes falcataria.*
- *S. yasi* with *Hibiscus tiliaceus* and *Cocos nucifera.*
- *S. spicatum* with *Acacia aneura.*

Spacing and layout in the plantation with respect to sandalwood and its secondary host will be dependent on the growth habit and potential end product of the host species. Fast-growing species with a wide spreading lateral root system can be grown further away from sandalwood than other species whose roots are more confined.

Two different planting spacings have been reported. In India, plantations are established with alternative rows of *S. album* and host trees. *S. album* rows are 5-6 meters apart while the hosts are interplanted at the same spacing. In New Caledonia, a more diagonal planting method is used, where the sandalwood is planted on 4 by 4 meter grid and the host is planted in the center of the square. In other situations, it may be more appropriate to plant the host species and the sandalwood in the same rows.

Direct Sowing

In a number of countries, sandalwood seed is in short supply, either because of past overexploitation or because of climatic factors, such as cyclones which have damaged seed-producing trees. In this situation, direct sowing is unlikely to be a viable method of plantation establishment.

However, in countries with a plentiful supply of seed, the following steps should be followed:

Seed should be dibbled into the ground in areas which already have potential hosts either naturally present or artifically established. Broadcasting of seed is **not** recommended.

In situations where sandalwood is sown directly in existing natural scrub, spacing and layout will depend upon the configuration of the natural species. Some lopping and pruning of the natural vegetation may be necessary before sowing to avoid excess shading.

In situations where artificially planted hosts have been established before direct sowing of sandalwood, layout and spacing should depend on the growth habit and longevity of the host plant, as with out-planted seedlings of sandalwood.

Enrichment Planting

In certain situations, sandalwood seedlings can be directly planted into areas that already have a natural secondary host species present. Examples of these could be the following:

- *Acacia spirorbis* (*S. austrocaledonicum*) in New Caledonia and Vanuatu.
- *Acacia koa* (*S. ellipticum*) in Hawai'i.
- *Acacia catechu, Dalbergia sissoo* and in dry deciduous forest *(S. album)* in India.

Excoecaria parvifolia and *Melaleuca acacioides* (*S. lanceolatum*) in North Queensland, Australia.

Species Selection

Research into the most suitable secondary host for a given sandalwood species and country should be carried out. Only by using the most suitable host will optimum results be obtained. Many of these host species likely will be leguminous and have the ability to fix nitrogen. In countries such as India and Nepal, it would be appropriate to utilize species that could produce fodder or fuelwood to meet local needs. In other countries, the secondary hosts could well be species that produce a valuable product in their own right, e.g., timber, cabinet quality wood, or edible material.

MANAGEMENT

Protection

Fire

Sandalwood is susceptible to fire. Direct or even indirect contact with fire will result in the mortality of even large trees. In *S. spicatum,* coppice from the base of the fire-killed stem has been observed, but it has not survived beyond 2 years. Other species in more favorable climates may well be able to produce viable coppice. A fire that affects only part of the stem may kill part of the cambium and create an entry point for decay of the sapwood.

Grazing

As noted elsewhere, sandalwood foliage is palatable to grazing animals such as rabbits, sheep, goats, cattle, pigs, horses, and camels. In Australia, kangaroos are also occasionally a problem. It is essential to exclude grazing animals from stands containing small trees, as grazing will substantially reduce their growth and can, as in Western Australia, virtually preclude any regeneration.

Exclusion of grazing may well, on drier sites, bring with it a requirement for more weed control to enable the sandalwood seedlings to survive the first dry season. In native stands, wild animal populations may need to be controlled for a period to achieve adequate regeneration.

Illegal Cutting

Due to the high value of sandalwood logs relative to average incomes in most areas where they are found, illegal harvesting is often a severe management problem, to the extent that it can seriously threaten the long-term future of the species. Active management of the remaining stands of sandalwood, wherever they occur, is essential. This implies the enforcement of regulations applying to their conservation and of severe harvesting control procedures. Where such regulations and procedures are lacking, they should be developed urgently in view of the apparent threat to survival of the germ plasm of some provenances. (See section on Conservation of Germ Plasm).

Natural Stands

Harvesting Techniques

Sandalwood growing in natural stands is harvested by taking the whole tree down to quite small branches. In *S. album, S. spicatum,* and *S. austrocaledonicum,* the stump and larger roots are also used, as they contain the best quality wood and highest oil content. Either live or dead trees may be used, as the wood retains its scent for many years after the death of the tree.

Although heartwood is the most valuable portion of the tree, markets do exist for the sapwood of the three species mentioned above, since their sapwood contains some oil.

In most areas where sandalwood harvesting regularly takes place, a well developed product grading system exists. Larger butt logs suitable for carving rate the highest quality, while chipped branches and even sawdust are assigned lower grades.

Trees are selected for harvest on the basis of size, which is related to heartwood content. The ratio of heartwood to sapwood varies considerably between species and even within species (especially the Hawaiian sandalwoods).

In north Queensland, trees of *S. lanceolatum* are considered harvestable if the diameter is greater than 12 cm d.b.h. outside bark and when the sapwood is less than 1/6 the diameter of the tree at 1.3 m above the ground. Measurements are taken by the cutters by chopping into the stem into the heartwood boundary. This avoids unnecessary fellings of trees that cannot be utilized. In Western Australia, there is a simple minimum cutting system: only live trees with a diameter greater than 12.7 cm at 15 cm above the ground can be harvested. This height is a reflection of the frequent multi-stemmed habit of this species. In Queensland, sandalwood branches are utilized down to a heartwood diameter of 3 cm, and down to 1 cm in *S. album* in India and *S. spicatum* in Western Australia.

In both India and Western Australia, dead trees of any size may be taken, and in some parts of both of these areas, dead trees form a major proportion of the harvest.

Natural Regeneration

Species that grow in relatively favorable environments appear to readily regenerate naturally. Regeneration of the Australian

species is much more uncertain and is dependent on having a series of good seasons in the arid zones in which they grow.

Birds are an effective dispersal agent for sandalwood seeds as they are attracted to the succulent exocarp. Consequently, regeneration is often found beneath trees is which birds roost. In Western Australia, the large seeds of *S. spicatum* are dispersed by the large, flightless emu.

The ability of a species to coppice or develop root suckers also has implications for management. If coppicing is to be used, either as the main form of regeneration or as a supplement to seedling regeneration, the harvesting techniques should preclude the removal of stumps. If the species does not produce root suckers readily, then it is feasible to utilize the stump. On steep land this may be undesirable because of potential soil erosion problems.

Plantations

Relatively little experience with managing sandalwood plantations has been accumulated, except with *S. album* in India and *S. austrocalodonicum* in New Caledonia. Periodic cutting back of the secondary host is necessary, as is livestock or wildlife exclusion when trees are small.

Little is known about the effect of fertilizers on the growth of sandalwood, apart from research in India that indicates an adverse effect of the application of boron. In Australia, chlorosis of *S. album* seedlings has been remedied by the application of iron chelates.

Conservation of Germ Plasm

Given the generally depleted state of sandalwood populations in most countries (except India and Australia), resource management agencies in countries with sandalwood should do the following to identify and protect the remaining higher quality stands as a future seed source:

(1) Identify and"formalize" seed stands of various species and provenances. These areas should be set aside as protected seed reserves.

(2) Identify "elite" trees with high oil content, high ratio of heartwood to sapwood, and vigor. Investigations will be needed to determine genetic "superiority" versus phenotypic variation due to site-tree interactions. For example, are oil content and heartwood to sap ratio dependent on site alone or are genetic factors involved?

(3) Provide seed to other countries for species and provenance testing. All seed tested should be fully documented for source, latitude, altitude, rainfall and temperature information, date of collection, method of collection, and handling and storage.

(4) In areas where the indigenous sandalwood is threatened by overexploitation or damaging environmental factors, seed should be collected and ex situ seed stands established.

HARVESTING, MARKETING, AND UTILIZATION OF SANDALWOOD AND OIL

Harvesting

Much of the sandalwood harvested today is dead wood, i.e., either standing or fallen trees. Buyers in many ways prefer deadwood because it contains less moisture and thus provides more volume per tonne. Deadwood is also easier to clean than greenwood since sapwood is already decaying. Greenwood is defined as wood taken from standing trees with green leaves. In some cases, a load of deadwood commands higher prices than those currently received for a mix of greenwood and dead wood. However, the mix is sometimes produced since harvesting deadwood is generally more costly than harvesting greenwood because of the labor intensive process required to find dead trees.

To date, sandalwood has not been managed on a sustained yield basis, and over-mature, standing trees show signs of decline with dead branches or rot. The value of these Trees is thus decreasing, although in many cases they will yield sufficient heartwood to be commercially viable.

Harvesting mature trees should be very selective. Tests should be taken to determine the ratio of heartwood to sapwood, and this can be done quite easily by using increment borers or portable drills. Care should be taken to retain at least some of the best mature stems for seed production.

At present, many of these criteria are not understood and therefore not practiced. Hopefully current research and communication will lead to better management of this resource.

While most sandalwood is harvested using simple equipment (often a chain saw and a truck), the high value of good material can make it financially feasible to use a higher level of technology. For remote areas and high value material, helicopters have been used for assembling material.

Marketing and Utilization

Raw sandalwood has three major uses: carving, incense, and oil. Quality specifications, and hence prices for raw sandalwood, vary considerably between species in each of these categories, so it is best to look at each category separately, even though the markets for each use are not strictly differentiated *(Appendix A)*.

Carvings

Carvings utilize the best quality sandalwood. Finished products range from large statues of deities to animals, boxes, beads, and other handicrafts. Fans are also made in considerable quantities both by hand and machine. Logs selected for carving usually fall into two major grades. Grade specifications differ for each country (or perhaps between buyers), but in general logs selected for carving must be 1 m (3 ft) in length, defect free (i.e., no cracks, rot, or other blemishes), and have a heartwood diameter of at least 12.5 cm (5 in). Distinctions between grades are made on the basis of heartwood diameter, and examples of grade specifications for three production regions are given in *Appendix B*.

Major buyers of sandalwood logs for carving are from Hong Kong and Taiwan. They in turn distribute to China, Japan, and Singapore. India produces the best sandalwood logs for carving due to the fine grain of the *S. album,* but utilizes it all domestically. Export of *S. album* logs is prohibited. Major exporters of top quality logs are Hawai'i, Fiji, Indonesia, and Western Australia. Vanuatu, a producer of quality sandalwood, currently has a 5-year moratorium on all cutting and export. Tonga has also been a producer of quality logs, but its prgsent status is unknown. Papua New Guinea also supplies logs, but they are considered lower quality. Many logs for carving are sold clean of sapwood, though buyers prefer Grade A logs with sapwood in order to prevent cracking and splitting. The ends of logs for carving are usually sealed with a compound to prevent cracking and oil loss. Logs should have an oil content of at least 2 percent to facilitate carving.

Incense

The market for incense, an essential component of Hindu and Buddhist religions, is large and increasing. It has also been increasing in the Western world over the last two decades. Singapore and Taiwan are the two major incense (joss-stick) manufacturing sites. Mills reduce the wood into powder, which is either attached to bamboo slivers with wood resin or simply compacted into sticks. The latter are mainly for the Japanese and Saudi Arabian markets.

The incense market absorbs mostly C grade logs, which are either below minimum length or have smaller heartwood diameters. Many buyers prefer to purchase logs and do their own powdering to ensure quality. They also take roots and butts, as well as wood that has been chipped or powdered in the country of origin. Wood sold as chips and powder command prices of around $2,300 U.S. per tonne, and Singapore absorbs most of this product. The roots and butts of *S. spicatum* and *S. album* have a high oil content and are valued for incense, bringing at this writing some $7,000 U.S. per tonne. Prices of logs and pieces for incense vary from $2,000 to $5,000 U.S. per tonne, depending on quality, although prices higher than this may be obtained for *S. album* and *S. spicatum.* Australia supplies most of the world incense market at present. Although India allows some powder and chip export, quantities are limited. Since the sapwood of *S. spicatum* has a thin sap and a low oil content, the logs do not need to be de-sapped before use and the whole log can be chipped and then powdered.

Oil

Sandalwood oil, obtained from the heartwood of the stem and the root of the sandalwood tree, is one of the most valuable oils in the world. It is a colorless or pale yellow liquid with a sweet and persistent woody odor, containing not less than 90 percent free alcohols by weight. The alcohols are principally of the sesquiterpene group and are referred to collectively as santalol. The major odiferous components are a-santalol and b-santalol, while a-santalene, b-santelene and santalyl acetate also contribute in a minor way to the overall odor character of the oil.

Distillation and Extraction—The water distillation method has been carried out in India in small units of production located principally on the West Coast, along the periphery of the Mysore Plateau, and at Kannuj in North India, since ancient times. The heartwood powder is soaked in water in a copper vessel which is then heated on an open fire. The vapors from the still are conducted through a bamboo or copper pipe to receivers kept in cold water. The floating oil in the distillate is mechanically ladled off, and the oil is refined further by filtration and decantation. In this way, yields as high as 4.5 percent are obtained. The oil obtained by this method is claimed to possess a finer odor than the one produced in modern steam stills.

More than 90 percent of the present production of sandal oil in India comes from four government factories employing the modem steam distillation method. The important distilleries are located in Karnataka, Andha Pradesh, Tamil Nadu, and Mahrashtra. These factories each utilize 1.50 tonnes of wood daily, which yield 90 kilograms of oil. The export price of the oil starts at $1,500 U.S. per kilogram and may go beyond this depending upon quality. The final product is a yellow oil, optically clear, possessing the characteristic sandalwood odor, and conforming to pharmacopoeial standards. Average yield of oil ranges between 4.50 and 6.25 percent. Two distillation plants are located on Timor and in New Caledonia.

Production of oil by solvent extraction is possible; however, the product obtained by this method is not preferred by the perfume industry.

Uses—Sandalwood oil is highly prized as a raw material in perfumery, because of its nonvarying composition, fixative properties, and—most importantly—its sweet, warm, spicy, and tenacious fragrance. Sandalwood oils are also used in soaps, face creams, and toilet powder.

Apart from being a supremely satisfying source of the fragrance, sandalwood oil has many medicinal uses. The oil is used as an antiseptic, an antiscabietic, a diuretic, and for the treatment of gonorrhea, bronchitis, and bladder infections. However, its use as a base of fragrance has far outweighed its use in medicine.

Most sandalwood oil is exported to perfumeries in France and New York.

RESEARCH NEEDS

Information is still lacking on many aspects of sandalwood from many of the countries where it grows, and the following research needs should be given a high priority:

(1) Investigating the use of extracts from sandalwood leaves and other substances to improve germination percentages and to speed up the germination process.

(2) Developing techniques to improve the germination of species from Papua New Guinea, Fiji, Hawai'i, and other Pacific island countries.

(3) For some species, such as those from Hawai'i and Fiji, for which little is known about potential primary hosts, identifying suitable indigenous host plants and nutritional requirements.

(4) Determining the optimum spacing and layout of sandalwood and secondary hosts depending on the growth habits of the host species and its end use.

(5) Identifying the nature, quality, and quantity of the oils of those sandalwood species for which that information is unavailable.

(6) Developing reliable resource information for existing natural stands to support management for conservation of the species.

(7) Developing yield tables for different sites and species in plantations and natural forests.

(8) Defining the effects of different land use practices on sandalwood stand dynamics, growth, and distribution.

(9) Establish an information network on individuals and institutions that carry out research or management of sandalwood.

APPENDIX A

Distribution and Marketing of Sandalwood Logs 1989-1990

Producing Country	Species	Log Exports tonnes per annum (approx)	Log Import Country
India	*S. album*	Prohibited, except small quantities	Nepal
Indonesia	*S. album*	?	Hong Kong/ Taiwan
Australia	*S. lanceolatum* *S spicatum*	500 1,800+	Taiwan Taiwan, Singapore, Hong Kong
Hawai'i	*S. ellipticum*	300+	Hong Kong, Taiwan
Fiji	S. *yasi/album*	250	Hong Kong
Tonga	*S. yasi*	40	Hong Kong, Taiwan, Singapore
Vanuatu	*S. austrocaledonicum*	5 yr moratorium since 1987	Hong Kong, Taiwan, Singapore
New Caledonia	*S. austrocaledonicum*	None (only oil)	France
Papua New Guinea	*S. macgregorii*	250+	Hong Kong, Taiwan, Singapore
Marquesas[1]	*S. insulare*		?
	S marchionense		?
Solomon Islands[1]	?		Taiwan+?

[1] Not known if currently producing.

APPENDIX B

Grades and Approximate Prices Per Tonne (Metric) for Three Major Sandalwood Production Areas

India—*S. album*

Average selling price (green and dead), assuming 90 percent cleaned

1987	US$4,590 /tonne	(78,000 rupees)
1990	US$9,410 /tonne	(160,000 rupees)

Wood

A-grade logs 15 cm (6 in.) minimum heartwood, minimum 2 foot length:
Average price: US$ 10,000 tonne

B-grade logs under 15 cm (6 in.) heartwood, butts, and roots:
Average price: US$7,060 /tonne

C-grade defective A and B grade logs & pieces:
Average price: US$4,700 /tonne

Chips and Powder

Average price: US$2,300 /tonne

Oil

Oil content is a crucial determinant of wood quality. Oil content of *S. album* is between 2.8 - 6.5 percent for the quantity of oil, differs between trees, and is difficult to determine beforehand.

Price for oil (government factories) is $1,500/kilo (export price)
$ 470/kilo (internal price)

Australia

Western Australia—*S. spicatum*

Logs, green and dead, sapwood on.

Grade: Single grade, min. length 1 m (3 ft)
Average Price: US$4,260 /tonne ($AUD5,700 /tonne)

Grade: Roots & Butts
Average Price: $5,600 US/tonne ($7,500 AUD/tonne)
(Chips and powder; prices unknown)

Queensland—S. *lanceolatum*

Logs, green and dead, all 90 percent cleaned of sapwood

Grade 1. Min. length 1 m (3 ft), minimum heartwood diameter 7.5 cm (3 in.)
Average price: US$2,000/tonne (AUD$2,500 /tonne)

Grade 2. Under 1 m (3 ft) length, heartwood diameter less than 7.5 cm (3 in.) (billets)
Average price: US$1,600 /tonne (AUD$2000 */tonne)*

Hawai'i

S. ellipticum logs, green and dead, 90 percent cleaned

Grade A: 10 in. heartwood diameter and minimum length 3 ft, defect free
Average price: US$ 10,000 /tonne

Grade B: 5-10 in. heartwood diameter, minimum length 3 ft defect free
Average price: US$4,500 /tonne

Grade C: 2-5 in. heartwood diameter, minimum length 2 ft 5 in.
Average price: US$3,400 US/tonne

Wood under 2 in. must be solid heart and sap free, and is included in grade C as also are roots and butts.

Note: Grade A buyers prefer sapwood on the logs to prevent cracks and splits, and price per *tonne* is adjusted accordingly.

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