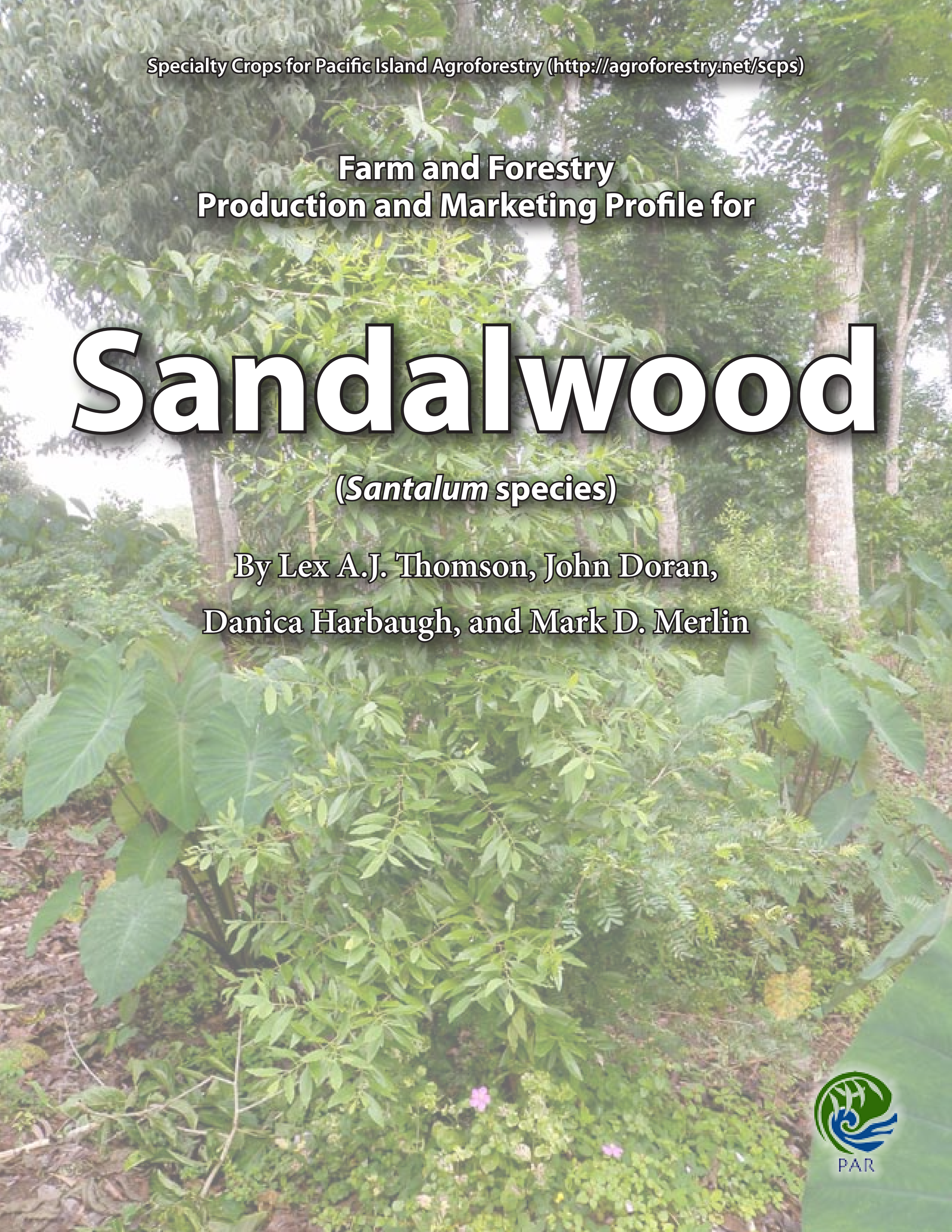

Specialty Crops for Pacific Island Agroforestry (http://agroforestry.net/scps)

Farm and Forestry Production and Marketing Profile for

Sandalwood

(*Santalum* species)

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PAR

USES AND PRODUCTS

Wood from the Hawaiian and South Pacific sandalwoods traditionally had a diversity of uses such as carving, medicine, insect repellent when burnt (St. John 1947), and fuel (Wagner 1986). The grated wood was used to a limited extent to scent coconut oil (for application to the hair and body) and cultural artifacts such as tapa cloth (Krauss 1993; Kepler 1985). In Hawai'i, sandalwoods were used to make musical instruments such as the musical bow (*'ūkēkē*) and to produce *hoe* (paddles) as part of traditional canoe construction (Buck 1964; Krauss 1993). The highest-value wood from the sandalwoods is used for carving (i.e., religious statues and objects, handicrafts, art, and decorative furniture). For most purposes larger basal pieces and main roots are preferred due to their high oil content and better oil profiles, being generally richer in santalols.

Traditional medicinal uses of sandalwood are generally not well documented. In Samoa, a decoction of sandalwood and *Homolanthus* leaves is taken to treat elephantiasis or lymphatic filariasis. The fragrant heartwood (*'la'au 'ala*) of Hawaiian sandalwood trees (collectively known as *'iliahi*) was used in medicines. A shampoo made from a leaf infusion was used for curing dandruff and eliminating head lice. A drink made from finely ground, powdered heartwood, mixed with other plants, followed by laxative was used in curing diseases of both male and female sex organs (Krauss 1993). However, apart from carving, sandalwood is rarely used in many of these traditional ways nowadays because of its scarcity and economic value.

Commercial exploitation of sandalwood commenced in the Hawaiian and some South Pacific islands during the late 18th and early 19th centuries when the aromatic lower trunks and rootstock of native *Santalum* species were harvested in great quantity and shipped to China. There they were used to make incense, fine furniture, and other products. The extensive and often exploitative sandalwood trade in Hawai'i was an early economic activity that adversely affected both the natural environment and human health. Indeed, this activity represented an early shift from subsistence to commercial economy in Hawai'i that was to have far-reaching and long-lasting effects in the islands (Shineberg 1967).

Heartwood from Pacific sandalwoods yields an aromatic essential oil that is widely valued and is second only to carving wood in economic value per unit weight of wood. The heartwood oil is extracted by steam distillation and is used for cosmetics, scenting of soaps, perfumery, aromatherapy, and medicinal purposes. The oil content of heartwood and oil quality varies considerably among species, individual trees, and location within the tree. Oil content is typically in the range of 3–7% for basal stem and large root sections.

Both *Santalum austrocaledonicum* (native to New Caledonia and Vanuatu) and *S. yasi* (native to Fiji and Tonga) produce

Left: Nine-year-old *Santalum austrocaledonicum* tree on Mangaia, Cook Islands. Middle: Distilled sandalwood oil produced in factory on Maré Island, Loyalty Group, New Caledonia. Right: Carving logs of *Santalum austrocaledonicum*, ready for shipment from a commercial venture in Vanuatu.

A ship's hull template called *lua na moku ʻiliahi* (sandalwood measuring pit) located adjacent to the Maunahui Forest Reserve on Molokaʻi, Hawaiʻi. It was used to measure an amount of sandalwood that would fit in a ship's hull. When the template was filled, the logs were carried down the mountain to a waiting ship.

highly prized santalol-rich heartwood oils. The santalol-rich oils within these species are similar in chemical composition to and, in some individual trees, are equal in quality to the well known *S. album* from India and Indonesia. The heartwood of *S. yasi* was a major export during the early 1800s, and the sandalwood trade was one of the first commercial attractions drawing Europeans to the South Pacific. Sandalwood from *S. yasi* is still exported to a limited extent from Fiji and Tonga. This trade experiences short-lived boom periods associated with a buildup of sandalwood stocks, such as during the mid-late 1980s in Fiji when a ban on commercial exploitation was lifted, and again in Fiji and Tonga in the mid-2000s. *Santalum austrocaledonicum* was heavily exploited over about three decades in the middle of the 1800s in New Caledonia and Vanuatu, and has since been utilized periodically. Carvings, essential oil, and incense production, listed in order of highest to lowest value, are the three major present-day wood uses of *S. austrocaledonicum.*

BOTANICAL DESCRIPTION

Preferred scientific names

Melanesian sandalwoods

Santalum austrocaledonicum Viell.
var. *austrocaledonicum*
var. *minutum* N.Hallé
var. *pilosulum* N.Hallé
Santalum yasi Seem.

Hawaiian sandalwoods

Santalum ellipticum Gaudich.
Santalum freycinetianum Gaudich.
Santalum haleakalae Hillebr. var. *haleakalae*
Santalum haleakalae Hillebr. var. *lanaiense* (Rock) Harbaugh
Santalum involutum H.St.John
Santalum paniculatum Hook. & Arnott
Santalum pyrularium A.Gray

Family

Santalaceae

Common names

Melanesian sandalwoods

Santalum austrocaledonicum: *sandalwud* (Vanuatu: Bislama)
Santalum yasi: *ahi* (Tonga); *yasi* (Fiji); *asi manogi* (Samoa)

Hawaiian sandalwoods

Santalum ellipticum: *ʻiliahialoʻe* (Hawaiʻi)
Santalum freycinetianum, *S. haleakalae*, *S. involutum, S. paniculatum, S. pyrularium*: *ʻiliahi, ʻaʻahi, ʻaoa, lāʻau ʻala, wahie ʻala* (Hawaiʻi)

Other generic common names

bois de santal, santal (French)
sándalo (Spanish)
sandalwood (English)

Brief botanical description

Santalum austrocaledonicum

***Habit and size*:** A shrub or a small tree typically 5–12 m (16–40 ft) tall and 4–8 m (13–26 ft) in crown width. The maximum tree dimension is about 15 m (50 ft) tall and 10 m (33 ft) in crown width. Maximum bole diameter at breast height is 40–50 cm (16–20 in).

***Form*:** Shrub to small tree typically with a short, crooked bole and spreading crown in open situations. In forest and sheltered situations, the bole may be straight for more than half the total height. In older specimens the crown is light, straggly, and with drooping branches. The bark is smooth to rough, slightly longitudinally fissured or reticulated, which can be more pronounced with age, (greyish or reddish brown, mottled with patches of lichen).

***Leaves*:** The foliage shows wide variation. Leaves are opposite, usually in one plane, frequently decussate on erect new growth, simple, entire, glabrous, dark green, and shiny on top and dull light green to glaucous underneath. The shape of the leaf is initially long and thin (5–9 by 0.5 cm [2–3.5 by 0.2 in]) in seedlings and young plants to about 3 years of age, becoming shorter and broader in older plants. Mature leaves are narrowly elliptic, but maybe ovate, lanceolate, or obovate, (3–)4–6(–8) cm × (1–)1.5–2.5(–4.5) cm ([1.2–]1.6–2.4[–3.1] in × [0.4–]0.6–1[–1.8] in), with 6 to 15 pairs of barely visible secondary nerves tapering equally to the base and blunt tip. Variety *minutum* has smaller, more glaucous, bluish-green leaves, about 2 by 0.8 cm (0.8 by 0.3 in).

***Flowers*:** The small flowers are clustered in terminal or axillary panicles about 4.5 cm (1.8 in) long. The bell-shaped flowers open to about 5 mm (0.2 in) across and have parts typically in fours. Buds and newly opened flowers have greenish white to cream-colored corolla lobes, shorter, dark yellow disk lobes alternate with the corolla lobes. The anthers are yellow and the style and stigmas are cream/pale yellow.

***Fruit*:** The fruit is a sub-globose or ellipsoid, one-seeded drupe (7–20 mm [0.3–0.8 in] long by 10–15 mm [0.4–0.6 in] diameter), green and firm, ripening red, and turning purplish black and thinly fleshy when mature. Fruits have four longitudinal ridges and a square calyx scar at the apex. Fruits from Aniwa (Vanuatu) are much larger (20 × 15 mm [0.8 × 0.6 in]) than those from the Loyalty Islands (15 × 12 mm [0.6 × 0.5 in]).

***Seed*:** The kernel consists of a hard (woody), smooth or slightly rough, light-colored endocarp enclosing a single seed. Within var. *austrocaledonicum* the seeds from the Loyalty Islands are much bigger (2,400 per kg [1,100 seeds/lb]) than those from the Isle of Pines (6,000 per kg [2,700 seeds/lb]), while those from Vanuatu are intermediate (3,300–4,500 per kg [1,500 seeds/lb]). Variety *pilosulum* has smaller seeds (8,400 per kg [3,800 seeds/lb]).

Santalum yasi

***Habit and size*:** Mature specimens typically grow to about 8–10 m (26–33 ft) tall by 8–12 m (26–40 ft) in crown width, maximally reaching 15 m (50 ft) tall by 13 m (43 ft) in crown width. Maximum bole diameter at breast height is 40–50 cm (16–20 in).

***Form*:** Shrub to small tree typically with a short, crooked bole and spreading crown in open situations. In forest and sheltered situations, the bole may be straight for more than half the total height. In older specimens the crown is light, straggly, and with drooping branches. The bark is smooth to rough, slightly longitudinally fissured or reticulated, which can be more pronounced with age, (greyish or reddish brown, mottled with patches of lichen).

***Leaves*:** Seedlings have very slender, near-linear leaves. Leaves are simple, opposite, narrow to broadly lanceolate, shiny, and typically 6–7 cm × 1.5–2 cm (2.4–2.8 in × 0.6–0.8 in). There is considerable variation in foliage size; adjacent plants have been observed to range from 5 cm × 1 cm (2 in × 0.4 in) to 8 cm × 2.5 cm (3.1 in × 1 in). The foliage is light to dark green, but plants growing in the open with few host trees available may have a yellowish-green appearance.

***Flowers*:** The small flowers are clustered in terminal or axillary panicles about 4.5 cm (1.8 in) long. The bell-shaped flowers open to about 5 mm (0.2 in) across and have parts typically in fours. Buds and newly opened flowers have greenish white to cream-colored corolla lobes, turning light pink, through pink to dark red at maturity. Shorter, dark yellow disk lobes alternate with the corolla lobes. The anthers are yellow and red-tinged and the style and stigmas are cream/pale yellow.

***Fruit*:** The fruit is a one-seeded, ellipsoid drupe, ca. 12 mm (0.47 in) long by 11 mm (0.43 in) diameter with a small, round calyx scar (about 2 mm [0.08 in] diameter) at the apex, enclosing a rather stout, cone-shaped point. Immature fruits are light green, turning reddish-purple, and finally dark purple or black at full maturity.

***Seed*:** The kernel consists of a hard (woody), smooth or slightly rough, light-colored endocarp enclosing a single seed. The seeds are 9–11 mm by 6–7 mm (0.35–0.43 in by 0.24–0.28 in) with approximately 6,000–7,000 per kg (2,700–3,200 seeds/lb).

Hawaiian sandalwoods

Santalum ellipticum

***Habit and size*:** A sprawling shrub to small tree, typically 1–5 m (3.3–16 ft) tall and 1–3 m (3.3–10 ft) in canopy diameter, maximally reaching 12 m (39 ft) tall and 5 m (16 ft) in canopy diameter, and bole diameter at breast height (dbh) of 30 cm (12 in). This species is extremely variable in vegetative and floral characters (Wagner et al. 1999; Little and Skolmen 1989).

***Leaves*:** Leaves are 2.5–6.1 cm (1–2.4 in) long and 1.7–4 cm (0.67–1.6 in) wide, with petioles up to 15 mm (0.6 in) long. They are elliptic to orbicular, ovate, or obovate in shape and leathery to succulent. They have dull, greyish green, frequently glaucous upper and lower surfaces.

***Flowers*:** The inflorescence is greenish in bud; after opening, the corolla remains greenish but is tinged with brown, orange, or salmon. Flowers are about as long as wide, produced in terminal or (more or less) axillary, compound cymes. Pedicels are 0–1 mm (0–0.04 in) long, the floral tube

Top left: *Santalum austrocaledonicum* flowers. Top right: *Santalum yasi* flowers. Bottom left: Santalum yasi tree growing in home garden, Hihifo, Tonga. Bottom middle: Leaf variation in *Santalum austrocaledonicum*, Tanna, Vanuatu. Bottom right: *Santalum austrocaledonicum* fruit, Santo, Vanuatu.

is campanulate to conical, 4–7 mm (0.16–0.28 in) long, and the ovary is inferior. Flowers produce a sweet fragrance.

***Fruit*:** Mature fruits are purple to black drupes, often glaucous, 9–12 mm (0.4–0.5 in) long, with a distinctive apical receptacular ring.

***Seed*:** The kernel consists of a hard, woody, smooth or slightly rough, light-colored endocarp enclosing a single seed. Data is lacking for seed size for the Hawaiian species. Birds are the principal means of seed dispersal. However, in many habitats the fruits and seeds are consumed by rats (*Rattus exulans*, which were introduced by Polynesians before 1778, and more recently, *R. rattus*).

Santalum freycinetianum

(adapted from Harbaugh et al. 2010)

***Habit and size*:** A small shrub to tree typically 4–10 m (13–33 ft) tall and 3–7 m (10–23 ft) in canopy diameter. The maximum tree dimension is 20 m (66 ft) tall and 10 m (33 ft) in canopy diameter, and bole diameter at breast height is 80 cm (31.5 in) (Wagner et al. 1999; Little and Skolmen 1989; Harbaugh et al. 2010).

***Leaves*:** Leaves are opposite, 4–10 cm (1.6–3.9 in) in length and 1.2–4.4 cm (0.5–1.7 in) wide, with an acute to rounded apex. Petioles are 7.7–20.7 mm (0.3–0.8 in) long. The leaves are light to dark green, occasionally slightly glaucous, more or less wilted in appearance, and tinged with purple when immature.

***Flowers*:** Flowers are longer than wide, and produced in terminal or (more or less) axillary, relatively open, compound cymes. Pedicels are normally 1–2 mm (0.04–0.08 in) long, with bracts that are rapidly deciduous. The floral tube is yellowish white to white but turns pink to dark pink as it ages; it is campanulate to cylindrical, usually 3–6 mm (0.1–0.2 in) long and 2–3.4 mm (0.08–0.13 in) wide. The ovary is partly inferior. Flowers produce a weak fragrance.

***Fruit*:** Mature fruits are reddish purple to almost black drupes at maturity, 9–14 mm (0.35–0.55 in) long, with a distinctive sub-apical receptacular ring.

Seed**:** The kernel consists of a hard, woody, smooth or slightly rough, light-colored endocarp enclosing a single seed that has a rough surface and is pointed at one end. Data is lacking for seed size for the Hawaiian species. Birds are the principal means of seed dispersal. However, in many habitats the fruits and seeds are consumed by rats (*Rattus exulans*, which were introduced by Polynesians before 1778, and more recently, *R. rattus*).

Santalum haleakalae Hillebr. var. *haleakalae*
Santalum haleakalae Hillebr. var. *lanaiense* (Rock) Harbaugh

(adapted from Harbaugh et al. 2010)

Habit and size**:** A small to medium, single or multi-stemmed shrub or tree, typically 1–8 m (3.3–26 ft) tall and 2–4 m (6.6–13.2 ft) canopy diameter. Maximum bole dbh is 20 cm (8 in) (Wagner et al. 1999; Little and Skolmen 1989; Harbaugh et al. 2010).

Leaves**:** Leaves are opposite, 2.2–8.4 cm (0.9–3.3 in) long and 1.2–4.9 cm (0.9–3.3 in) wide with 1.2–21.7 mm (0.05–0.85 in) long petioles. Leaf shape is ovate, elliptic to orbicular, and from wilted to stiff . The leaves are light olive to dark green, frequently tinged purple, and normally glaucous.

Flowers**:** Flowers are longer than wide, deep pink to red throughout or with white to pink interiors, and produced in sparse or congested, terminal, compound cymes, very occasionally with a few extra axillary flower clusters. The pedicels are 0.7–4.4 mm (0.03–0.17 in) long. The bracts are persistent after flowering in var. *haleakalae* and not persistent in var. *lanaiense*, and the campanulate to cylindrical floral tube, 2.0–11.2 mm (0.08–0.44 in) long and 1.9–4.0 mm (0.07–0.16 in) wide, is white, turning dark red as it ages. Pedicels are 0.7–4.4 mm long (0.03–0.17 in). Corolla lobes are 2.0–7.1 mm (0.08–0.28 in) long; their outer surfaces are dark red and glaucous externally, turning to the same color on the inner surface after opening. The ovary is partly inferior. Flowers produce a weak fragrance.

Fruit**:** Mature fruits are black or purplish black drupes 9–16 mm (0.35–0.63 in) long, with a distinctive sub-apical receptacular ring

Seed**:** The kernel consists of a hard, woody, smooth, or slightly rough, light-colored endocarp enclosing a single seed with rough surface and pointed at one end. Data is lacking for seed size for the Hawaiian species. Birds are the principal means of seed dispersal. However, in many habitats the fruits and seeds are consumed by rats (*Rattus exulans*, which were introduced by Polynesians before 1778, and more recently, *R. rattus*).

In fact, rats have all but eliminated reproduction of the endangered Lānaʻi variety of *S. haleakalae* in the wild by eating the fruits before they fall (Ziegler 2003).

Santalum involutum

(adapted from Harbaugh et al. 2010)

Habit and size**:** Small, evergreen tree typically 2–7 m (6.6–23 ft) tall

Leaves**:** Leaves are opposite, yellowish-green to grayish-green, thin and papery (often translucent) often drooping, more glaucous and slightly lighter on lower surface, linear elliptic (rarely conduplicate-falcate), sides rolled upwards (rarely flat), 4.6–8.2 cm (1.8–3.2 in) long and 1.4–1.8 cm (0.6–0.7 in) wide, margins flat, apices acute, bases cuneate,

Left: A shrubby *Santalum haleakalae* tree about 1.5 m (5 ft) tall growing on cliff in Haleakalā National Park, Maui, Hawaiʻi. Right: *Santalum haleakalae* flowers and leaves, Haleakalā National Park, Maui.

petioles yellowish to pinkish, 7.0–17.0 mm (0.28–0.67 in) long.

***Flowers*:** Flowers are greenish-white throughout (sometimes turning red with age) carried on a sparse terminal or axillary cyme. Floral tubes campanulate to cylindrical 5–11 mm (0.2–0.43 in) long and 2–3 mm (0.08–0.12 in) wide, without vertical keel below each corolla lobe; corolla lobes 4, concave with thickened margins, 3–5 mm (0.12–0.2 in) long and 1.5–3.0 mm (0.06–0.12 in) wide; disk lobes lingulate, apices acute or round; stigma lobes 3; stamens 4; ovary inferior.

***Fruit*:** A drupe, elliptic with apical ring, 13–20 mm (0.51–0.79 in) long.

***Seed*:** The kernel consists of a hard, woody, smooth or slightly rough, light-colored endocarp enclosing a single seed that has a rough surface and is pointed at one end. Birds are the principal means of seed dispersal. However, in many habitats the fruits and seeds are consumed by rats (*Rattus*

Top left: A 15–18 m (50–60 ft) tall *Santalum freycinetianum* tree of in Honouliuli Preserve, Oʻahu. Top middle: *Santalum pyrularium* flowers, Nāpali Kona Forest Reserve, Kauaʻi, Hawaiʻi. Top right: A *Santalum paniculatum* tree, Mauna Kea, Hawaiʻi. Bottom left: *Santalum paniculatum* flowers. Bottom right: *Santalum paniculatum* fruit and leaves.

exulans, which were introduced by Polynesians before 1778, and more recently, *R. rattus*).

Santalum paniculatum

***Habit and size*:** A shrub or tree 3–10 m (10–33 ft) tall and 3–7 m (10–23 ft) canopy diameter. In some relatively protected situations, *S. paniculatum* will grow to heights of 15–20 m (49–66 ft).The maximum canopy diameter is 10 m (33 ft) with a bole diameter at breast height of 1 m (3.3 ft) (Wagner et al. 1999; Little and Skolmen 1989).

***Leaves*:** Leaves are 2.5–8 cm (1–3.1 in) long and 2–4.5 cm (0.8–1.8 in) wide with 2–15 mm (0.08–0.6 in) long petioles. Leaf shape is ovate, elliptic, or obovate, and the surfaces have glossy upper sides and dull, sometimes pale, lower sides. Both surfaces are often glaucous, and usually of different colors, occasionally yellowish orange to bluish or olive green.

***Flowers*:** Flowers are approximately as long as wide, greenish in bud, and produced in terminal or (more or less) axillary, compound cymes. The pedicels are about 1 mm long. The floral tube is campanulate to conical. The corolla is 4–8 mm (0.16–0.32 in) long and greenish but tinged with brown, orange, or salmon after opening. The ovary is inferior. Flowers produce a sweet fragrance.

***Fruit*:** Mature fruits are purple to black drupes 10–12 mm (0.4–0.5 in) long, with a distinctive apical receptacular ring.

***Seed*:** The kernel consists of a hard, woody, smooth or slightly rough, light-colored endocarp enclosing a single seed. Data is lacking for seed size for the Hawaiian species. Birds are the principal means of seed dispersal. However, in many habitats the fruits and seeds are consumed by rats (*Rattus exulans*, which were introduced by Polynesians before 1778, and more recently, *R. rattus*).

Santalum pyrularium

(adapted from Harbaugh et al. 2010)

***Habit and size*:** A single or multi-stemmed shrub or small tree, 1–5 m (3.3–16.4 ft) tall.

***Leaves*:** Leaves are opposite, medium to dark green, thin and papery to leathery, more glaucous and very slightly paler on lower surface, narrowly to broadly elliptic, ovate, to oblong (rarely conduplicate-falcate), 3.6–9.4 cm (1.4–3.7 in) long and 1.2–3.8 cm (0.47–1.5 in) wide, margins flat (rarely wavy), apices acute to obtuse (rarely acuminate), bases cuneate or rounded, petioles 5.9–15.7 mm (0.23–0.62 in) long.

***Flowers*:** Flowers are cream to purple throughout, or greenish with purple interior borne on a sparse axillary (or rarely terminal) cyme. Floral tubes campanulate to cyrindrical, 3.6–13.0 mm (0.14–0.51 in) long and 2.6–4.4 mm (0.1–0.17 in) wide, with vertical keel below each corolla lobe; pedicels 1.0–3.1 mm (0.04–0.12 in) long; corolla lobes 4, concave with thickened margins, papillate, 3.4–5.8 mm (0.13–0.23 in) long and 2.0–3.7 mm (0.08–0.15 in) wide; disk lobes lingulate, apices acute or round; stigma lobes 3; stamens 4; ovary inferior.

***Fruit*:** A drupe, elliptic with apical ring, 15–22 mm (0.59–0.87 in) long.

***Seed*:** The kernel consists of a hard, woody, smooth or slightly rough, light-colored endocarp enclosing a single seed that has a rough surface and is pointed at one end. Birds are the principal means of seed dispersal. However, in many habitats the fruits and seeds are consumed by rats (*Rattus exulans*, which were introduced by Polynesians before 1778, and more recently, *R. rattus*).

Variation within species

Melanesian sandalwoods

Santalum austrocaledonicum and *S. yasi* both exhibit considerable morphological variation, and numerous traditional varieties are recognized. There are three formally described varieties of *S. austrocaledonicum* in New Caledonia.

Santalum austrocaledonicum var. *austrocaledonicum* and var. *pilosulum* have large leaves (about 5 cm × 2 cm [2 in × 0.8 in]) and long petioles (6–16 mm [0.24–0.63 in]) and corolla lobes (1.3 mm × 0.8 mm [0.05 in × 0.03 in]). The flowers and new shoots of var. *austrocaledonicum* are glabrous whereas those of var. *pilosulum* are villous or hairy. Variety *minutum* has much smaller leaves (about 2 cm × 0.8 cm [0.8 in × 0.3 in]) and corolla lobes (1.3 mm × 0.4 mm [0.05 in × 0.02 in]).

Hawaiian sandalwoods

All species exhibit considerable morphological variation, and numerous traditional varieties are recognized. Originally there were two species, *S. ellipticum* and *S. freycinetianum*, recognized in the Hawaiian Islands, representing the white-flowered and red-flowered taxa. There have been numerous subsequent revisions recognizing up to nine different Hawaiian *Santalum* species. The six species most recently described in a taxonomic revision with the support of modern DNA research (Harbaugh et al. 2010) appear to have been derived from two separate colonizing events from Australia (Harbaugh and Baldwin 2007; Harbaugh 2008). These are represented by two sections of the genus *Santalum*. Section Solenantha Tuyama includes *Santalum freycinetianum*, *S. haleakalae*, *S. involutum,* and *S. pyrularium,* which are characterized by red or red-tinged petals with flowers longer than wide that produce much nectar. The endemic section Hawaiiensia Skottsb. includes *S. ellipticum* and *S. paniculatum*, which are typified by flowers that are approximately as wide as long, producing little or no nectar, with green petals that become yellowish brown, orange, or occasionally salmon.

Known varieties (Wagner et al. 1999; Harbaugh et al. 2010)

S. ellipticum

This species is highly variable, both in vegetative and floral characters. As many as six taxa have been proposed for individuals belonging to *S. ellipticum*. However, there is no single or group of characters that provide a sound basis for an enhanced subdivision of this species. Research by Stemmermann (1980), based on leaf succulence, glaucous fruit, and shrubby habit, recognized a coastal type as var. *littorale*. However, all of the characters used to differentiate the variety can also be found in inland plants in *S. ellipticum*. Furthermore, the coastal form represents an extreme of the variation pattern. Essentially, this form represents an ecotype and probably does not warrant formal recognition.

S. freycinetianum

Santalum freycinetianum previously was circumscribed to include two varieties (*lanaiense* and *pyrularium*) found on all of the major Hawaiian Islands (except Hawai'i). However, a recent taxonomic revision by Harbaugh et al. (2010), combining analyses based on DNA, microsatellite and morphological variation, has shown *S. freycinetianum* to comprise only one entity that is restricted to upland areas of two mountain ranges on the island of O'ahu.

S. haleakalae

As now circumscribed following the recent taxonomic revision of Harbaugh et al. (2010), *S. haleakalae* is widespread and occurs in two varieties. These are *Santalum haleakalae* Hillebr. var. *haleakalae,* which is rare and restricted to the East Maui volcano and *S. haleakalae* Hillebr. var. *lanaiense* (Rock) Harbaugh (syn. *S. freycinetianum* Gaud. var. *lanaiense* Rock), which is a morphologically variable taxon occurring on the three islands of Maui, Lāna'i and Moloka'i.

S. involutum

This Kaua'i endemic exists as small populations in and around Kalalau Valley and has not been commonly recognized. Harbaugh et al. (2010) hypothesize that this species was created by an ancient hybridization event between the red- and white- flowering Hawaiian sandalwood clades.

S. paniculatum

Although Fosberg (1962) included this species as a variety of *S. ellipticum*, more recent taxonomic research by Stemmermann (1980) indicates that based on differences in leaf form and color, and shrub or tree habit, there are two significantly intergrading varieties of *S. paniculatum*; these are var. *paniculatum* and var. *pilgeri*.

S. pyrularium

Once regarded as a Kaua'i variety of *S. freycinetianum* (var. *pyrularium*), Harbaugh et al. (2010) have re-raised this variety to species rank.

DISTRIBUTION

Native range

Melanesian sandalwoods

Santalum austrocaledonicum

This species is naturally found in the island archipelagos of New Caledonia and Vanuatu in the southwest Pacific.

Var. *austrocaledonicum* is common in the Loyalty Islands and the Isle of Pines but is uncommon on the main island of Grande Terre. It is also present in the Belep islands. In Vanuatu the principal occurrence is around the northwest, west, and southwest portions of Erromango, and on the west coast of Espiritu Santo; it is also found on Tanna, Aniwa, Futuna, Malekula, Efate, and Aneityum.

Var. *pilosulum* is restricted to low elevations on the main island of New Caledonia near Noumea. It also has limited occurrence at high elevation in the Karaka region (northeast slope of Mt. Do between Boulouparis and Thio).

Var. *minutum* is restricted to the northwest side of the main island of New Caledonia.

Santalum yasi

This species occurs in lowland, drier, and more open forest types in Fiji, Niue, and Tonga. The Niuean population may be an ancient or Polynesian introduction. There is one record for Samoa (Savai'i), where it appears to be introduced but not naturalized. The range extends from Niue and 'Eua, a southern island in the Tongan group, through Tongatapu, Ha'apai, and Vava'u (Tonga), west and northwards, through the Fiji Islands (Lau group, Kadavu, Nausori Highlands/Viti Levu, Bua/Vanua Levu) to the Udu Peninsula, NE Vanua Levu, northern part of Fiji.

Hawaiian sandalwoods

Santalum ellipticum

Endemic to Hawaiian Islands, this species can be found as a sprawling to bushy shrub near the ocean shore. It is also occasionally found as a somewhat larger shrub to small tree in dry gulches, on slopes or ridges, and frequently in 'a'ā lava or rocky habitats. The species also grows in arid shrub land and forest most commonly on the island of O'ahu, often persisting in areas invaded by non-native species up to elevations of 560 m (1,840 ft), and sometimes as high as 950 m (3,120 ft) elevation on all of the main islands. It is now extinct on Kaho'olawe and Laysan, rare on Kaua'i, and on Hawai'i it is only known to exist in scattered areas, such as in the Kohala Mountains, Puʻuwaʻawaʻa in the North Kona District, and Puʻupāpapa and several other of the nearby cinder cones in the South Kohala District. It may also be found very rarely in the lower subalpine area between Mauna Kea and Mauna Loa (Wagner et al. 1999).

Santalum freycinetianum

This species has a scattered distribution on slopes or ridges of both the Waiʻanae and Koʻolau Mountain Ranges on the island of Oʻahu. Altitudinal range is 300–800 m (980–2,620 ft) (Harbaugh et al. 2010).

Santalum haleakalae

Santalum haleakalae var. *haleakalae* is endemic to Eastern Maui and is restricted to scattered areas in the subalpine shrub land on dry slopes, especially in foggy areas at 1,800–2,700 m (5,900–8,860 ft) on Haleakalā (Wagner et al. 1999; Harbaugh et al. 2010).

Santalum haleakalae var. *lanaiense,* according to a recent taxonomic revision by Harbaugh et al. (2010), occurs on the islands of Maui, Lānaʻi and Molokaʻi. In Maui, it is found in the mountains of West Maui in exposed or semi-shaded scrublands from 800–1,300 m (2,620–4,260 ft) and also on the southern slopes of Haleakalā Crater on East Maui at 1,200–1,350 m (3,940–4,430 ft). In Lānaʻi it is scattered in the eastern mountains at 750–950 m (2,460–3,120 ft) elevation while it is rare within the Kānepuʻu Preserve on western Lānaʻi at 550 m (1,800 ft). It is scattered in eastern Molokaʻi at elevations of 950–1,250 m (3,120–4,100 ft).

Santalum involutum

This species is restricted to the island of Kauaʻi where it occurs in valleys (Hanakāpīʻai, Pōhakuao, and Kalalau) running down to the northwestern Nāpali coast, Wainiha Valley in the north and the southern region of Wahiawā. Altitudinal range is 120–750 m (390–2,460 ft). Harbaugh et al. (2010) state that, although it is observed in *Metrosideros* wet forest, *S. involutum* seems to prefer *Diospyros* mixed mesic forest, which is extremely rare and noted for its floristic diversity.

Santalum paniculatum

Endemic to Hawaiʻi Island only, this species is found in dry forest areas on lava substrates or on cinder cones up to higher elevations in more humid forest, or in secondary *Metrosideros* forest from about 450–2,550 m (1,480–8,360 ft) in elevation (Wagner et al. 1999).

Santalum pyrularium

Harbaugh et al. (2010) describe the range and environment of *S. pyrularium* as restricted to the island of Kauaʻi where it can be prevalent around Waimea Canyon and Kōkeʻe State Park at an altitudinal range of 270–1,400 m (890–4,590 ft). It consistently prefers partial to full shade and is most often associated with mesic (summer dry) forest communities but it occasionally invades wet forest communities and bog margins.

Current distribution

Melanesian sandalwoods

Santalum austrocaledonicum

Outside of its native range this species has been little planted, mainly for trial purposes in Australia, Fiji, and the Cook Islands.

Santalum yasi

This species has been planted on a small scale outside of its natural range, mainly for trial purposes in Australia. Some of its occurrences, e.g., on Niue, may be comprised of naturalized populations following introduction by humans.

Hawaiian sandalwoods

Hawaiian species have primarily been planted inside of their natural range for economic or conservation purposes. Judd (1926) describes early attempts to cultivate sandalwood in Hawaiʻi.

ENVIRONMENTAL PREFERENCES AND TOLERANCES

Climate

Melanesian sandalwoods

Santalum austrocaledonicum and *S. yasi* prefer warm to hot, lowland, subhumid or wet/dry tropics, with an annual rainfall of 1,250–1,750 mm (50–70 in) and a distinct dry season of at least 3–5 months. Tropical cyclones are a feature of the entire distribution, occurring mainly during the hot, wet season (December–April).

Hawaiian sandalwoods

Hawaiian species are variously adapted to a variety of ecological ranges (from sea level to the subalpine zone) as represented by the existing populations.

Other tolerances

Drought

They are able to survive a long dry season (up to 5–6 months) when attached hemi-parasitically to suitably drought-tolerant host plants.

Full sun

They grow well in full sun when their roots are attached hemi-parasitically to suitable host species; otherwise, plants growing in full sun can become yellow and even die.

Shade

They can tolerate up to 60–70% shade, but growth will be very slow at higher shade levels. The optimum level of shade is up to about 25–35%, preferably as "side shade." Side shade is provided by planting adjacent rows of bushy but not spreading plants, which grow up to about the same height as sandalwood without overtopping them and casting overhead shade.

Fire

Sandalwoods are sensitive to fire (and grazing from cattle, goats, and deer) particularly in the first few years of growth. Individuals of some sandalwood species will regrow from coppice following fire, e.g., *S. austrocaledonicum* and younger specimens of *S. album*.

Frost

All species are frost-sensitive with the possible exception of *S. haleakalae*, which is adapted to the subalpine zone of Haleakalā, Maui.

Waterlogging

They prefer good drainage and will die or die back following any prolonged period of waterlogging (greater than 1–2 weeks).

Salt spray

Plants growing in near-coastal situations may suffer severe scorching by salt-laden winds and total defoliation following cyclonic storms, but usually they recover fully. A coastal ecotype of *S. ellipticum* is an exception; it is adapted to growing near or along the coast, usually as a sprawling or small shrub.

Wind

Mature plants are typically of low stature and are somewhat resistant to strong winds associated with cyclonic storms, except in open areas. Younger plants in open areas, especially if they have grown quickly and have a heavy canopy, may be blown over or suffer breakage of stems and branches during high winds. Older trees growing among established forests can also suffer from limb damage during cyclone events. The most susceptible trees are those with heavy canopies and forked trunks, which can easily split.

Table 1. Elevation, rainfall, and temperature

Elevation range (m)	**lower**	**upper**
Melanesian sandalwoods		
Santalum austrocaledonicum	5 m (16 ft)	800 m (2,400 ft)
Santalum yasi	1 m (3 ft)	600 m (2,000 ft)
Hawaiian sandalwoods		
Santalum ellipticum	1 m (3 ft)	950 m (3,120 ft)
Santalum freycinetianum	300 m (980 ft)	800 m (2,620 ft)
Santalum haleakalae var. haleakalae	1,800 m (5,900 ft)	2,700 m (8,860 ft)
Santalum haleakalae var. lanaiense	550 m (1,800 ft)	1,350 m (4,430 ft)
Santalum involutum	120 m (390 ft)	750 m (2,460 ft)
Santalum paniculatum	450 m (1,480 ft)	2,550 m (8,360 ft)
Santalum pyrularium	270 m (890 ft)	1,400 m (4,590 ft)
Mean annual rainfall	**lower**	**upper**
Melanesian sandalwoods		
Santalum austrocaledonicum	800 mm (30 in)	2,500 mm (100 in)
Santalum yasi	1,400 mm (55 in)	2,500 mm (100 in)
Hawaiian sandalwoods Direct rainfall data is lacking. General information on moisture regime is: *Santalum ellipticum*—Xeric lands *Santalum freycinetianum*—Mesic to wet forest *Santalum haleakalae* var. *haleakalae*—Xeric subalpine *Santalum haleakalae* var. *lanaiense*—Mesic to wet forest *Santalum involutum*—Mesic to wet forest *Santalum paniculatum*—Xeric to wet forest *Santalum pyrularium*—Mesic to wet forest		
Dry season duration (consecutive months with <40 mm rainfall)	2–5 months during the cooler months, June–October (Southern Hemisphere), January–May (Northern Hemisphere)	
Mean annual temperature	**lower**	**upper**
Melanesian sandalwoods		
Santalum austrocaledonicum	23°C (73°F)	27°C (81°F)
Santalum yasi	23°C (73°F)	29°C (84°F)
Hawaiian sandalwoods Direct temperature data correlated to species is lacking.		
Mean maximum temp. of hottest month	**lower**	**upper**
Melanesian sandalwoods		
Santalum austrocaledonicum	29°C (84°F)	33°C (91°F)
Santalum yasi	24°C (75°F)	31°C (88°F)
Hawaiian sandalwoods Direct temperature data correlated to species is lacking.		
Mean minimum temp. of coldest month	**lower**	**upper**
Melanesian sandalwoods		
Santalum austrocaledonicum	16°C (61°F)	22°C (72°F)
Santalum yasi	18°C (64°F)	25°C (77°F)
Hawaiian sandalwoods Direct temperature data correlated to species is lacking.		
Minimum temperature tolerated For all species, the entire distribution is frost-free, with the exception of *S. haleakalae*. **Melanesian sandalwoods** *Santalum austrocaledonicum:* 10–16°C (50–61°F), but possibly as low as 5–7°C (41–45°F) on Maré, Loyalty Islands, New Caledonia. *Santalum yasi:* The absolute minimum experienced is around 8–9°C (46–48°F) at the higher elevation sites in western Viti Levu. **Hawaiian sandalwoods** Direct temperature data correlated to species is lacking.		

Soils

Melanesian sandalwoods

Both species

Both *S. austrocaledonicum* and *S. yasi* occur on a range of soil texture types. They are generally found on light to medium sandy loams but can be found growing on coralline soils through to basaltic ferrosols. Both species require freely draining soils.

Both species may grow on acid to alkaline soils (pH 4.0–8.0), but prefer neutral soils (pH 6.1–7.4). Development and spread of the pathogenic brown root rot (*Phellinus noxius*) may be reduced in alkaline soils. Both species can tolerate shallow and infertile soils.

Santalum austrocaledonicum

In the Poya region of New Caledonia, var. *austrocaledonicum* grows in ferrallitic/ultramafic soils with a limestone substrate. These soils have high levels of exchangeable calcium and potassium and are rich in nickel and chrome. Further north, around Pouembout, it grows in a highly acidic to neutral, magnesium-rich black clay derived from basalt. Var. *minutum* occurs on immature colluvial soil on serpentine peridotite/metamorphic and ultramafic gravels. Such soils are infertile with very low levels of phosphorus, potassium, and calcium, but are relatively high in magnesium, nickel, chrome, and manganese. In Vanuatu, the species grows well on pure coralline soil, volcanic ash, schist or sedimentary substrates. The species prefers well drained acidic to alkaline conditions and does not grow well on waterlogged soils and strongly acidic clayey soils.

Santalum yasi

In Fiji the soils are mainly well drained, humic and ferruginous latosols. In Tonga, its best development is on soils derived from volcanic ash overlying coralline rock.

Hawaiian sandalwoods

Hawaiian sandalwoods prefer light and medium, well drained soils (sands, sandy loams, loams, and sandy clay loams). All species require freely draining soils. Acid to neutral soils (pH 4.0–7.4) are acceptable, but they prefer neutral soils (pH 6.1–7.4). The species tolerate shallow and infertile soils. *S. ellipticum* thrives in sandy soils, including those derived from raised limestone, but also does well in clay soils and can regenerate on lava beds. Additional soil data for the other five Hawaiian sandalwood species are lacking

GROWTH AND DEVELOPMENT

Melanesian sandalwoods

Santalum austrocaledonicum

In New Caledonia in young plantations up to 5 years old, individuals show mainly an increase in height with a mean annual growth increment in trunk diameter of about 6 mm (0.24 in). The average diameter growth rate in older plants is 3.8–4.8 mm/yr (0.15–19 in/yr). In Vanuatu young plants (up to 3 years old) can grow at moderately fast rates, e.g., 1–1.5 m (3–5 ft) height per annum and 1 cm (0.4 in) diameter increment (measured at 20 cm [8 in] above ground level) per annum. Diameter growth averaged 6–10 mm/yr (0.24–0.4 in/yr) at 18–26 years, and 6–7 mm/yr (0.24–0.27 in/yr) after 28–33 years. Trees can grow at moderate rate over the projected rotation period of about 20–40 years.

Santalum yasi

Early height growth is slow to moderate, e.g., 0.5–0.7 m/yr (1.6–2.3 ft/yr), but is variable depending upon environmental conditions and host species. Under suitable growing conditions it may attain harvestable size in about 25 years; e.g., 20–25 cm (8–10 in) diameter near ground level, with substantial heartwood development.

Hawaiian sandalwoods

After exhausting energy stored in the seed, seedlings may stop growing for a number of weeks during what may be termed a "waiting period." When necessary root contacts are established with host species, a rapid increase in growth of the plant begins. Frequently, the new growth in *S. ellipticum* and *S. paniculatum* manifests as a distinct alteration of leaf color from an initial red or pink to a bluish green. Rapid addition of new foliage is a strong indication that the plant has established good water and nutrient uptake by its own roots in the soil and through its unions with roots of host plants. Development regimes and longevity records for Hawaiian sandalwood species are lacking.

Rooting habit

Sandalwoods have a widely spreading surface root system and roots are rarely found more than 50–100 cm (20–40 in) below the soil surface. Spreading root structure ensures the grafting (via haustoria) onto many other plant species and tapping into the host plants' water and mineral nutrients.

Reaction to competition

Sandalwoods, especially as young plants, react poorly to competition from monocotyledons (including grasses and palms such as coconut) and to overshading by faster growing plants. Being hemi-parasitic, they grow best in close proximity to suitable host species.

Regeneration

Natural regeneration of wild sandalwood stands typically occurs very slowly following harvesting due to the removal of most of the larger fruiting specimens.

Self-prune

Self pruning is variable; in open situations, sandalwood plants often retain branches to near ground level. In shadier situations, especially where the shade is cast from overhead, the plants exhibit reasonably good self-pruning characteristics. For *S. yasi* suitable shade regimes to keep plants growing straight and to avoid a bushy habit include strong lateral shade with no overhead shade or a high canopy producing intermediate shade.

Coppice

Plants frequently resprout from basal coppices or by root suckering off lateral roots (following removal of the stump and major roots). Many species are capable of root suckering as long as not too much of the root system is removed during harvest. Such coppice regrowth is likely to die out in heavily shaded situations.

Santalum austrocaledonicum **roots grafted to** ***Sesbania formosa*** **root via haustoria. The necessity to root-graft to other species makes** ***Santalum*** **species partially dependent upon neighboring plants for nutrients and water for their survival.**

Pollard

Plants can be pollarded, but this is not an appropriate regime for sandalwood where the economic value is concentrated in the heartwood in the lower bole and large woody roots and regrowth is slow.

Flowering and fruiting

Melanesian sandalwoods

Under favorable conditions plants begin flowering and fruiting from an early age, typically about 18 months to 3 years in *S. austrocaledonicum* and 3–4 years in *S. yasi*. There is considerable variation in seasonality of flowering and fruiting.

In *S. austrocaledonicum* trees flower and fruit throughout the year, usually with two peaks. In Vanuatu, flowering occurs in January–April, July, and October. In New Caledonia, flowering occurs throughout the year, but there are flowering peaks in February and October, and flowering is rarely observed in June and July. Mature fruits have been reported almost throughout the year, but the main fruiting season is November–January. In New Caledonia, two fruiting seasons are observed: the main fruiting season is from December to February and with a light fruiting season from July to August. Fruits mature about 3–4 months after flowering.

In *S. yasi* trees flower and fruit throughout the year, usually with two peaks. The two main flowering periods for *S. yasi* in Fiji are October–November and February. In the southern islands of Tonga (‘Eua and Tongatapu), the main flowering period is (June–) July–August (–September). Further north in the Ha‘apai and Vava‘u groups the peak flowering period is November–December. The main fruiting season corresponds to the wet season, December–March, with light fruiting in the cooler, dry season (June–August). Fruits mature about 3–4 months after flowering.

Hawaiian sandalwoods

Under good conditions the Hawaiian sandalwoods begin flowering from an early age, typically about 3–4 years, but heavy flowering and fruiting may take 7–10 years. There is considerable variation in seasonality of flowering and fruiting. Trees flower and fruit throughout the year, usually with two peaks. Most species have a fruiting season throughout the year except for winter.

AGROFORESTRY AND ENVIRONMENTAL SERVICES

Alley cropping

Sandalwoods are suitable for inclusion in alley cropping systems, especially where the other alley species include good hosts, e.g., *Calliandra* and *Casuarina* spp.

Homegardens

The trees are very suitable for planting in homegardens, which have the advantages of a mixture of host species, intermediate/variable light levels, and high security. For example, sandalwoods are often planted in Fijian village homegardens with ornamentals and cultural species (e.g., *Pandanus tectorius*, *Polyscias*, *Croton*, *Cordyline,* and *Euodia hortensis*) and fruit trees (e.g., *Artocarpus altilis*, *Citrus* spp., *Musa* spp., and *Pometia pinnata*).

Improved fallows

Sandalwood could be included in improved fallows of nitrogen-fixing trees, with a fallow rotation of 20 or more years to ensure that sandalwoods attain commercial maturity.

Woodlots

Sandalwoods are suitable for inclusion in woodlots, especially when planted along sun-exposed edges of the woodlot and in combination with compatible species, e.g., with *Pinus caribaea*, as has been done in Tonga and Cook Islands, or with *Acacia koa* in Hawai'i.

Advantages and disadvantages of growing in polycultures

As sandalwoods are obligate root hemi-parasites, it is necessary to grow them in an environment with several other plant species to act as hosts. Obligate root hemi-parasites need a host to provide water and certain nutrients to grow well. It has been shown that nitrogen-fixing species generally make the best hosts for sandalwood.

Over the life of a sandalwood tree and throughout the seasons, its nutrient and water requirements will change. By providing a range of host species, including both long- and short-lived species, this will ensure that the needs of the sandalwood tree will be met throughout its life.

If only one or two host plant species are used, there is a high risk that the sandalwood trees could become severely stressed at some point, with risk of plant death or early senescence associated with poor water and nutrient supply, and insect or fungal attack. For example, *Calliandra calothyrsus* and *Citrus* are excellent hosts in terms of promoting sandalwood growth, but are easily stressed and if mortality is associated with a root rot fungus, such as *Phellinus noxious*, then this can easily spread to sandalwood through interconnected root systems.

Top: These 3-year-old *S. austrocaledonicum* trees in Vanuatu will loose vigour due to the dense planting and lack of permanent hosts. Middle: A promising system with *S. austrocaledonicum* (2 years old) planted within *Casuarina equisetifolia* woodland on Mangaia, Cook Islands. Bottom: *S. austrocaledonicum* plantation (about 10 years old) with *Casuarina equisetifolia* as windbreak and permanent hosts in Efate, Vanuatu.

Top left: Two-year-old smallholder agroforestry system incorporating planted ground cover legumes and grasses with *S. austrocaledonicum* in Efate, Vanuatu. Top middle: One-year-old system incorporating *S. austrocaledonicum*, papaya (*Carica papaya*), tannia (*Xanthosoma* sp.), *Gliricidia sepium*, and *Flueggea flexuosa* in Efate. Top right: Home garden incorporating *S. austrocaledonicum* and coffee in Tanna, Vanuatu. Middle left: Smallholder system with *S. austrocaledonicum*, papaya, Pacific spinach (*Hibiscus manihot*), tannia, and sweetpotato (*Ipomoea batatas*) in Efate. Bottom left: *S. austrocaledonicum* planted with kava (*Piper methysticum*) in Santo, Vanuatu. Bottom right: *S. austrocaledonicum* planted with various fruits in Malekula, Vanuatu.

Furthermore, the sandalwood root structure is not necessarily strong enough to support a large tree without wind protection from neighboring host trees. However, sandalwoods can lose vigor and produce less fragrant heartwood if too heavily shaded (more than about 50% shade). Furthermore, they should not be grown under trees and palms prone to dropping branches or large fronds which can damage and break the main leader.

Environmental services

Windbreaks

Sandalwoods are suitable for inclusion in windbreaks, especially where the main windbreak species are also good host species, e.g., *Casuarina* spp.

Native animal/bird food

The fruits of sandalwood are consumed by various bird species, including pigeons. For soft-beaked species the seeds may pass through the digestive system intact and be widely disseminated.

Host plant trellising

There is minor potential to trellis slow-growing vines that would not interfere with full sun reaching the canopy, such as *maile* (*Alyxia stellata* and *A. oliviformis*).

Bee forage

When in flower, the trees are attended my many pollinators, including honeybees.

Coastal protection

Sandalwoods can often grow near (within a few meters) of the sea, but they provide limited protection due to their shallow surface rooting habit and their leaves are burnt by strong salt winds.

Ornamental

All species are quite attractive, especially when in flower, and suitable for home and village gardens. They could have a place in urban environments, but they require proper care and protection (e.g., no herbicide, no nearby foot or vehicle traffic, etc.), which may mean significant alterations in regular landscaping practices.

Before planting sandalwood, a plan should be made to ensure it has the company of other plants that will act as hosts throughout its lifetime. When planting short-lived hosts such as *Dodonaea* (hop bush), *Sesbania* (Dragon tree), or *Cajanus* (pigeon pea), a long-term host such as *Acacia* or *Casuarina* should also be planted nearby well before the short-term host dies. It is best to think of sandalwood as a member of a plant community, rather than a lone specimen. Because of the slow rate of growth and relatively small size of the tree, growing too large for the home garden is usually not an issue.

Rate of growth in a landscape

Under optimum conditions, the growth rate can be 0.7–1 m/yr (2.5–3.3 ft/yr) in height, although it is usually slower. As with most trees, the rate of growth in height decreases as the tree gets older.

PROPAGATION AND PLANTING

All *Santalum* species are readily propagated by seed in the nursery. The use of gibberellic acid can dramatically speed up the sometimes very slow germination process, as can scoring or cracking the endocarp. They may also be propagated through encouraging seedling development underneath selected heavy-fruit-bearing plants, then transplanting recently geminated wildlings (<4–6 weeks) to a new location. Vegetative cuttings may be struck under mist from seedling material. Cuttings from seedlings and young plants initiate and develop adventitious roots much more readily than cuttings from more mature plants. The propagation of material from macro cuttings has never been commercially successful, because rooting rates are low (generally <25%) and specialized equipment is needed. Recent work with tissue culture is producing better results (although as yet not well documented by publications in the public domain), however root development from seedlings from tissue culture seedlings is reported to be very poor compared with seedling-derived plants. Grafting and root-segment cuttings from mature specimens can be used to conserve selected individuals or bring them into breeding programs.

Plants of Hawaiian sandalwood species rarely develop beyond the seedling stage in containers. They should be outplanted before 6 months of age (Culliney and Koebele 1999).

Propagation using wildlings

The following technique is useful for promoting germination of wildlings, which can then be transplanted and grown in the nursery before field planting in a suitable location:

- Select sandalwood trees that are fruiting or are otherwise known to fruit heavily
- Clean all undergrowth from beneath the canopy of the selected sandalwood trees
- Loosen the soil in the cleared area by shallow digging or cultivating only the top 5 cm (2 in) of soil
- Wildlings begin to germinate in the cultivated area about 1–2 months after soil disturbance
- If possible water the cultivated area during dry periods or after some germination is observed
- Keep the cultivated area free of weeds.

RECOMMENDED HOSTS

For Melanesian species

Acacia species, *Alternanthera* spp., *Arachis pintoi, Calliandra calothyrsus,* and *Casuarina* spp. may be used as pot hosts but some varieties of *Alternanthera, Calliandra,* and *Casuarina* need frequent cutting back to prevent them from overtopping the sandalwood.

S. austrocaledonicum

Acacia spirorbis makes a good long-term host plant under both natural conditions and in plantations. For ultramafic soils in New Caledonia, other good nitrogen-fixing host species are *Casuarina collina* and *Gymnostoma deplancheana*.

S. yasi

Good long-term hosts include *Acacia richii*, *Calliandra calothyrsus, Casuarina equisetifolia, Citrus* spp., *Dalbergia* spp. and *Flueggea flexuosa*.

For Hawaiian species

Koa (*Acacia koa*), koaiʻa (*Acacia koaia*), aʻaliʻi (*Dodonaea viscosa*) and koʻokoʻolau (*Bidens spp.*) are thought to be good native Hawaiian host plants. Exotics such as amaranth (*Amaranthus* sp.), strawberry (*Fragaria* sp.) and beggar's tick (non-native *Bidens spp.*) are reputed to be good short-term hosts. Other exotics that are used outside Hawaiʻi as long-term hosts (but not recommended in Hawaiʻi unless already present on site) include *Calliandra* spp., *Casuarina* spp., and *Pinus caribaea*.

Top left: Approximately 4-month-old *S. austrocaledonicum* seedlings with the pot host *Alternanthera*, ready for field planting in Port Vila, Vanuatu. Top right: *S. austrocaledonicum* planting in Efate. Bottom left: *S. austrocaledonicum* planted with the living ground cover and host *Arachis pintoi*. Bottom right: *S. austrocaledonicum* together with red *Alternanthera* (nursery container host) and pigeon pea, both intermediate-term hosts in the field.

Propagation by vegetative cuttings

The propagation of the Pacific sandalwoods by vegetative cutting has been tested in a number of research trials. The trials have shown that the rooting of cuttings varies considerably between species and half-sibling families, and rooting success declines rapidly with stock plant age. Successful root initiation and development greater than 40% is rare and can only be obtained using shoot material collected from seedlings and struck under intermittent misting in suitable media (e.g., 1:1 sand/peat or 1:1 sand/coconut coir). Although tests have shown that *S. yasi* cuttings root more easily than those of *S. austrocaledonicum*, it is still difficult to consistently obtain high rooting levels greater than 40%. There is a need for further work to identify appropriate stock plant treatments and environmental conditions to optimize rooting success for each species. Data on success with propagating the Hawaiian sandalwood species by vegetative cutting is lacking.

Propagation by root segments

Root segments (about 5–10 cm [2–4 in] long and greater than 1 cm [0.4 in] in diameter) may be collected from larger specimens of *S. yasi* (and probably other sandalwood species) and used to strike cuttings. The root segments are treated with rooting powder (e.g., Seradix B_2) and placed horizontally at a depth of 1 cm [0.4 in] in a freely draining medium (e.g., 50:50 coarse washed river sand and peat moss) that is kept moist (but not saturated) in a glasshouse (or alike). The time for sprouting is about 1 to 3 months. The percentage of root segments forming shoots and roots is typically low (e.g., 10–50%) and dependent on seasonal factors. On older specimens, near-surface lateral roots may be severed (1–2 cm [0.4–0.8 in] diameter) or partially severed (4.5–5 cm [1.8–2 in] diameter), and root suckers allowed to develop over 3–4 months and be used as a source of vegetative propagation material (Maloni Havea, pers. comm.).

Recommended outplanting techniques

Sandalwoods need to be either planted out among established long-term host plants, or else together with intermediate hosts (relatively short-lived woody perennials) while longer-term hosts are established.

Survival rates are high (often above 80%) for larger, healthy seedlings planted at the onset of the rainy season and kept well weeded in the first 2 years. Survival and growth will be low for plants established:

- with poorly developed root systems
- in more shady forest situations
- in grassy, sunny situations
- underneath coconut plantations.

CULTIVATION

Basic crop management

The main management objective should be to establish and manage a good mixture of host plant species that provide a suitable light/shelter regime.

Host tree species may need to be pruned or progressively thinned to maintain good levels of sunlight to maturing sandalwood plants.

For *S. yasi,* careful pruning of side branches, removing no more than 25% of canopy at any one time, has been advocated to encourage development of a main bole. Regular removal of competing leaders (breaking by hand) in younger specimens may be a more satisfactory approach for creating a single main bole.

For soils of lower fertility, periodic fertilizing with 100 g (3 oz) of multi-elemental fertilizer (N-P-K) per tree, well distributed up to 50 cm (20 in) from stem (rather than heaped adjacent to stem), could promote more rapid growth. If trees are showing signs of nutrient deficiency such as yellowing or slow growth, an application of multi-elemental fertilizer could reduce symptoms. As the sandalwood is obtaining much of its nutrients from host trees, it will sometimes be just as important to apply any fertilizer to the host trees as well, but fertilizer should not be applied onto already vigorously growing host plants.

Sandalwood seedlings will react quite quickly, although temporarily, to applications of foliar fertilizers. For seedlings that are showing signs of nutrient deficiencies, this is a short-term solution.

Weed growth, especially long, flammable grasses, needs to be well controlled in the early years. Weeds should be manually removed to avoid the risk of herbicide drift and/or translocation through weeds to sandalwood plants via root system connections. Another option is to spread a 3 cm (1.2 in) deep layer of compost around the tree, and cover it with 5–10 cm (2–4 in) of woody mulch such as chipped tree limbs. This mulch slowly adds nutrients and organic matter to the soil, protects the tree's surface roots, and helps conserve soil moisture. Be sure to keep the mulch 10 cm (4 in) away from the trunk of the tree to avoid rotting the bark and girdling the tree.

PESTS AND DISEASES

Susceptibility to pests/pathogens

Sandalwood species are hemi-parasitic, with the potential to root-graft onto many species and link together plant communities. They are therefore at particular risk of pathogenic fungi such as *Phellinus noxius* that can also spread from tree to tree through root grafts.

Melanesian sandalwoods

Santalum austrocaledonicum

In New Caledonia plants are sometimes attacked by insects (*Ceroplastes* and *Coccus*), but damage is rather minor. Fungal damage has been observed on leaves of nursery seedlings. Plants are susceptible to brown root rot (*Phellinus noxius*).

Santalum yasi

Yasi is susceptible to brown root rot, and mature specimens may quickly succumb to it. This disease is potentially serious, as it can spread rapidly to adjacent trees through root grafting. In cool, wet, cloudy weather, seedlings can be attacked by a fungus (anthracnose type) that can cause severe leaf spotting (hypersensitive reaction) followed by defoliation. Seedlings are susceptible to root rot-fungi in poorly draining and unsterilized media. Yasi may be attacked by scale insects with lower leaves blackened by associated sooty mould, especially on the underside. This can become a problem for slow-growing plants in shadier situations.

The native sandalwood in India (*S. album*) is affected by Spike disease, which is spread by mycoplasma that causes dieback of branches and eventually can be fatal. It is thought that most *Santalum* species are susceptible to Spike disease. However, currently Spike disease mycoplasma are not present in the Pacific region.

Hawaiian sandalwoods

Hawaiian sandalwood species generally appear to resist most insect attack, although small infestations of whitefly or scale insects sometimes do occur. Insecticidal soap may be used to treat whitefly or scale insect infestations. Infrequently, a small grey weevil feeds on the young leaves, but usually does not cause significant damage. Some insects such as cockroaches, sow bugs, crickets, and a variety of cutworms may nibble at ground-level stem parts. Slugs and snails may also feed on newly sprouted plants and may need to be manually or chemically controlled. To avoid lethal girdling of seedlings by cutworms and other similar pests, a

Left: This mature *Santalum haleakalae* tree growing in pasture in Maui, Hawai'i is 3 m (10 ft) tall, with a trunk 30 cm (12 in) in diameter. Right: Demonstration of correct method for pruning young sandalwood in Efate, Vanuatu.

Brown root rot (*Phellinus noxius*) symptoms on a S. austrocaledonicum trees. This serious disease can quickly spread to other trees through root grafts.

protective barrier such as a plastic container should be used to protect each newly planted seedling.

DISADVANTAGES

Some factors holding back sandalwood cultivation are:

- lack of seed and planting materials
- lack of varieties or cultivars with known oil qualities and yields
- relatively complex silviculture and need to be grown with suitable host plant species
- susceptibility to root and butt rot fungi and rapid death of plants when grown in higher rainfall zones
- risk of theft of trees when nearing maturity
- Potential decline in world market price for sandalwood oil due to establishment of large plantations in Australia and Asia, and/or potential production of santalum-type oils (santalols) by genetically modified yeasts.

Potential for invasiveness

Sandalwoods have a good regeneration potential and ability to colonize/invade nearby suitable sites. Birds spread the fruit from mature, fruit-bearing trees. Their invasive potential, however, is seldom considered a drawback due to the exceptionally high value of their heartwood. Furthermore, their small stature and susceptibility to being shaded out means they never become dominant and/or substantially modify or replace existing plant communities.

There is a risk that some planted host species, especially exotic leguminous trees, might become invasive. Accordingly, it is recommended that local plant species are screened first for suitability as hosts and used preferentially, especially in and around areas of high conservation value.

COMMERCIAL PRODUCTION

Postharvest handling and processing

The principal commercial products from sandalwood are the heartwood and the essential oil distilled from the heartwood. One of the key advantages of growing sandalwoods is their high-value, non-perishable product (heartwood) that can provide cash income even when grown on a small scale and in outer island locations remote from markets.

Preparing the heartwood for market begins with whole tree harvesting, including collection of major roots and larger branches that contain heartwood. The main on-farm processing consists of careful removal of the bark and most of the sapwood, using an adze or sharp knife, but preferably leaving a thin covering of lighter coloured sapwood. The sawdust created from cutting the bole and branches into billets should be collected, as it is also marketable.

It is anecdotally reported that sandalwood logs stored in dry conditions for several months may exhibit small increases in oil content and improvement in quality, but this is at least partly off-set by a lower weight due to water loss.

Value-added processing

Essential oil

Sandalwood essential oils are extracted by the technologically simple process of steam distillation. In some cases it might be economically feasible to establish a community facility for distillation of oil and thus add to community income generation compared to sales of heartwood alone. Depending on sandalwood species the value of the extracted heartwood oil is typically 20–50 times the value of the heartwood (but which may only contain 2–3% oil content). Economic analyses of the estimated returns in Fiji from several scenarios in the production of *S. yasi* heartwood and oils showed that community oil production in conjunction with intercrops provide the greatest returns. While these scenarios are hypothetical, a practical, working example of what can be achieved through community collaboration in sandalwood oil production can be found on Mare Island and on Isle of Pines, New Caledonia. Here community distillation plants run by village cooperatives have been successfully producing and marketing oil of *S. austrocaledonicum* for several years (See "Example Successes" below).

The main requirements for establishing a successful collaboration in sandalwood oil production are:

- adequate and sustainable supply of raw material (heartwood) with due consideration of the long rotation lengths (minimum of 17–20 years) and average oil yields and oil qualities
- a village social structure that facilitates collaboration and is capable of organizing and controlling the operation including ensuring that adequate labour will be available for harvest, wood processing, and distillation (continuous distillation durations of 48 to 72 hours are standard and require shift workers)
- adequate financial resources
- equipment available to finely chip the heartwood to the size of coarse sawdust, ca. 1 mm thick and 4–5 mm long (recommended)
- an appropriate distillation apparatus including water supply for condensation and fuel (ideally a sustainable supply of biomass) for distillation
- appropriate containers and apparatus for packaging the oil
- an assured market offering an economically viable price for the oil produced.

A simple distillation apparatus is made entirely of stainless steel, as the oil interacts with mild steel affecting oil colour and quality. The apparatus consists of a pot (usually 0.5–1.0 m^3 [132–264 gal] capacity) either placed above a water bath heated from below by a locally produced and sustainable fuel (e.g., wood, coconut husks, spent charge), or receiving steam at the bottom of the charge from a separate steam boiler. An apparatus employing hydro-distillation, as in the first case above, is not pressurized, while steam from a boiler can be injected at slight pressure (1.4–2.8 kg/cm^2) to speed up oil extraction. The oil is separated from the distillate through a stainless steel condenser receiving a steady flow of cool water (gravity-fed or mechanically pumped) from a nearby stream or tank. The resulting lighter-than-water sandalwood oil will be tapped from a stainless steel collector designed for this purpose. The oil thus produced should be free of impurities and can usually be packaged at the still for transport and sale to the broker or end-user that is responsible for any further processing of the oil.

Design of an appropriate distillation apparatus, giving due consideration to the local circumstances, is a specialist field, and expert help should be sought before embarking on construction or procuring off-the-shelf stills.

Wood

Sandalwood heartwood is highly regarded by wood carvers and high prices are paid for the largest and relatively defect-free sections of tree trunks. The roots, larger branches and parts of the tree trunk unusable by wood carvers are used for oil production.

Heartwood sawdust, branches with a mere hint of heartwood formation and spent charge (heartwood chips after distillation) are all marketable. These can be ground to a fine powder used in the manufacture of incense sticks (joss-sticks) and for other religious or non-religious purposes in Asia (Weiss 1997).

Product quality standards

Oil composition of any sandalwood of international commerce is invariably judged by its comparison with that of the oils of *S. album* (Indian sandalwood), the benchmark species from India and Indonesia. Indian sandalwood oil is described by Weiss (1997) as a pale yellow (aging to golden yellow) viscous liquid of great tenacity, which gives off a soft, sweet-woody animal balsamic odour. It is widely used in the fragrance and cosmetic industries, especially in the manufacture of fine perfumes, where it displays excellent blending and fixative properties for other fragrances, e.g., in the manufacture of rose attar in India (Coppen 1995, Weiss 1997). Indian sandalwood oil is classed as a non-toxic, non-irritating, non-sensitizing oil (Tisserand and Balacs 1995) and also finds use in folk medicines and aromatherapy (Weiss 1997).

Oil quality of Indian sandalwood is defined by an International Standard (ISO/FDIS 3518 2002). The two main desirable oil constitutes are alpha (α) and beta (β) santalols with a combined total content of santalols up to 90%. The ISO standard range for alpha (α) is between 41–55% and beta (β) is 16–24%. This standard has been set due to the great variation in the occurrence and concentration of santalols among sandalwoods (Doran et al. 2005a).

Oil concentration in sandalwood heartwoods varies within and between species and is greatest in older trees. Within a particular species, both oil concentration and quality (santalol content) is highest usually in the main woody roots near the base of the stem (up to 10% for *S. album*) and lowest in chips of a mixture of heartwood and sapwood (1.5–2% for *S. album*). There are few published estimates of oil concentration for the Pacific sandalwoods. The mean oil concentration of commercially distilled *S. austrocaledonicum* in Vanuatu ranges from 3.0% to 4.6% (Peter Murphy, pers.

comm. 2005, cited in Page et al. 2007). These yields are consistent with those reported for *S. album* in India (Coppen 1995, Weiss 1997). Page et al. (2007) reported large differences in *S. austrocaledonicum* oil concentration (0.05%–8%) within and between island populations of Vanuatu (from <1.5% on Aniwa to >3.5% on Malekula).

Variation in oil composition follows similar trends. Doran et al. (2005a), in a review of knowledge on commercial sandalwoods, reported that *S. yasi* commonly produce oils with 60–70% total santalols while *S. austrocaledonicum* also produced oils with high levels of santalols (60%) along with low santalol-yielding forms with substantial proportions of Z-nuciferol (7–25%) and/or Z-lanceol (15–41%) were also present often in the same population. Page et al. (2007), in a systematic study of the oils of Vanuatu *S. austrocaledonicum* populations, found continuous variation in all the major essential oil constituents in the species and concluded that chemotypes are not present as had been previously been suggested (Ehrhart and Raharivelomanana 1998).

Hawaiian sandalwoods

There is no contemporary literature describing the oil qualities of the Hawaiian sandalwoods. Ball (1916) gave the following account of oil steam distilled from the heartwood of *S. freycinetianum* and assayed by wet chemistry methods, "The resulting oil amounting to 0.75–1% of the weight of the wood taken, was a clear yellow, somewhat thick liquid of a characteristic aromatic odour, but much milder and less pungent than the sandalwood oil of commerce…The oil was assayed for santalol according to the method outlined in the U.S. Pharmacopeia VIII, and the percentage of santalol found to be 96–97%…it is readily seen that the oil of this species of sandalwood compared favorably with the better grade of oil of *Santalum album*, which assays from 90–98% santalol. The oil of *Santalum freycinetianum* meets the requirements of sandalwood oil according to the U.S. Pharmacopeia VIII."

Product storage requirements and shelf life

Sandalwood oil is a high value product and should be stored in appropriate containers and under conditions that do not cause any change in the composition of the oil even after long storage periods. In order to minimize degradation and oxidation, containment of the oil should be in nearly full, tightly sealed (avoid plastic or rubber seals), dark glass, stainless steel or perfumery industry alloy containers stored in a cool, dark and dry place.

Recommended labeling

Sandalwood oil producers and brokers need to familiarize themselves with the requirements for labeling, packaging and the regulations governing air, land, and postal shipment of their oils to particular countries. Ideally, labels on pure sandalwood oils should give the botanical name of the species, country of origin and method of distillation. A Materials Safety Data Sheet for the particular sandalwood oil will most likely be required (the oil is still classified as hazardous in some countries such as Australia, even though it is a non-flammable liquid).

SMALL SCALE PRODUCTION

Sandalwood trees are ideal for home gardens and can be easily grown together with a mixture of ornamental and productive plants. They grow very well next to walls/fences and with low growing ornamentals (which provide the benefit of being host plants but do not overshade the sandalwood). Due to the high value and demand for even a single mature tree, there is effectively no minimum area or number of trees required for commercial production. They are well suited to commercial production on small urban lots to supplement

Steam distillery apparatus for sandalwood oil at Tropical Rainforest Aromatics, Vanuatu.

incomes. They are also suitable for planting on small farms, through incorporating into windbreaks and/or boundary plantings. Whilst mature sandalwood fruits are edible and have good nutrient values, they are generally considered too small or sour/bitter to be consumed. The crop has local medicinal and other uses, but is generally sold to provide income. Rather than acting as an import substitute, sandalwoods have high potential to provide cash income that can be used to buy needed products.

As discussed above, sandalwood can be converted into a valuable essential oil, but usually this activity would need to be undertaken on a village or more highly aggregated level to ensure supply of enough raw material. On a small family farm, the most appropriate value adding is to remove sapwood. A single bole should be encouraged through early, regular pruning and removal of competing leaders in order to maximize potential for development of carving-grade logs (>10–15 cm [4–6 in] diameter heartwood).

YIELDS

Expected range of yields per plant

The yield of heartwood typically varies by species, location, age of the tree and individual phenotype. Annual increases in girth of 5–6 cm/yr (2–2.2 in/yr) have been recorded for irrigated plantations of *S. album* in the Kimberley region of Western Australia, with heartwood produced as early as 3 years of age and rotation lengths of 13 years proposed for a heartwood oil concentration approaching 3%. Similar growth and heartwood yields are possible for native Pacific Island sandalwoods, including *S. austrocaledonicum* and *S. yasi*, grown in well managed and maintained plantings. Even higher rates of growth and heartwood sequestration are expected with good F_1 hybrids (*S. yasi* × *S. album* and *S. austrocaledonicum* × *S. album*).

However, after a study of the heartwoods of young planted or naturally regenerating *S. yasi*, *S. album,* and their hybrid in Fiji, Tonga and Niue, Doran et al. (2005b) concluded that rotation lengths of 25–30 years may be required to ensure that most trees give high yields of heartwood.

The plantation area required to provide raw material for a small- to medium-scale oil distillation operation of *S. austrocaledonicum* is estimated to be about 60–120 ha (150–300 ac), based on a 30-year rotation. Such an operation can produce 800 liters per annum (845 qt/yr) from 20–40 MT (22–44 t) of heartwood.

Recommended planting density

Spacing for commercial production varies considerably depending on the type of planting. A final crop stocking of around 100 mature sandalwood trees per hectare (10 × 10 m [33 × 33 ft]) is recommended for smallholder plantings in Pacific islands due, in part, for the need to include host tree/shrub species at a rate of 2–4 host plants for each sandalwood, depending on host species. Planting of sandalwood at too high a stocking and with too few hosts is a common mistake in cultivation of sandalwoods throughout the Pacific and one that inevitably results in disappointing results or crop failure.

Commercial producers of Indian sandalwood in Australia grow sandalwood on a 15-year rotation under intensive silviculture including irrigation. They aim for a final stocking of 400 sandalwood stems/ha. Long-term hosts are planted at 660 stems/ha (260 stems/ac). Short-term or intermediate hosts are included and are planted at 500 stems/ha (190 stems/ac). The host stem to sandalwood stem ratio is about 3:1, at least for the early growing period of the plantation.

MARKETS

Local markets are generally not important or relevant for sandalwoods grown in Pacific islands. There are three distinct markets for sandalwood: 1) sapwood (white chips) and spent powder for incense manufacture and other religious purposes; 2) heartwood for handicrafts; and 3) sandalwood oil for cosmetics and fragrances. The first two markets account for only 20% of the annual sandalwood harvest in India, the world's major sandalwood producer, while 80% is used in oil production.

The difficulties of providing accurate statistics for the sandalwood industry arise from producer secrecy. Furtive activities include the substantial level of undocumented illegal harvesting and smuggling in India and the widespread use of substitutes (e.g., *Osyris lanceolata* Hochst. and Steud. oil from Tanzania, and known as East African sandalwood oil) and adulterants (e.g., polyethylene glycols, castor oil, and coconut oil) as reported in Chawla (2008).

Annual global demand for sandalwood heartwood has been generally estimated to be approximately 5,000–6,000 MT, however, production has declined markedly over the past 20–30 years. China, Taiwan, Singapore, Korea, and Japan, with no natural resources of sandalwood, are the main markets, together with India, which has its own production capability. Production of sandalwood heartwood from the South Pacific is highly variable, experiencing periods of boom and bust since exploitation commenced in the early 1800s (Shineberg 1967). Vanuatu has a sustainable harvest rate estimated to be 80 MT/yr; the average harvest between 2000 and 2009 was 95 MT/yr, with a range of 70–120 MT/yr. The annual harvest quota in New Caledonia is 55-60 MT. In Tonga, sandalwood exports recently peaked in 2007 at 203 MT, and then subsequently plummeted to only 8 MT in 2008. A similar situation occurred in Fiji with 306 MT harvested in 2008, plummeting to 46 MT in 2009.

Current world demand for sandalwood oil was estimated in conference papers to be about 250 to 300 MT/yr, which equates to over 15,000 MT of wood. India (85% of world production) produces about 120–150 MT of sandalwood oil per year with about 80 MT/yr used domestically and the remainder exported (ca. 40 MT/yr), Indonesia (10% of world production) exports about 15 MT/yr, while other sources including substitutes accounted for 5% (7.5 MT/yr) of world production. If these estimates of global production are correct, it can be deduced that there is a current shortfall in oil production of at least 100 MT/yr.

Details of *S. austrocaledonicum* oil export from New Caledonia and Vanuatu are unavailable publicly. Lincoln (2008) reported that the Lush Co. uses 1 MT/yr of New Caledonian sandalwood oil but the sustainability of this harvest has been questioned by Burfield (2009). It is probable that sandalwood oil production in Vanuatu reaches similar levels (i.e., ± 1 MT/yr). Currently only a small amount of *S. yasi* oil is being produced in Fiji and Vanuatu (from heartwood imported from Fiji).

The main importers of sandalwood oil are Europe and the U.S., the latter of which is the single largest market outside India. Prices are high as a consequence of demand exceeding supply. For example, a George Uhe Co Market Report (2009) gives a price for top-quality *S. album* E.I. oil of US$2,000/kg (US$900/lb, cost plus air freight) in limited quantities and Sri Lankan *S. album* oil at US$1,550/kg (US$700/lb, cost plus air freight).

Historically, *S. austrocaledonicum* and *S. yasi* heartwood and oils have not commanded the same price as *S. album* because of their chemical variability and odour profiles deemed inferior to *S. album* by the market. This problem can be ameliorated by the careful grading of heartwood with the top grades providing oil equivalent (or even superior) to high grade *S. album* oils and attracting prices of US$800/kg (US$360/lb, cost plus air freight) for quantities of 50 kg (23 lb) or more and up to US$2,000/kg (US$900 cost plus air freight) for 1 kg (2.2 lb) quantities.

Specialty markets

A number of fragrance companies purchasing sandalwood oil have adopted sustainable supply and fair trade policies (Choueiri 2008, Lincoln 2008) and this trend is likely to increase. In the future, Pacific producers of sandalwood and sandalwood oil will need to demonstrate sustainability (e.g., Rainforest Alliance certification) and legality (e.g., Forest Stewardship Council certification) if they want to access higher paying markets in Europe, the U.S., and elsewhere.

A niche market focus for Vanuatu sandalwood is based on the customer intimacy model. This would entail establishing supply chains that focus on a few appropriately sized, premium niche markets in which the buyer places a significant commercial value on developing long-term relationships with suppliers. Ideally these Vanuatu suppliers would be independently certified as practicing sustainable, ethical production systems, whilst also producing high quality products in accordance with predetermined quality standards (Page et al. 2010a).

Branding

Pacific island producers of sandalwood may develop unique brands and products based on local species and sources in order to remain competitive with large, new plantation sources of *S. album* sandalwood from Australia and China. For example, some sources of *S. yasi* have higher levels of β-santalols than *S. album*, which may be keenly sought after by perfumers.

Potential for Internet sales

There is high potential for Internet sales, and this is already occurring both for sandalwood oils and for larger carving pieces that are individually auctioned on the Internet.

EXAMPLE SUCCESSES

New Caledonia

As in other Pacific islands, sandalwood has been subjected in the past to over-exploitation dating back to the early 1800s in the French Territory of New Caledonia. In 1988 an inventory of *Santalum austrocaledonicum* was carried out on the Loyalty Islands and the Isle of Pines to determine an acceptable annual harvesting rate for each island. A follow-up inventory in 1994 suggested sustainable cutting rates of heartwood per year of 30 and 45 MT, respectively. The aim of sandalwood management is to regenerate and sustain the resource while maintaining the activity of local distillation units. The distilleries on Maré (Loyalty Islands) and on the Isle of Pines (Wapan tribe) are now owned by local tribes, and each have 3–4 full time employees. During the period 2003–2008, between 45 and 53 MT/yr was harvested by local tribes for distillation. The Maré distillery produces 600 kg of essential oil per year, while the Isle of Pines distillery produces 1,000 kg per year. Depending on market and quality, the essential oil from *S. austrocaledonicum* sells for anywhere between US$500–1,000/kg (in 2009) in North America and Europe and is used in high quality perfumery, aromatherapy, and beauty care products.

Negotiations between the Kanak chief landowner representatives and Government determine the locality for sandalwood harvesting each year. Forest officers identify and mark mature trees, typically in excess of 50 years, and greater than 12 cm dbh before any tree can be harvested. A policy of replanting has been put in place by the New Caledonian Authorities. For every sandalwood tree harvested, three sandalwood seedlings are replanted, but probably on average

Processing at the sandalwood oil factory on Maré Island, Loyalty Group, New Caledonia. Top: Incoming logs. Middle: Chipped logs ready for the distillation process. Bottom: Wood-fired oven.

only one will reach through to maturity. The seedlings are planted in carefully chosen microsites in the slightly disturbed, and more open secondary bush where sandalwood grows best and in areas from which trees have been recently harvested.

Since 2003, these operations have been an excellent example of small-scale sandalwood distillation, providing valuable income for the local population, whilst maintaining sandalwood resources and their genetic integrity by using local seed sources. In future, when Indian sandalwood oil is being produced in greater quantities in plantations, it is anticipated that the New Caledonian sandalwood oil will still have good market prospects as a promising raw material for the fragrance industry with interesting odour properties.

Pacific Reforestation Fiji Pty Ltd, Fiji (Mr. Wilson Chow, Director)

Pacific Reforestation Fiji (PRF) has been undertaking research and development on sandalwood and other high value tree species in Fiji since the early 1990s. The company has developed state-of-the-art technologies for propagation, establishment, and management of sandalwood in a humid zone of Fiji, building on the work of the Silvicultural Research Division of the Fiji Forestry Department. Over the past five years, PRF has established 5 ha of sandalwood plantations in Naitisiri Province, Fiji. These plantings comprise mainly *Santalum yasi*, *S. album*, *S. austrocaledonicum,* and seedling hybrids, as well a large number of grafted F_1 hybrids that are grafted onto any available sandalwood rootstock.

In parts of Fiji where *Santalum album* has been planted near to *S. yasi*, the two species spontaneously hybridize. Natural seedling regeneration is initially a mixture of pure species and hybrids, but within a few months the seedlings of both pure species usually die out, leaving almost solely hybrids. The F_1 hybrid of *Santalum album* and *S. yasi* has the best growth rate in more humid zones (>2,000 mm [80 in] rainfall per year). PRF is presently achieving high rates of sandalwood survival (>80%) and height growth rates of around 2 m/yr (6.5 ft/yr) through use of high quality planting stock (>25 cm [10 in] tall at planting), mounding of plantings sites, trenching and incorporation of biochar to improve drainage, and use of diverse and appropriate host species. The main host species currently being used are *Acacia auriculiformis, Acacia crassicarpa*, *Alternanthera* spp., *Arachis pintoi*, *Casuarina equisetifolia*, *Calliandra surinamensis*, *Citrus* spp., *Dalbergia cochinchinensis*, *Flueggea flexuosa*, and *Swietenia macrophylla*.

A major risk to growing sandalwoods in humid zones is root rot fungi, and care is taken to remove diseased plants and rotten timber to minimize the spread of *Phellinus noxious* (brown butt rot). Sandalwood regeneration is also occur-

Left: *Santalum* hybrid stand at Naitisiri, Fiji. Host plants include *Swietenia, Flueggea,* and *Casuarina* and intercrops include taro (*Colocasia esculenta*) and bananas. Right: Close-up of a hybrid sandalwood tree.

ring through root suckering, which occurs when there is any damage to roots. Such regeneration can be useful so long as it not too dense, as it has potential to slow growth of original parent, and is more susceptible to being blown over in strong or cyclonic winds. More vigorous hosts such as *Calliandra calothyrsus* require frequent pruning to prevent them from shading and suppressing sandalwood saplings. PRF has been producing essential oils of primarily *Melaleuca* and *Leptospermum* species in Fiji for about 10 years, and plans to produce sandalwood oil once its plantations mature and have a high proportion of heartwood.

ECONOMIC ANALYSIS

An economic analysis was undertaken of a model sandalwood (*Santalum yasi*) agroforestry system for Vanua Levu, Fiji (Sanfred Smith and Lex Thomson, pers. comm., 2010). This system involved planting sandalwood at wide spacing (100 stems/ha, 40 stems/ac) with agricultural intercrops throughout the entire projected sandalwood rotation of 20 years. In the first 3 years, the agricultural intercrops were peanut and sweetpotato, while the intercrops from years 4–20 were kawai (sweet yam, *Dioscorea esculenta*), passion fruit (*Passiflora* sp.) and watermelon (*Citrullus lanatus*). The main input costs (in US dollars) were for planting materials of sandalwood trees ($175/ha, $70/ac), and hosts ($75/ha, $30/ac), fertilizer in first 3 years ($125/ha, $50/ac), labour for planting and maintenance especially in early years ($90/ha [$36/ac] in Year 1 to $30/ha [$12/ac] in later years). The major inputs for intercrops species were seedlings/seeds, fertilizers, chemicals, crops and labour. The average estimated heartwood yield per sandalwood was 30 kg (66 lb), and the price used was $35/kg (current market price). The economic returns were highly favourable with an internal rate of return of 20% and a net present value of approximately $106,000/ha ($42,400/ac) using an interest rate of 8%.

An economic analysis of smallholder sandalwood (*Santalum austrocaledonicum*) plantings in Vanuatu with 833 trees planted found that total earnings after 15–20 years would be approximately US$150,000, which, after accounting for all capital and labour inputs, would have a net present value of approximately US$14,500, using a discount rate of 10%, a heartwood price of US$10/kg, and 18 kg of heartwood per tree (Page et al. 2010b).

FURTHER RESEARCH

Potential for crop improvement

Superior germplasm sources exhibiting disease resistance, rapid growth, good bole form, early heartwood formation, and desirable heartwood oil composition are being developed for *S. album* in India, Indonesia, and Australia. Substantial numbers of candidate plus trees have been identified (e.g., 79 candidate plus trees in southern India). Progeny trials of *S. album* have been established on multiple sites in India, Indonesia, and Australia, and seed stands and clonal seed orchards have been developed in India (Karnataka and Andhra Pradesh) to provide improved seed for planting programs (CABI 2001, Chawla 2008). Chawla (2008) reported that the first generation progeny from these clonal seed orchards are performing well. Investigations into clonal multiplication of *S. album* are continuing and it has been shown that it is possible to use tissue culture for the rapid multiplication and propagation of selected parent trees (see CABI 2001). Dey (2001) discusses the usefulness of somatic embryogenesis in *S. album* multiplication.

In comparison to *Santalum album* there has been much less improvement work on Pacific Island sandalwood species. Seed orchards of selected phenotypes have been established in the Cook Islands (*S. album*), Fiji (*S. yasi* and *S. album*) and Vanuatu (*S. austrocaledonicum*) (refer to papers in Thomson et al. 2007).

Improving potential for family or community farming

Sandalwood production is well suited for small-scale production. There is an urgent need for more high-quality sandalwood seedlings to be propagated and distributed at reasonable cost either by government or private nurseries in all Pacific island countries where sandalwood is being grown.

Genetic resources where collections exist

Seed of the candidate plus trees of *S. album* in India are maintained at Indian Council of Forestry Research and Education's Institute of Wood Science and Technology Germplasm Bank in Gottipura, Bangalore, Karnataka (Chawla 2008). In Indonesia the responsible body is the Centre for Forest Biotechnology and Tree Improvement, Yogyakarta.

In the case of the Pacific sandalwoods, national Forestry Departments usually hold seed stocks of indigenous sandalwoods and sometimes exotic species like *S. album* (e.g., Fiji and Tonga). Commencing in 2011 the recently established Tree Germplasm Unit of Secretariat of the Pacific Communities' Centre for Pacific Crops and Trees (CePaCT) in Suva, Fiji will be facilitating the exchange of germplasm of important Pacific island trees including sandalwoods.

REFERENCES CITED AND FURTHER READING

Anon. 2009. Marketing Report—Socio-economic constraints to smallholder sandalwood in Vanuatu. ACIAR FST/2007/057.

Ball, A.A. 1916. The oil of *Santalum freycinetianum* Gaud. In: Rock, J.F. (ed.). The Sandalwoods of Hawaii: A revision of the Hawaiian species of the genus *Santalum*. p 15. Terr. Hawaii, Board Agr. and For., Bot. Bull. 3.

Buck, P. 1964. Arts and Crafts of Hawaii. Publication 45. Bishop Museum, Honolulu.

Burfield, T. 2009. Sandalwood—a critical view of developments. Cropwatch, February 2009. http://www.cropwatch.org/sandalcrit.pdf.

CABI. 2001. *Santalum album*. Global Forestry Compendium. CD-ROM. CAB International, UK.

Chawla, G.S. 2008. The demise of India's supply: resorting to substitutes to meet demand. Paper to TFS Sandalwood Conference—Revolutionising the Global Indian Sandalwood Supply: Creating a Sustainable Supply of Indian Sandalwood Oil and Wood, Kununurra, WA 2008.

Choueiri, A. 2008. Sandalwood in luxury perfumery and the interest of sustainable supply and fair trading. Paper to TFS Sandalwood Conference—Revolutionising the Global Indian Sandalwood Supply: Creating a Sustainable Supply of Indian Sandalwood Oil and Wood, Kununurra, WA 2008.

Coppen, J.J.W. 1995. Flavours and Fragrances of Plant Origin. Non-Wood Forest Products 1. FAO, Rome.

Culliney, J.L., and B.P. Koebele. 1999. A Native Hawaiian Garden: How to Grow and Care for Island Plants. University of Hawai'i Press, Honolulu.

Dey, S. 2001. Mass cloning of *Santalum album* L. through somatic embryogenesis: scale up in bioreactor. Sandalwood Research Newsletter 13: 1–3.

Doran, J.C., L.A.J. Thomson, and J.J. Brophy. 2005a. Sandalwood—a global perspective. pp 29–49. In: Thomson, L., Bulai, S. and Sovea, L. (eds). Proceedings of a regional workshop on sandalwood research, development, and extension in the Pacific Islands and Asia (3rd: 7–11 October 2002: Noumea, New Caledonia). Secretariat of the Pacific Community, Suva, Fiji.

Doran, J., L.A.J. Thomson, J.J. Brophy, B. Goldsack, P. Bulai, T. Faka'osi, and T. Mokoia. 2005b. Variation in heartwood oil composition of young sandalwood trees in the South Pacific (*S. yasi*, *S. album* and F1 hybrids in Fiji, and *S. yasi* in Tonga and Niue). Sandalwood Research Newsletter Issue 20: 3–7.

Ehrhart, Y., and P. Raharivelomanana. 1998. Oil composition of the sandalwood (*Santalum austrocaledonicum*) from Erromango and Aniwa islands, Vanuatu. CIRAD-Forêt, Nouvelle-Calédonie.

Fosberg, R. 1962. Miscellaneous notes on Hawaiian plants—3. Occasional Papers of the Bernice P. Bishop Museum 23 (2): 29–44. Honolulu.

Gowda, V.S.V., and B.H.A. Kumar. 2008. Decline in supply of natural sandalwood oil: deforestation, adulteration and synthetics. Paper to TFS Sandalwood Conference—Revolutionising the Global Indian Sandalwood Supply: Creating a Sustainable Supply of Indian Sandalwood Oil and Wood, Kununurra, WA.

Harbaugh, D.T., and B.G. Baldwin. 2007. Phylogeny and biogeography of the sandalwoods (*Santalum*, Santalaceae): repeated dispersals throughout the Pacific. American Journal of Botany 94 (6): 1030–1042.

Harbaugh, D.T., H.L. Oppenheimer, K.R. Wood, and W.L. Wagner. 2010. Taxonomic revision of the endangered Hawaiian red-flowered sandalwoods (*Santalum*) and discovery of an ancient hybrid species. Systematic Botany 35 (4): 1–12.

International Standard ISO/FDIS 3518. 2002 (Final Draft). Oil of sandalwood (*Santalum album* L.) ISO, Geneva.

Judd, C.A. 1926. The natural resources of the Hawaiian forest regions and their conservation. Territorial Division of Forestry. Unpublished manuscript.

Kepler, A.K. 1985. Sandalwood: Hawaii's precious ʻiliahi. Mauian 2(6): 6–11.

Krauss, B.H. 1993. Plants in Hawaiian Culture. University of Hawaiʻi Press, Honolulu.

Lincoln, M. 2008. Sourcing a sustainable supply—the Lush ethos and the TFS partnership. Paper to TFS Sandalwood Conference—Revolutionising the Global Indian Sandalwood Supply: Creating a Sustainable Supply of Indian Sandalwood Oil and Wood, Kununurra, WA.

Little, E.L., and R.G. Skolmen. 1989. Common Forest Trees of Hawaii (Native and Introduced). Agri. Handbook 679. US Forest Service, Washington, DC.

Merlin, M., and D. VanRavenswaay. 1990. The history of human impact on the genus *Santalum* in Hawaii. In: Hamilton, L., and C.E. Conrad (eds.). Proceedings of the Symposium on Sandalwood in the Pacific, April 9–11, 1990, Honolulu, Hawaiʻi. General Technical Report PSW–122. Pacific Southwest Research Station, USDA Forest Service, Berkeley, California.

Merlin, M.D., L.A.J. Thomson, and C.R. Elevitch. 2006. *Santalum ellipticum, S. freycinetianum, S. haleakalae,* and *S. paniculatum* (Hawaiian sandalwood). Traditional Trees of Pacific Islands: Their Culture, Environment, and Use. pp 695–714. Permanent Agricultural Resources, Holualoa, Hawaii. http://www.traditionaltree.org

Padmanabha, A. 2008. Indian sandalwood—the history, the uses, the future of supply. Paper to TFS Sandalwood Conference—Revolutionising the Global Indian Sandalwood Supply: Creating a Sustainable Supply of Indian Sandalwood Oil and Wood, Kununurra, WA.

Page, T., H. Tate, C. Bunt, A. Potrawiak, and A. Berry. 2010a. Socio-economic constraints to smallholder sandalwood in Vanuatu. Project Final Report FST/2007/057. Australian Centre for International Agricultural Research, Canberra.

Page, T., A. Potrawiak, A. Berry, H. Tate, J. Tungon, and M. Tabi. 2010b. Production of sandalwood (*Santalum austrocaledonicum*) for improved smallholder incomes in Vanuatu. Forests, Trees and Livelihoods 19, 299–316.

Page, T., I. Southwell, M. Russell, H. Tate, J. Tungon, C. Sam, G. Dickinson, K. Robson, and R.R.B. Leakey. 2010. Geographic and Phenotypic Variation in Heartwood and Essential-Oil Characters in Natural Populations of *Santalum austrocaledonicum* in Vanuatu. Chemistry & Biodiversity. 7(8):1990–2006.

Page, T., H. Tate, J. Tungon, C. Sam, G. Dickinson, K. Robson, I. Southwell, M. Russell, M. Waycott, and R.R.B. Leakey. 2007. Evaluation of heartwood and oil characteristics in nine populations of *Santalum austrocaledonicum* from Vanuatu. In: Thomson, L., S. Bulai, and B. Wilikibau (eds.). Proceedings of a regional workshop on sandalwood research, development, and extension in the Pacific Islands and Asia (4th: 28 Nov–1 Dec 2005: Nadi, Fiji). pp 123–129. Secretariat of the Pacific Community, Suva, Fiji.

Shineberg, D. 1967. They Came for Sandalwood: A Study of the Sandalwood Trade in the South-west Pacific 1830–1865. Melbourne University Press, London and New York.

Stemmermann, R.L. 1980. Observations of the Genus *Santalum* (Santalaceae) in Hawaii. Pacific Science 34(1): 41–54.

St. John, H. 1947. The history, present distribution, and abundance of sandalwood on Oʻahu, Hawaiian Islands. Hawaiian Plant Studies 14, 1(1): 5–20.

Thomson, L.A.J. 2006. *Santalum austrocaledonicum* and *S. yasi* (sandalwood). In: Elevitch, C.R. (ed.). Traditional Trees of Pacific Islands: Their Culture, Environment, and Use. pp 675–694. Permanent Agricultural Resources, Holualoa, Hawaii. http://www.traditionaltree.org

Thomson, L., S. Bulai, B. Wilikibau (eds.). 2007. Proceedings of a regional workshop on sandalwood research, development, and extension in the Pacific Islands and Asia (4th: 28 Nov–1 Dec 2005: Nadi, Fiji). Secretariat of the Pacific Community, Suva, Fiji.

Tisserand, R., and T. Balacs. 1995. Essential Oil Safety. Churchill Livingstone, London, UK.

Wagner, J.P. 1986. The rape of the fragrant trees. Honolulu. Magazine, November, 97 ff.

Wagner, W., D. Herbst, and S. Sohmer. 1999. Manual of Flowering Plants of Hawaii, Vol. I and II, rev. ed. Bishop Museum Press, Honolulu.

Weiss, E.A. 1997. Essential Oil Crops. CAB International, Wallingford, UK.

Ziegler, M. 2003. E Hoʻomau I Ke Ola: ʻIliahi. Environment Hawaiʻi 13: 9 (March 2003).

Farm and Forestry Production and Marketing Profile for Sandalwood (*Santalum* species)

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