Australian Government
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Sandalwood Regional Forum

150
ACIAR PROCEEDINGS

Sandalwood Regional Forum

Proceedings of a regional meeting held in Port Vila, Vanuatu, 11–13 November 2019

Tony Page, John Meadows and Toufau Kalsakau (Editors)

ACIAR

2021

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Page T, Meadows J and Kalsakau T (eds) (2021) 'Sandalwood Regional Forum – proceedings of a regional meeting held in Port Vila, Vanuatu, 11–13 November 2019', *ACIAR Proceedings 150*, Australian Centre for International Agricultural Research, Canberra.

ACIAR Proceedings Series No. 150 (PR150)

ISSN 1038-6920 (print)
ISSN 1447-0837 (online)
ISBN 978-1-922635-74-7 (print)
ISBN 978-1-922635-75-4 (online)

Technical editing by Dr Joely Taylor
Design by Redtail Graphic Design
Printing by CanPrint
Cover: Vanuatu traditional performers open the Sandalwood Regional Forum, Port Vila, Vanuatu.

Foreword

Sandalwood from the Indo-Pacific region has been highly sought after for generations, with demand for its essential oil and heartwood remaining strong since it was first harvested more than 200 years ago.

As such, the sandalwood trade provides an important source of income for many smallholders in the region. However, wild sandalwood resources have been largely exhausted through overharvesting, fire and theft, and many countries are transitioning to planted sandalwood. This transition has been challenging, particularly for prospective smallholders in Asia and Pacific island countries seeking to optimise commercial returns from sales. Grower knowledge of sandalwood products and their associated prices is an essential element of favourable harvest and sales negotiations with traders.

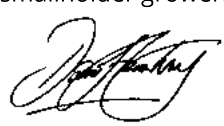
The Australian Centre for International Agricultural Research (ACIAR) was mandated, as set out in the ACIAR Act (1982), to work with partners across the Indo-Pacific region to generate the knowledge and technologies that underpin improvements in agricultural productivity, sustainability and food systems resilience. We do this by funding, brokering and managing research partnerships for the benefit of partner countries and Australia. Sandalwood has particular advantages for smallholders because it can be traded in very small volumes and has a high value-to-volume ratio.

For the past 30 years, ACIAR has invested in considerable research and development of best practices in the cultivation of sandalwood by smallholder farmers, and this has been exemplified by rapidly expanding areas of smallholder plantings.

These proceedings contain the research papers and abstracts of work presented at the Sandalwood Regional Forum in Vanuatu, in 2019. The forum was the ninth sandalwood-focused conference since 1990 and the proceedings bring together the latest knowledge and insight into sandalwood production and trade for smallholder farmers across the Asia-Pacific region.

These proceedings explore resource conservation and planting, propagation and domestication, heartwood biology and oil chemistry, species resource assessments and smallholder woodlots, product grading and standards, and value chains and marketing. While the publication is targeted at practitioners, extension agents, researchers, policy makers and industry representatives across the Asia–Pacific region, the knowledge and lessons gained from the forum contribute to improved management of the sandalwood resource at farm, community and policy levels.

Ultimately, the investment of ACIAR and its brokering of collaborative research and development will increase the sustainable supply of sandalwood and the incomes of smallholder growers, fulfilling the ACIAR mission.



Daniel Walker
Chief Executive Officer (Acting), ACIAR

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Acronyms and abbreviations

Term	Description
2CC	second cutting chips
4MT4Y	4 Million Trees in 4 Years initiative
30MT15Y	30 Million Trees in 15 Years initiative
ASL	above sea level
ACIAR	Australian Centre for International Agricultural Research
AGL	above ground level
BLUP	best linear unbiased prediction
CA	clonal archive
CD	committee draft
CFBTI	Centre for Forest Biotechnology and Tree Improvement
CPT	candidate plus tree
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CV	coefficient of variation
CYP	Cape York Peninsula
DBHOB	diameter at breast height over bark
DIS	Draft International Standard
DNA	deoxyribonucleic acid
ENT	East Nusa Tenggara
FDIS	Final Draft International Standard
FOB	free on board
FW	fresh weight
GC/FID	gas chromatography/flame ionisation detector
GC/MS	gas chromatography/mass spectrometry
GDP	gross domestic product
GG	genetic gain
GGT	genetic gain trial
GPS	global positioning system
GSO	grafted seed orchard
GTZ	German Agency for Technical Cooperation

Term	Description
HW	heartwood
ILG	Incorporated Land Group
IRR	internal rate of return
ISO	International Organization for Standardization
ISO/CS	International Organization for Standardization/Central Secretariat
ITTO	International Tropical Timber Organization
IUCN	International Union for Conservation of Nature
JV	joint venture
LSD	least significant difference
MAF	Ministry of Agriculture and Fisheries
MAFFF	Ministry of Agriculture and Food, Forests and Fisheries
MAI	mean annual increment
MFAT	Ministry of Foreign Affairs and Trade
NGO	non-government organisation
NIR	near-infrared
NIST	National Institute of Standards and Technology
NPA	Northern Peninsula Area
NPK	nitrogen-phosphorus-potassium
NPV	net present value
NTB	West Nusa Tenggara (Nusa Tenggara Barat)
NTT	East Nusa Tenggara (Nusa Tenggara Timur)
NWIP	new work item proposal
ODK	Open Data Kit
ORIA	Ord River Irrigation Area
PCA	principal component analysis
PIFON	Pacific Island Farmers Organisation Network
PNG	Papua New Guinea
PNGFA	Papua New Guinea Forest Authority
PT	progeny trial

Term	Description
SD	standard deviation
SE	standard error
SPA	seed production area
SPC	Pacific Community
SPRIG	South Pacific Regional Initiative on Forest Genetic Resources
SW	sapwood
TC/SC	technical committee or subcommittee
TTS	Timor Tengah Selatan
TTU	Timor Tengah Utara
VANWODS	Vanuatu Women Development Scheme
VCA	value chain analysis
VDoF	Vanuatu Department of Forests
VISA	Vanuatu Islands Sandalwood Association
WD	working draft
WG	working group

Units

Unit	Definition
cm	centimetre
cmAGL	centimetres above ground level
DBHOB	diameter at breast height over bark
FJD	Fijian dollar
g	gram
ha	hectare
K	Papua New Guinea kina
kg	kilogram
km	kilometre
kPa	kilopascal
kV	kilovolt
L	litre
m	metre
Ma	mega annum (one million years)
mAGL	metres above ground level
mASL	metres above sea level
mg	milligram
mL	millilitre
mm	millimetre
mmAGL	millimetres above ground level
m/z	mass/charge number of ions
ppm	parts per million
Rp	Indonesian rupiah
s	second
t	tonne, metric tonne (1,000 kg)
USD	US dollar
VUV	Vanuatu vatu
µm	micrometre

National reports

1 Building links between science, government and industry for sandalwood conservation and development in Vanuatu

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Introduction

In Vanuatu, all forests are owned by customary landowners, and these forests play an important part in the lives of the population who live on the 80 islands that make up this archipelago nation.

Sandalwood (*Santalum austrocaledonicum*) has been harvested and traded by Vanuatu landowners for centuries. Recently, effort has been devoted to regenerating this important natural resource in Vanuatu. Recognising its important economic value, the Government of Vanuatu, through the Department of Forests, identified sandalwood as one of the country's five priority tree species. Therefore, government and private promotion of sandalwood planting has led to a rise in smallholder plantings and some large-scale plantations.

Sandalwood is an important export product for Vanuatu, and one that is highly valued in the international marketplace. The series of Australian Centre for International Agricultural Research (ACIAR) projects since 2004 has boosted Vanuatu's work on increasing the volume and improving the quality of its sandalwood to remain internationally competitive.

Although this is encouraging, further new plantings are needed, and greater emphasis needs to be placed on improving management practices (silviculture) to improve the quality of sandalwood and retain its high-value, niche markets. This is particularly important because Vanuatu, due to its small land area and population, will always remain a small volume producer of sandalwood.

Sandalwood products

Sandalwood trees are highly valued for their fragrant heartwood oils and are recognised as one of the most precious non-timber forest products. The oils have been used for centuries for religious and customary purposes, and are now used internationally for cosmetics, aromatherapy, scenting of soaps, perfumery and medicines. The oil-bearing heartwood is also used for ornamental or ceremonial carvings, or powdered for the manufacture of incense joss sticks, which are valued in the international incense market.

Sandalwood market

The extraction and export of sandalwood was the first international industry in Vanuatu (well before copra production) and was driven primarily by Australian merchants.

The export of sandalwood to China began in the late 1820s and continued for 30 years. After this period, the sandalwood trade continued sporadically, most likely as sandalwood tree populations recovered and small commercial volumes became available. A modest commercial industry has been operating consistently in Vanuatu since the 1970s, with a current annual quota of 80 t.

Sandalwood is used mainly in India, Taiwan and Hong Kong, with smaller markets in Europe, Japan and North America. Vanuatu sandalwood production currently represents around 1% of world production; therefore, an increase in local production in Vanuatu is unlikely to have an impact on world markets and pricing.

The high demand for sandalwood products and the low level of commercial production of these trees have resulted in a sharp decline in the natural supplies of many sandalwood species. International prices for sandalwood have therefore risen consistently over the past few decades. In Vanuatu, the price paid to villagers for 1 kg of heartwood has risen at an annual rate of 10% since 1990.

Sandalwood regulation and management

The sandalwood trade is regulated and managed by the Vanuatu Department of Forests (VDoF) through a licensee system that also generates revenue from sandalwood heartwood and processed products that are traded and exported. The revenue is collected by the VDoF. The trade was first regulated by the 1997 law, *The Forestry (Management and Control of Sandalwood Trade and Exports) Order No. 3 of 1997 (repeal and replace Order 2004)*, with the purpose of introducing a system for licensing, collecting government royalties, and specifying a harvest season with limits placed on production levels.

The law states that:

> *The provision of this Order shall apply to any person who is involved in sandalwood harvesting, purchasing, trading, processing and/or export operations. The Order contains regulations regarding sandalwood licenses to carry out value addition/ processing or export of sandalwood heartwood. The Order gives power to the Director of Forestry to issue licenses, collect license fees, grant export permits, set minimum prices and manage the sandalwood trade in accordance with its mandate. All necessary forms for application of licenses or export of products are included. The Director of Forestry is responsible for the monitoring and collection of all license fees and export duties levied (% of export value) on behalf of the Government of Vanuatu and utilised directly for the management of sandalwood forests.*

Licensing system

Each year, a quota is set by the VDoF. For the last 2 years, the allowable quota of 80 t has been reduced to 60 t. Any person can apply to be a licensee. There were 17 licensees registered in 2019. The VDoF carry out a selection process using certain criteria to screen and select applicants who have genuine production and trading experience in sandalwood. Only paid-up licensees are allowed to legally buy sandalwood from farmers and export the product.

Conclusion

Vanuatu continues to appreciate that sandalwood is one of the most valuable commodities in Vanuatu. Sandalwood provides high-value, low-volume, non-perishable products that are in high demand on the international market.

Now that wild-harvested sandalwood no longer forms the basis of the Vanuatu sandalwood industry, it is important to join efforts for mass replanting programs. This requires active promotion of sandalwood planting by the government and private sector support to increase sandalwood stocks and make the sandalwood industry more sustainable.

Areas for developing the sandalwood industry in Vanuatu

- Continue to focus on the genetic improvement of Vanuatu sandalwood.
- Develop appropriate/improved sandalwood planting models that can be adopted by local farmers.
- Conduct oil analysis and hardwood development studies on planted sandalwood trees for the main geographical areas in Vanuatu.
- Undertake market research to improve the value of the planted resource and promote better understanding of our marketable products and market requirements.
- Remove market barriers and better regulate sandalwood harvesting and processing.
- More clearly define the sustainability of Vanuatu's sandalwood resource and the allocations system so that it is better suited for the future of the Vanuatu sandalwood industry.

2 Prospects for marketing sandalwood in Papua New Guinea

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Background to sandalwood in Papua New Guinea

The sandalwood species endemic to Papua New Guinea (PNG) is *Santalum macgregorii* F.v.Muell. This species is not evenly distributed throughout PNG. It occurs naturally in the country's south-west region (Figure 2.1), primarily in the Central Province around Port Moresby and in a small adjoining area of the Gulf Province. There are also small populations recently discovered in the Buzi and Ber areas of Western Province. Harvesting of *S. macgregorii* in PNG dates back to the early 1800s. In more recent decades, there have been reports of sporadic overharvesting by locals for trading (Paul 1990). Due to this overharvesting, there is an urgent need for interventions to consider the future sustainable supply and production of sandalwood in PNG.

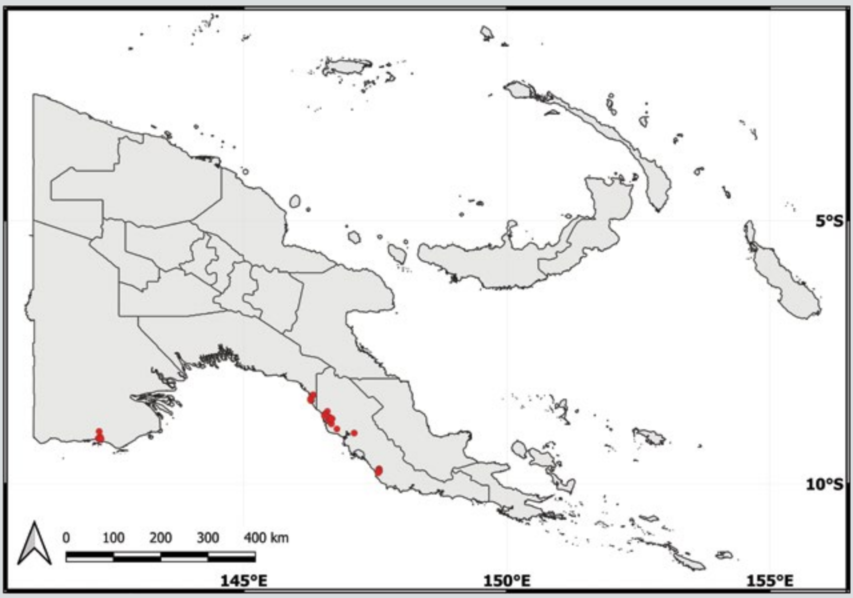


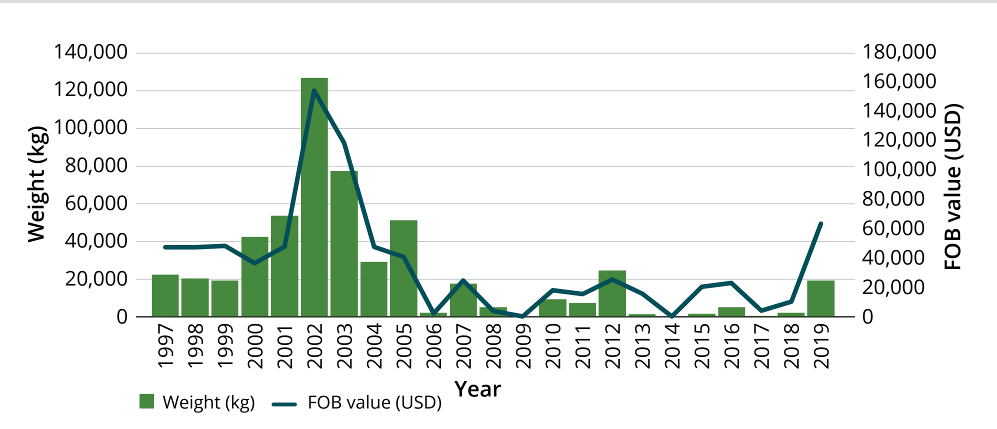
Figure 2.1 Map of Papua New Guinea showing the areas where *S. macgregorii* grows naturally around Port Moresby and Buzi Ber

Sandalwood status in Papua New Guinea

PNG has not undertaken an inventory of the country's natural stocks of sandalwood, but records indicate that harvesting began in the early 1800s. According to Howcroft (1990), about 9,000 t (9,000,000 kg) was harvested between 1891 and 1980. This equates to an estimated 100 t/year over a 90-year period, although harvesting occurred intermittently during that time. From 1997 to 2002, a total of 220 t was exported, fetching around USD280,800, which is approximately USD46,800/year (about USD1,276/t). It is noted that the spike in sandalwood exports from PNG in the early 2000s (Figure 2.2) was a result of improved road access into the areas where *S. macgregorii* occurs naturally in the Central and Gulf provinces. Since 2003, there have only been small volumes (<25 t) exported from PNG. More recently, in 2019, 19 t of sandalwood was exported from PNG. The more recent spike in sandalwood exports from PNG in 2019 (Figure 2.2) was a result of buyers from Asia travelling to local areas to buy the sandalwood from local traders. This was enabled by the improved road network. The 19 t traded in 2019 is, however, substantially less than that traded between 2000 and 2003. It is most likely that natural sandalwood resources are yet to fully recover from the high volumes harvested in the early 2000s.

While the export figures look promising, there is no clear policy on the harvesting and trade of non-timber forest products in PNG, including sandalwood. As a result, harvesting records and management planning for sandalwood in PNG are almost non-existent. Therefore, there is scope to evaluate policy that might support a more regulated and sustainable trade in PNG wild sandalwood.

In the recent past, some sandalwood trial plots and woodlots were established under the support of an Australian Centre for International Agricultural Research project (ACIAR project FST/2014/069) (Rome et al. 2020). This has included the establishment of *Santalum album* plantings, which is an introduced species, but the main aim is to conduct research into *S. macgregorii* to develop its potential in the international market.



FOB = free on board

Figure 2.2 Papua New Guinea's sandalwood export volume and value trend from 1997 to 2019

Source: PNGFA (2002, 2019)

Potential for the sandalwood market in Papua New Guinea

There is a growing interest in the sandalwood trade in PNG and with the abovementioned ACIAR work currently underway, there appears to be good prospects for PNG to harness its naturally occurring sandalwood populations and develop a sustainable planted resource for harvesting. There is also strong interest from local people in growing sandalwood (Page and Oa 2017); however, marketing of the local product remains a concern. With very little competition among buyers, resource owners can be exposed to uncompetitive pricing of sandalwood at the farm gate. PNG is strategically located within the Asia-Pacific region, which can assist its trade with the Asian market, including Australia and other Pacific island countries.

Constraints on sandalwood production in Papua New Guinea

Aside from the lack of a clear policy and strategy on sandalwood production and trade in PNG, there are also risks from fire outbreaks in the localities where sandalwood occurs naturally. The lack of knowledge/information on the silviculture of sandalwood is another important constraint on the development of the species as an export commodity for the country. More research to support the sustainable production and trade of sandalwood in PNG is therefore needed, including to determine the level and value of the oil content of *S. macgregorii* (Brophy et al. 2005).

Land ownership is another common problem in PNG that hinders research and development of forest resources in the country generally, including consideration for woodlots or plantations of tree crops such as sandalwood.

For PNG, and as noted from the Vanuatu experiences, the local people are generally not aware of quality considerations or the international market price for sandalwood. This results in acceptance of whatever price an overseas buyer offers. In some localities, this has also led to illegal harvesting and overharvesting of natural stocks (Gunn et al. 2002).

Options for improvement

The government agency responsible for forests in PNG (i.e. PNG Forest Authority) and other relevant agencies need to make applicable information on sandalwood readily available for public consumption. This information must especially be made available to the sandalwood resource owners. Furthermore, there is a need to amend or develop policies and strategies for non-timber forest products that will include the sustainable management of sandalwood.

It is further suggested that PNG consider placing a temporary ban (e.g. 10 years) on the harvesting of its natural sandalwood stands to help these areas regenerate. There is also a need to establish a regional sandalwood germplasm centre, along with nursery facilities, to support the establishment of research trials and community woodlots.

Conclusion

The harvesting of *S. macgregorii* in PNG is gaining momentum in terms of its production and trade. Overharvesting of natural stocks is placing a burden on its regeneration. Plantation establishment is urgently needed to release pressure on PNG's natural sandalwood stocks and to support a constant supply to meet the high demand from the growing international market.

Clear policies and strategies must be developed for the sustainable production and trade of sandalwood in PNG and the broader Pacific island region. More research and development work will be needed to help guide the future growth of the sandalwood industry in PNG and the surrounding region.

Acknowledgement

Aspects of this paper were published in Rome G, Turia R, Oa L, Page T, Applegate G and Saliau C (2020) 'Sandalwood trade and development in Papua New Guinea', *Australian Forestry*, 83(4):208–215.

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3 Sandalwood development in Fiji

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Introduction

Santalum yasi, locally known as '*yasi dina*', is a hemiparasitic tree species with aromatic wood that yields a commercially valuable heartwood and essential oil. It is an integral part of Fiji's traditional culture and is traditionally used by Fijians for scenting coconut oil. This became another source of income for Fijians as the sandalwood-infused coconut oil was traded and exchanged with neighbouring Pacific island countries. Other traditional uses of sandalwood included grated heartwood, which was placed on the head of the groom and bride during marriage ceremonies, and for medicinal and insect repellent purposes.

The demand for sandalwood in Fiji has remained strong over the years, which has resulted in overharvesting across the natural range of *S. yasi*. The market price has continued to increase over the years due to the different high-value uses of *S. yasi* in different markets. *S. yasi* remains a rare and highly valuable commercial tree species in Fiji.

In 2002, the Ministry of Forestry through its Silviculture Research Division formally incorporated sandalwood research into its 5-year development program (2002–07) in partnership with the AusAID-funded Commonwealth Scientific and Industrial Research Organisation (CSIRO) SPRIG project (South Pacific Regional Initiative on Forest Genetic Resources). The focus of SPRIG project research and development was to improve the propagation techniques of sandalwood and conservation of *S. yasi* through the establishment of ex-situ seed and gene conservation stands in specific locations in different parts of Fiji.

Currently, the Ministry of Forestry has two projects that are promoting the sandalwood industry through extension and advisory services and conserving the genetic diversity of sandalwood in Fiji. The projects are:

1. The Government of Fiji's Sandalwood Development Programme, which is focused on 'Reviving and revitalizing the three sandalwood species in Fiji'. Since the program's inception in 2011, it has received a total government allocation FJD0.9 million.
2. In 2016, the Ministry of Forestry worked in collaboration with the Australian Centre for International Agricultural Research (ACIAR) on a project that examines the 'Domestication and breeding of sandalwood in Fiji and Tonga'. The project focuses on the genetic makeup, conservation and domestication of native sandalwood (*S. yasi*) species in Fiji.

Resource base

Fiji's total land area is 18,275 km^2, 87% of which is concentrated on the two main islands of Viti Levu (50%) and Vanua Levu (37%). The mean annual rainfall in Fiji varies from 1,650 mm in the low leeward coast of the two main islands to over 5,000 mm in the upland interior regions. Generally, the natural hardwood forest areas receive more than 250 mm precipitation per month with only a short dry season of 4–6 months.

S. yasi has a wide geographical range in Fiji. It is known to grow extensively in the provinces of Bua, Macuata and the tip of Cakaudrove on the island of Vanua Levu. On Viti Levu, the species is recorded in the Navosa District of the Nausori Highlands. The species is also known to grow naturally in some parts of Kadavu Province, and in some islands in the Lau Group (Figure 3.1).

Studies have shown that there has been a decline in *S. yasi* along the western and northern coast of Vanua Levu and this is attributed to heavy cutting and uncontrolled fire (Jiko 1991). Traditionally, communities have relied on natural regeneration for their second crop, with hardly any intervention involving replanting sandalwood.

There are two main sandalwood species grown in Fiji, viz. *S. yasi* (*yasi*), and *Santalum album* (Indian sandalwood), with their hybrid (Bush et al. 2016), as well some minor plantings of *Santalum austrocaledonicum* (Coral Sea sandalwood).

S. yasi is the only sandalwood native to Fiji and is considered among the most valuable sandalwood species in the world with high-quality, oil-yielding wood. The species is harvested commercially and exported to Singapore, Taiwan, China/Hong Kong and Dubai, with smaller markets in Australia and Vanuatu (Thomson 2013).

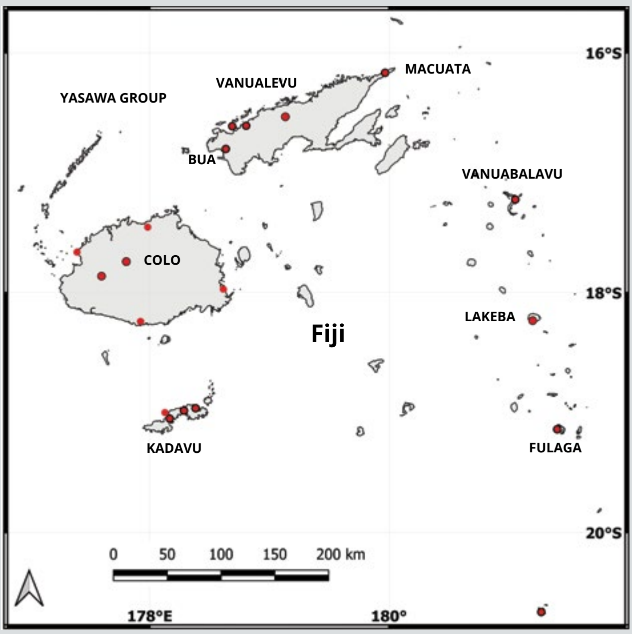


Figure 3.1 Map of natural distribution of *S. yasi* in Fiji

The introduction of *S. album* to Fiji could pose genetic threats to the integrity of Fijian *S. yasi*. The spontaneous hybridisation of *S. yasi* and *S. album* results in a hybrid F1 generation that may compete with the pure *S. yasi* species (Huish et al. 2015). The F1 hybrids, in comparison to either of the parental species, are both precocious and highly fertile and apparently exhibit hybrid vigour. Accelerated growth rates and heartwood formation and high oil yield have been observed (Doran et al. 2005; Thomson 2006), though more thorough examination of these aspects is required. It is also the case that the majority of pure *S. yasi* stands lack diversity and appear to be inbred (Bush et al. 2016), so there may be scope to increase the vigour of *S. yasi* by establishing seed orchards that include a more diverse selection of genotypes.

There has been significant progress between 2002 and 2007 by the Ministry of Forestry in partnership with the AusAID-funded SPRIG project where more knowledge has been acquired on seed technology, nursery operations and field planting. Another activity under this project included the vegetative propagation of germplasm of more than 100 individuals. Newly established seed production areas, including a grafted clonal seed orchard, were developed. The project produced grafted plants, and the provision of seedlings and seeds to villagers, farmers and the private sector. This has raised the prospects for a rapid increase in both quantity and quality of the sandalwood resource in Fiji within the next 15–20 years.

Current policy focuses on planting native *S. yasi*, as this can be marketed in an industry segment not occupied by the significant volume of plantation-grown *S. album* (see K Robson, these proceedings). However, in areas where *S. yasi* is not traditionally grown, including Rotuma, Taveuni and wetter zones of the main islands, the hybrid (*S. yasi* × *S. album*) may be better adapted and may be a good choice for growers.

While the characteristics of the *S. yasi* × *S. album* hybrid appear to be economically desirable, the introduction of *S. album* and the resulting hybridisation threatens the genetic integrity of the native *S. yasi*. Moreover, it is important that *S. album* seed is prohibited entry into Fiji to prevent the possible introduction of phytoplasma sandal spike disease, which currently threatens *S. album* plantings in India (Raychaudhuri and Varma 1988).

Trade and industry

In most parts of Fiji where sandalwood is available, it is still harvested and sold; however, there are considerable volume fluctuations between years (e.g. Thomson 2013, 2020). Currently, there are four registered exporters in Fiji with only a few local buyers. The price received by sandalwood resource owners for their heartwood is uncertain due to buyers offering different prices, but the typical price is currently around FJD100 (USD46) per kilogram for de-sapped heartwood. Some local sandalwood buyers do not comply with the licensing regulations. Such breaches may only come to the attention of the Ministry of Forestry when the exporter applies for a permit to export the sandalwood. Clearly there is a need for a new policy and regulatory mechanism to better regulate the harvesting of sandalwood in Fiji.

In 2007, an economic research study was conducted by the Ministry of Forestry on a 26-year-old sandalwood plantation, which consisted of a mixture of *S. yasi* (*yasi dina*) and *S. album* (East Indian sandalwood) species on Lakeba Island in the Lau Group. In this study, 6% of the total plantation was assessed with the focus on the volume of heartwood and sapwood. Results showed that the *S. album* trees were more vigorous and had a higher percentage of heartwood than sapwood compared with *S. yasi*.

The harvesting process for sandalwood in Fiji involves felling of the tree, unearthing roots and removing the sapwood. The local buyers in Fiji have different approaches when purchasing sandalwood from the resource owners. Some purchase sandalwood without the sapwood removed, while others purchase heartwood (sapwood removed) and sapwood chips separately. The current trading value of mature sandalwood heartwood is FJD100/kg, but sometimes this price is negotiable. Tabulated below is the local market value and volume for sandalwood trade with resource owners in Fiji as of May 2019. The volume and earnings for exported sandalwood was high for two consecutive years (i.e. 2012–13), but there was a dramatic decline in 2014, which has only slightly recovered by 2017 and 2018 (Table 3.1).

The reduced market value of sandalwood in 2016 was due to the combined effects of Severe Tropical Cyclone Winston, with most wood salvaged and of low quality, and the presence of a single buyer operating in Fiji at that time. Prices declined sharply between 2017 (FJD82.70/kg) and 2018 (FJD42.40/kg), despite a similar annual volume being traded. This might be reflective of a lower quality sandalwood that was available to the market in 2018.

After a series of consultations with local buyers, the data presented in Table 3.2 indicates the different categories and specifications of sandalwood and corresponding price ranges.

Socioeconomic benefits of sandalwood

The current standard planting spacing for sandalwood species is 5 m × 5 m (Page et al. 2012). For 1 ha (10,000 m^2), a total of 400 sandalwood seedlings can be planted within that area. Since sandalwood is one of the identified low-cost management species in the Pacific region, the return on investment and benefits will be significant to the resource owners, and will support livelihoods, education and investment for future generations (Table 3.3).

Table 3.1 Annual volume, total value and mean price per kilogram for sandalwood harvested in Fiji from 2012 to 2018

Year	Total value (FJD)	Weight (kg)	Price per kg (FJD/kg)
2012	3,055,146	20,545	148.71
2013	2,180,753	18,931	115.19
2014	105,224	901	116.79
2015	662,258	3,173	208.72
2016	3,852	321	12.00
2017	501,461	6,064	82.69
2018	245,994	5,806	42.37

Table 3.2 Specifications of sandalwood in Fiji with corresponding price ranges in 2019

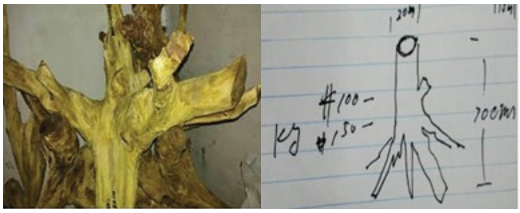
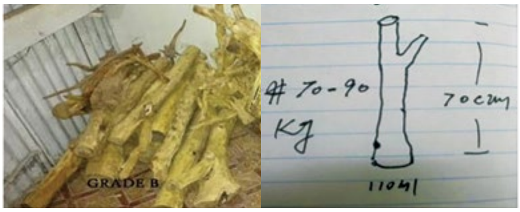
Category	Description	Image	Price (FJD)
1	Roots up to 70 cm above the basal trunk Recommended matured age 20–25 years old		100–150/kg
2	Trunk to branches 20–25 years old		70–90/kg
3	Sapwood and other minor pieces of sandalwood heartwood 20–25 years old		30–50/kg

Table 3.3 Undiscounted economic value of a hectare of sandalwood plantation

Variable	Value
1 ha	10,000 m^2
Standard spacing	5 m × 5 m
Number of sandalwood seedlings (trees) planted	400
Percentage survival	65%
Current standard price value	FJD100/kg heartwood
Recommended matured years	20 years and above
Approximate weight of heartwood per tree after 20 years	30 kg
65% survival of the planted trees	260 trees
Approximate value of sandalwood heartwood in 1 ha after 20 years	FJD780,000

Extension and awareness

One of the best possible ways of improving this high-value commodity nationally is to restore sandalwood resources by assisting local communities to establish sandalwood woodlots, and by growing sandalwood in home gardens. An extension and awareness program aims to increase community understanding of and interest in sandalwood planting. This awareness program has been undertaken via radio talkback shows, exhibitions and during forest restoration training programs with communities. The importance and benefits of replanting, the need for improved and/or genetically diverse seed sources and the need for capacity building are advocated.

The Ministry of Forestry Sandalwood Development Programme, in collaboration with international research organisations such as Pacific Community (SPC), ACIAR and CSIRO, has developed sandalwood awareness campaigns throughout the country. These campaigns focus on the sustainable production of *S. yasi* and include information brochures for growers, research papers, and training and workshops targeting communities, individuals and sandalwood grower groups for the purpose of reviving the sandalwood industry in Fiji (Figure 3.2).

Capacity building encompasses the transfer of relevant knowledge and in-house training for practices such as seed collection, seed processing, nursery production, field planting techniques and woodlot management in order to enhance the knowledge and technical skills of the communities. At the end of the training, sandalwood and host plant seedlings are supplied by the Ministry of Forestry for field planting. Through this program the Ministry of Forestry is attempting to maintain the sustainability of the sandalwood industry in Fiji.

To date, a total of 68,538 sandalwood seedlings have been planted under the two government-funded projects. Table 3.4 shows the total number of sandalwood seedlings planted since 2011 under the Sandalwood Development Programme and the Reforestation of Degraded Forests program, which is now administered under the 4 Million Trees in 4 Years initiative (4MT4Y).

Figure 3.2 The Ministry of Forestry developed and conducted community awareness campaigns for sandalwood conservation

Table 3.4 Sandalwood seedlings planted through the Ministry of Forestry extension services until 2019

Program	Commencement year	No. of sandalwood seedlings planted
Sandalwood Development Programme	2011	46,200
Reforestation of Degraded Forests program and the 4 Million Trees in 4 Years initiative	2015	22,338

Nursery and planting techniques

In both *S. yasi* and *S. album*, flowering and fruiting occurs sporadically throughout the year, but the peak flowering/fruiting period is during the wet season from January to March and again from October to November.

Generally, 2 years (*S. album*) to 3–4 years (*S. yasi*) after field planting, sandalwood starts to flower and produce seed. This enables communities to collect seeds from the tree crown or from the ground. After collection, the seeds are soaked in water for 1–3 days to soften the fruit pulp. The next step involves cleaning and air-drying the seeds at room temperature, out of direct sunlight, for several days before sowing, or alternatively the dried seed is dusted with fungicide and stored at 3–4 °C. Seed is then sowed in a mixture of mahogany compost, peat moss, fine river sand or commercial potting medium.

In the nursery, once the sandalwood seedlings reach the 2–4 leaf stage they are transplanted into polythene bags (16 cm × 6.5 cm). The potting mix typically comprises two-thirds topsoil and one-third river sand, with the addition of 2–3 kg of NPK (nitrogen-phosphorus-potassium) fertiliser per cubic metre of potting mix. *Alternanthera* cuttings are planted as pot hosts.

After 6 months of growth and when the seedlings reach a height of 30 cm, they are planted into the field. Tree placement is typically opportunistic in gardens containing existing trees and shrubs, but in more formal plantings sandalwood is established in lines and interplanted with host plants. Suitable hosts include *Citrus reticulata*/*Citrus maxima*, *Casuarina equisetifolia*, *Calliandra calothyrsus* and *Calliandra surinamensis*, *Acacia richii*, *Gliricidia sepium*, *Pongamia pinnata*, *Gymnostoma vitiensis* and *Serianthes vitiensis*. The Ministry of Forestry is also considering introducing some new permanent hosts to evaluate their effectiveness in the growth of sandalwood.

Research and development

Since 1996, the Ministry of Forestry, initially with assistance from the AusAid-funded CSIRO-led SPRIG program, has been conducting conservation programs and developing different techniques and methodologies for growing sandalwood to re-establish their populations. One of the outcomes of these programs is the supply of quality seedlings to interested communities who are keen on taking part in the Sandalwood Development Programme and investing in their future.

The research divisions of the Ministry of Forestry implement the Sandalwood Development Programme. This involves researching further into the various stages of sandalwood growth from seed procurement, processing, and growth inside the nursery to setting up of research trial plots throughout Fiji (Bulai 2005). The research plots were established to evaluate the effects of various host trees, different spacings in monoculture or mixed plantings, and the impacts of pests and diseases on the different stages of sandalwood's growth.

Through the ACIAR project 'Domestication and breeding of *S. yasi* in Fiji and Tonga', the Ministry of Forestry aims to establish a foundation for conservation and domestication of native sandalwood (*S. yasi*) in Fiji. This will support the development of a sustainable planted sandalwood industry and relates directly to the Ministry of Forestry Operation Plan on the Establishment of Gene Conservation Area.

The research objectives are to:

1. improve understanding of the breeding biology and genetic diversity of key traits in *S. yasi*
2. enhance the genetic conservation status of *S. yasi* in Fiji and Tonga
3. develop strategies to enhance the quality and availability of *S. yasi* germplasm and support development of sandalwood industries in Fiji and Tonga
4. disseminate the practical outcomes and implications relating to objectives 1–3 to growers and practitioners.

As part of this project an ex-situ Gene Conservation Area for *S. yasi* was established at Tutu, Taveuni (Figure 3.3). The source seeds for this conservation stand were collected from the Nausori Highlands, Bua and Lakeba Island, populations that were marked and DNA-confirmed as pure *S. yasi*. This conservation plot will be a valuable source of information for growth performance and quality of different *S. yasi* provenances grown in a single location.

National priority activities

National plans and strategies on the future management, conservation and development of sandalwood in the country include the following components:

30 Million Trees in 15 Years

In early 2019, the Government of Fiji through the Ministry of Forestry launched a new program called 4 Million Trees in 4 Years (4MT4Y), which will operate between 2020 and 2023. The target has now been revised to a national target of 30 Million Trees (all species) in 15 Years (30MT15Y). It is an initiative to mitigate and adapt to climate change, enhance watershed area management, boost timber and other wood production, reduce degradation of forest areas, improve opportunities for carbon financing and biodiversity conservation, reduce soil erosion and siltation, support food security, and improve agriculture production and practice. The Ministry of Forestry manages four projects, namely REDD+, Reforestation of Degraded Forest, Reforestation of Indigenous Species and Sandalwood Development, which can all contribute to the 30MT15Y initiative.

Figure 3.3 Establishment and initial measurement of the *S. yasi* Gene Conservation Area at Taveuni

The main objectives of the 30MT15Y initiative are to:

- identify and collaborate with development partners, government agencies, communities, civil society organisations, non-government organisation (NGOs), industries and corporate organisations in the delivery of the project
- establish a multisectoral steering committee to coordinate and monitor the implementation of the project
- create awareness and promote the project to all Fijians
- mobilise divisional working groups to implement and supervise tree-planting activities
- secure funding sources for the implementation of the project
- engage schools, youth groups, women's groups, resource owning communities, municipalities and farmers in tree-planting programs.

In order to achieve this target, the three main divisions of the Ministry of Forestry aim to plant 2 million trees per year until 2035 (i.e. the Northern, Central Eastern and Western divisions must each target to plant 666,666/year). These national programs and priorities will boost sandalwood resources for future economic returns, especially in the Maritime islands (including Lau Group and Rotuma).

Sandalwood Development Programme

The broad objective of the Fiji Sandalwood Development Programme is to facilitate the development of public–private partnerships for the replanting of *S. yasi*. The Ministry of Forestry, in its facilitative role, will ensure the inclusive involvement of target stakeholders for the implementation of the project. To date the major, primary beneficiaries for the Sandalwood Development Programme have been the targeted communities and resource owners in the Western and Northern divisions, and the Maritime islands.

The secondary beneficiaries will include those involved in transporting and processing, and the marketing chain (Thomson et al. 2020). Given the wide geographic coverage, the Sandalwood Development Programme will create economic opportunities for rural populations, leading to sustainable production of sandalwood and alternative livelihoods, enrichment of degraded forests and grasslands, and an increase in community-based development.

There is still a need for capacity building, and continual technical support by the government through the Ministry of Forestry means that resource owners, private agencies and communities can extend their planting areas every year in order to maintain the rotation of harvesting for a longer period, and not just as a one-off cycle. This ensures sustainability over generations as well as enhanced livelihoods, poverty alleviation and overall economic returns for the country at a much higher value than could ever be realised with other commodity species. Further downstream processing of heartwood into sandalwood oil can double the economic impacts in Fiji.

The sandalwood policy for Fiji

The Fiji Forest Policy 2007 covers a broad range of forest management policies and covers sandalwood on a broad scale. Thus, there is a need to have a more detailed sandalwood policy to guide on-the-ground management and development of sandalwood to benefit the Fijian environment and people.

A specific sandalwood policy is being drafted to:

- provide guidelines for the Ministry of Forestry to monitor, manage and control sandalwood activities. This includes issuing of licences and export permits, and overall direction to manage the sandalwood resource on a sustainable basis
- provide to the licensees their requirement for participating in the industry, and provide guidelines for industry planning
- clearly define the roles of the stakeholders in replanting sandalwood and research
- encourage local processing of high-value sandalwood products.

Acknowledgements

We would like to acknowledge the assistance of the following people:
The Conservator of Forests Ms Sanjana Lal, Executive Director Research and Development Mr Semi Dranibaka, Director Silviculture Research and Development Mr Jale Tauraga, and our ACIAR Yasi Project Partners Dr David Bush (CSIRO) and Dr Lex Thomson (University of the Sunshine Coast).

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4 Sandalwood development and production in the Kingdom of Tonga

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Abstract

Sandalwood species, including the native *Santalum yasi* (locally '*ahi*') and the introduced *Santalum album*, are culturally and economically important in Tonga. The industry is transitioning from harvest of wild sandalwood to cultivated trees. The popularity of planting sandalwood is increasing, with individuals, families and community groups enthusiastically planting large numbers of trees. However, practices such as heartwood checking and theft have become serious problems in Tonga, which has limited even wider planting. The Ministry of Agriculture and Food, Forests and Fisheries (MAFFF) has responded by introducing harvest and export controls for sandalwood. MAFFF is also involved in research and extension programs to educate growers and improve the growth performance of sandalwood in Tonga. This paper discusses the importance of sandalwood in Tonga, regulations relating to sandalwood, and methods of sandalwood cultivation introduced by MAFFF.

Introduction

Santalum yasi (locally '*ahi*') is an endemic sandalwood species in Tonga, Fiji and Niue. In earlier times, people in Tonga used the tree as firewood, fence posts, and even Christmas trees. While sandalwood has been traded since the 1800s (Akau'ola 2010), the importance of conserving natural sources or planting new sources of sandalwood has not been recognised. Sandalwood trade has occurred intermittently, where exploitation of native stands is characterised by short periods of intensive extraction followed by longer periods of resource regeneration (Akau'ola 2010).

Akau'ola (2010) quantified the export volumes for sandalwood in Tonga from 2000 to 2009 with a peak of 203 t in 2007. Since 2009, a significant export volume was recorded in 2011 (viz. 105 t), with very little exported after that year. Since that time, industry stakeholders and the Ministry of Agriculture and Food, Forests and Fisheries (MAFFF) have sought to better understand the potential of sandalwood to Tongan families, determining that an increase in sandalwood planting would be of benefit. Although sandalwood contributed to landowners' incomes and the national economy in the past, there was no effective regulatory system or a sandalwood regulation, and accordingly no sustainable income for landowners and the national economy.

Tonga has five island regions including the Tongatapu, Vava'u group, Ha'apai group, 'Eua and the Niuas. *S. yasi* grows throughout Tonga but its frequency varies between islands (Figure 4.1) (Akau'ola 2010):

- 'Eua – very common, especially in secondary forest and coastal areas but very rare in the south-eastern side of the island
- Tongatapu – rare to very rare in coastal and lowland forests
- Ha'apai – common in the Ha'apai group, especially in Foa and Pangai
- Vava'u – common in the northern side of Vava'u group and small outer islands.

The Forestry Division has staff in each of the island groups. The main function of the Forestry Division is to facilitate research and development activities and provide landowner extension relating to sustainable forest management, including sandalwood production.

Sandalwood regulations

A sandalwood regulation was launched in 2016 that includes provisions for sustainable management of natural and planted sandalwood resources. In 2019, MAFFF worked on translating and creating registration forms for sandalwood growers and traders. Sandalwood officers from Tongatapu, 'Eua, Ha'apai and Vava'u have completed awareness training and training on sandalwood regulation. These island groups have started and are ready to move on to registration of the growers and the traders of sandalwood.

The specific objectives of Tonga's sandalwood regulation are to:

1. ensure the sustainable management of the sandalwood resource in Tonga for current and future generations
2. promote the planting of sandalwood in Tonga in order to substantially increase the size and value of the resource so as to maximise its contribution to the national economy of Tonga.

The regulations include specifications for the following:

- a register of sandalwood growers and traders
- a declaration of sandalwood ownership
- a database of sandalwood tags
- sandalwood harvest dockets
- an application to register for sandalwood export licences.

The effects of the regulations have been positive for increasing confidence among smallholders to invest in planting sandalwood. Prior to the regulation, it was considered unsafe to plant sandalwood because of the widespread practice of heartwood checking and theft. Heartwood checking is conducted by would-be thieves by cutting into a sandalwood trunk to check for the formation of heartwood. Heartwood checking drastically reduces tree growth and product quality, resulting in extended rotations and diminished returns. Theft obviously removes any financial benefit to the resource owner. While the regulation is yet to eliminate these two practices, it has put in place systems to reduce the incidence of both.

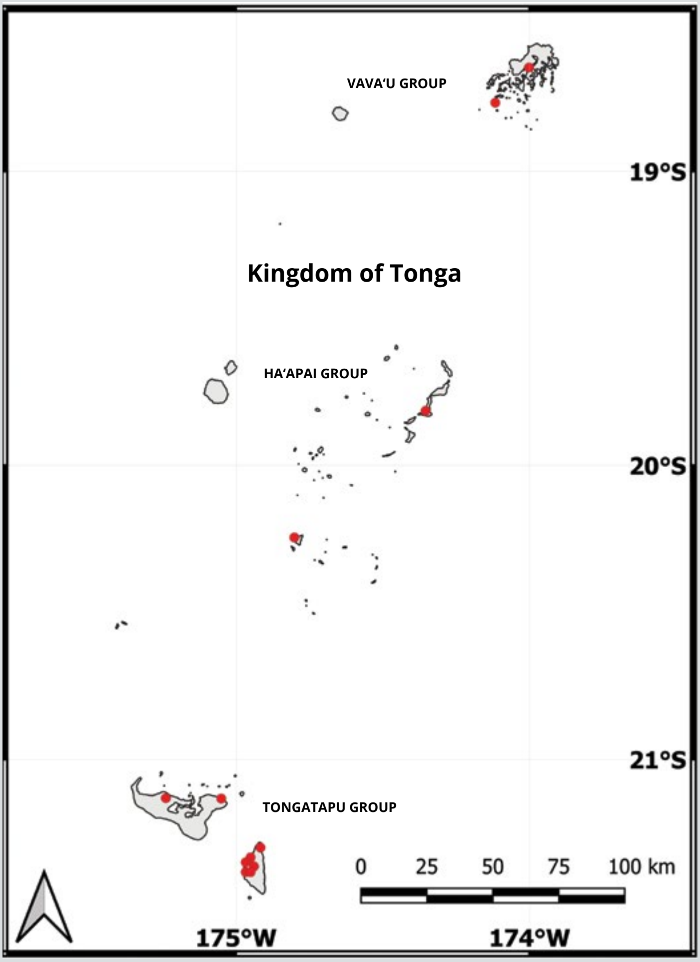

Figure 4.1 Map of the Kingdom of Tonga, with distribution of sandalwood
Source: Adapted from Akau'ola (2010)

Sandalwood production

MAFFF has encouraged local people to grow sandalwood as a future investment. Now almost every household in Tonga has at least one sandalwood tree in their homestead. This increase in planting has resulted in a gradual transition from harvesting of wild sandalwood resources to planted trees. Although communities now better appreciate the commercial value of sandalwood and want to grow more, there are ongoing issues associated with tree maintenance, which forestry extension hopes to address. Sandalwood is providing future economic empowerment to each and every person, in families, communities, churches and schools:

- Individuals and family units – People grow sandalwood as a family on their own piece of land (tax allotment) because of sandalwood's recognised commercial value. This is a big change from even 10 years ago, when planting was practised by only a few individuals. Tongan people now understand that sandalwood is an economic crop and in mixed plantings can contribute to climate change adaptation.
- Churches – Churches in Tonga are also planting sandalwood, where up to 50 or 100 plants are established in their compounds. Sandalwood can provide churches with a valuable source of money for renovating facilities in the future.
- Schools – In Tonga, there are 15 secondary and 40 primary schools, and almost every school has planted sandalwood on their grounds to provide educational opportunities and future revenue for the school. Many school principals understand the importance of sandalwood, so the school plantings offer teachers, parents and students the opportunity to learn how to apply methods of production in their own homes.

Land

The Kingdom of Tonga is a constitutional monarchy where all land belongs to the Crown. Estate holdings by nobles and the government are allocated by the Crown and as estate holders, ownership is not absolute. Apart from a specified area of land that a noble may hold for personal use, the remainder of the noble's estate is held for: (1) distribution to male Tongans as town and tax allotments; and (2) for leasing by the estate holder of up to 5% of the total estate area. The sale of land by estate holders is also prohibited. By law, every male Tongan from the age of 16 years is entitled to a small piece of agricultural land (tax allotment of around 8 acres) and a small town plot (town allotment with minimum area of 30 perches (760 m^2) and a maximum area of 1 rood 24 perches (1,618 m^2)).

Methods of production

Sandalwood propagation is mainly undertaken using seeds. The broad steps for propagating and planting sandalwood in Tonga are outlined below:

Seed collection and preparation

- Picking of seed – Pick the ripe fruit from the tree, and freshly fallen fruits from the ground.
- Clean – Rub the fruit to remove the flesh from the seeds. Rinse the seeds in water to remove the impurities.
- Float – Place seeds in a bucket of water, retain only those that sink (filled seed) and discard those that float (unfilled seed).
- Dry – Dry the clean seeds on a flat surface in a warm, dry place. Avoid the full sun as this can 'cook' and kill the seeds.
- Store – Store dried seeds in a clean paper bag, in a dry, cool place. Store away from vermin.

Types of planting

Tongan people plant sandalwood in their tax allotment, while others also plant in the town allotment, the backyard, schools and churches. Sandalwood is also planted for beautification, boundary plantings and in wind breaks.

- Enrichment – Sandalwood planting within existing secondary forest is practised by only a very few landowners, mostly on tax allotments.
- Woodlots – Woodlot plantings are not yet common, although there is increasing activity. Most of these types of plantings are planted on a tax allotment.
- Boundary plantings – This is done by most of the schools in Tonga, as many grow sandalwood as a boundary.
- Villages – Village plantings are the most common way to plant sandalwood, where trees are planted in home gardens either in backyards or around houses. It has been found that sandalwood grows well when protected by a building wall.
- For gardens and agroforestry – Agroforestry plantings are not yet common on tax allotments due to the great risk of theft. Small agroforestry sandalwood plots are mostly around houses and idle town allotments.

Propagation

- Sow – Sow seeds in a seedling tray or pot using a medium composed of a mixture of topsoil, sand and compost. Sow the seeds 5–10 mm below the soil surface and of a density where the seeds do not touch each other.
- Water – Keep the medium moist but not too wet. During the wet season, trays may need to be located out of the rain to avoid prolonged wetness.
- Protect – Protect germinating seedlings from the full sun, rats and birds.
- Stem cultivation – Alternatively, some have started to use stem cultivation, where branches are cut from the sandalwood tree and propagated during a full moon, which is the best time.

Out planting

- Prepare planter bag – Use a sterilised growing medium in the planter bag that has 50% sand to assist drainage and 50% soil to improve water-holding capacity. Some well-rotted compost is also desirable.
- Prick out – Prick out the seedlings when they are at the 2–4 leaf stage by lifting the root system with a clean dipping stick and pulling gently on the base of the stem.
- Transplant – Plant the seedlings firmly in the medium at the same level they were growing in the germination medium, ensuring roots are not bent or curved.
- Raise bags – Place the planter bag on raised benches: this is vital during the rainy season to help drainage.

Hosts

Knowledge of sandalwood's hemiparasitic nature is widespread, so people are aware that the trees must grow with other species to survive and thrive. The following hosts are most common:

- Short-term host (nursery) – *Alternanthera* spp. (loseli) are usually used as the host for the seedling when it is in the pot. This should be planted as a stem cutting after the sandalwood is at the 5–6 leaf stage.
- Intermediate to long-term hosts – Hiapo (*Broussonetia papyrifera*), ohai (*Delonix regia*), *Calliandra* spp. and olive (*Murraya paniculata*) are used as an intermediate host plant and planted about 1 m away from the sandalwood tree. It can also be used as a long-term host plant, at least 3–4 m from the sandalwood.
- Long-term host – Mandarin and other citrus as well as fau (*Hibiscus tiliaceus*) can be a good host for sandalwood. Fau can be unruly, and its growth needs to be controlled by regular pruning. Beach she-oak (*Casuarina equisetifolia*) is one of the hosts that is used widely as a sandalwood host. It provides good side protection without overtopping the sandalwood.

Growth rate and rotation

Sandalwood production in Tonga is a long-term crop typically taking 17 to 25 years to mature ready for harvest. To quantify sandalwood growth rates, trees on 4–5 island groups were marked in 2015 and re-measured in 2018 and 2019. The results demonstrate an average annual diameter growth of 1 cm, but with a few trees growing more vigorously with a 2-cm diameter increase per year.

There is a wide age distribution of sandalwood trees in Tonga, ranging from 0 to 32 years. Sandalwood trees older than 16 years old are few and are mainly found in the wild. Approximately half of the sandalwood grown in Tonga is wild grown and the remaining is grown as planted specimens.

Seed sources

Sandalwood seed has been mainly collected locally from naturally grown mother trees, although increasingly seed is being purchased from sandalwood growers. Nowadays some seed is procured from family or friends in Fiji and Vanuatu, but this has the risk of bringing in disease and maladapted germplasm. People are, however, interested in growing *S. album* and its hybrid with *S. yasi*, owing to their more vigorous growth rates (Thomson et al. 2018). Despite its good growth rate, *S. album* is more susceptible to strong winds associated with tropical cyclones and is slower to develop heartwood when compared with *S. yasi*, although this is only now being understood by landowners.

Production issues

Sandalwood theft is the main issue for sandalwood production, and this issue extends to both mature sandalwood and newly planted seedlings. The MAFFF *Sandalwood Regulations 2016* (Kingdom of Tonga 2016) is starting to provide the foundation for reducing these problems.

Inadequate seedling supply has become an issue, especially where people have the initiative to plant more and larger woodlots but are constrained by a shortage of seed and/or seedlings. Now in Tonga there are entrepreneurial landowners that seek to buy more than 1,000 sandalwood seedlings to grow on their own land. This has stimulated a vibrant market for seed and seedlings in Tonga, which is a good small business for those that own seed-producing trees.

Conclusion

Sandalwood is a very important tree crop for Tonga, with the potential to bring substantial economic benefits. Tonga must continue to transition from wild harvesting to cultivating trees. The steps that MAFFF has taken to educate communities about growing sandalwood, the research that MAFFF has carried out into the best methods for cultivation, and steps taken to better regulate the harvest and export of sandalwood are very important for industry sustainability. In the future it will also be important for more research to be carried out to develop trees that can produce high-quality heartwood. Better information and development of markets are required to ensure good returns for Tongan sandalwood growers. Reliable supply of sufficient quantities of good-quality product will be needed to develop the potential of the industry.

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5 National sandalwood report for Indonesia

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Abstract

Sandalwood (*Santalum album* Linn.) is an endemic species of East Nusa Tenggara (NTT)/West Timor, Indonesia. The natural distribution of sandalwood in NTT is on the islands of Flores, Adonara, Solor, Lomblen, Alor, Pantar, Rote, West Timor and Sumba, and also islands in the Maluku Province (Wetar, Roma and Leti). Sandalwood has been exploited and traded since the 10th century in Timor by Chinese traders taking the product to India and what was then known as Malaya. Continual harvesting combined with very little regeneration because of fires, shifting cultivation and cattle grazing, has led to serious declines in wild populations. Such exploitation of sandalwood resources has continued until today. Due to the rapid decline of sandalwood resources in NTT, the International Union for Conservation of Nature (IUCN) has listed the species as Vulnerable.

Sandalwood inventories in Sumba revealed 27,900 trees in 1990, which had declined to 3,253 by 2001, representing an 88% decline over 11 years. On Timor Island, an inventory carried out by the Provincial Forestry Service during the 10-year period from 1987 to 1997 indicated the number of sandalwood trees dropped by almost 50%, from 544,952 trees to only 250,940 trees. A recent survey (ITTO 2010) in District Timor Tengah Selatan (TTS) found that most sandalwood trees are small and would take at least 10 years before they can be harvested. No province-wide survey has been carried out by the Provincial Forestry Service in recent years, but according to one local forestry officer, very few old trees remain, especially on privately owned land or community lands.

As the supply of sandalwood timber is dwindling, the industry that processes sandalwood oil, handicraft and joss sticks is suffering. It is not known if these industries are still operating using legally cut sandalwood timber. Attempts to determine if a sandalwood oil extraction facility is still operational was unsuccessful, since the owner has restricted engagement with and access by researchers.

The depletion of sandalwood in NTT has also been triggered by local regulations and policies that discourage farmers from caring for sandalwood trees. Until 2000, all wild sandalwood (living plants, dead plants and wood parts) was owned by the government. Privately grown sandalwood was permitted but 85% of revenue from wood sales was retained by the government (PERDA No. 16/1986). Since 2000, sandalwood trade has been under the control of the District Government and regulations in TTS (Perda 25/2001) and East Sumba (Perda 19/2000) recognise landowner rights to sandalwood trees occurring on their land.

Sandalwood owners can claim part of the sales (amounting to 15%) from the local government after showing evidence of their land title status (Governor Decree No. 7/1993). The current policies and regulations have emphasised farmers' rights and given more economic benefit to growers as well as promoting planting programs by providing free seedlings. It will take many years for sandalwood to regenerate in NTT to the extent that it will provide economic benefits, but the change in policy and regulations is in the right direction.

With the diminishing sandalwood resources in NTT, Indonesia needs to consider growing sandalwood in other areas. In fact, places like the western part of Bali, West Nusa Tenggara (NTB) and the central part of Java/Yogyakarta are suitable locations for sandalwood cultivation. In the District of Gunung Kidul near Yogyakarta, sandalwood was first planted in the 1960s as part of a regreening program. Nowadays in this area, there are scattered trees as large as 30 cm in diameter.

Introduction

Sandalwood belongs to the family Santalaceae, subfamily Santalineae, order Santalales and genus *Santalum*. There are several species of sandalwood, but the species *Santalum album* Linn. is endemic in the Timor region of Indonesia. Two varieties of *S. album* are found in the Timor region. These varieties are *S. album* L. var. *album*, which is characterised by small leaves, and *S. album* var. *largifolium*, which has larger leaves (Harisetijono and Suriamihardja 1992). The natural distribution of sandalwood in East Nusa Tenggara (NTT) Province is on the islands of Flores (West and East Flores), Adonara, Solor, Lomblen, Alor, Pantar, Rote, West Timor and Sumba, and also on islands in the Maluku Province (Wetar, Roma and Leti) (Figure 5.1).

Sandalwood is valued for its heartwood, which contains a fragrant oil. Natural sandalwood stands in NTT have been exploited for centuries. Indeed, since the 10th century, sandalwood has been commercially traded in Timor by Chinese traders taking the product to India and what was then known as Malaya. During the 15th century, following the Portuguese colonisation of Timor, western traders were attracted to sandalwood, although the earliest records of sandalwood trade from Timor date back to the 3rd century AD (Husain 1983).

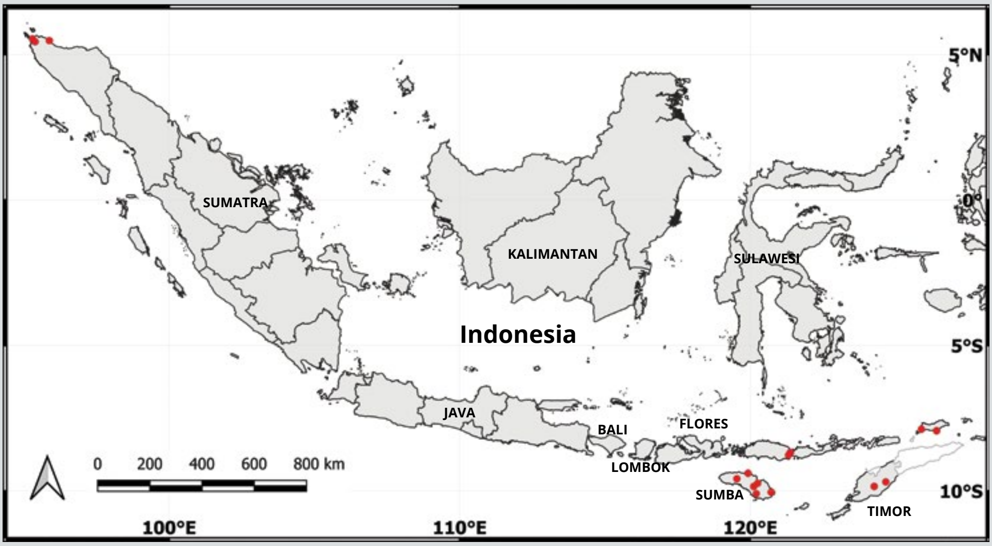

Figure 5.1 Generalised natural distribution of sandalwood in Indonesia

The decline in abundance and economic importance of sandalwood for the NTT Province is reflected by the proportion that revenue from sandalwood contributes to income. This proportion stood at around 38.26% between 1989 and 1994 and dropped to 12.17% between 1995 and 2000 (Darmokusumo et al. 2001). At some point in time, nearly 30% of the global production of sandalwood and sandalwood oil was exported from the ports of Kupang (NTT) and Dili (Timor-Leste), while the rest was exported from southern India (Yusuf 1999).

Excessive harvesting combined with very little regeneration due to human-induced disturbance such as fires, shifting cultivation and cattle grazing, has led to serious declines in wild sandalwood populations in NTT. The International Union for Conservation of Nature (IUCN) has listed sandalwood as Vulnerable, reflecting the diminishing resources of sandalwood in NTT. The species is threatened by overexploitation and degradation of habitat, mainly due to fire.

Government policy on sandalwood has also discouraged people from planting and looking after the trees. For instance, in local legislation or Perda 16/1986, if farmers harvest and market sandalwood trees growing on their land, they only receive a 15% share of profits, while 85% of the profit goes to the government. It is important to note that only 7% of sandalwood trees grow on public lands including forestland, while 93% grow on private land (Ardjoyuwono 1986). Monopolistic rule on sandalwood has prevented farmers from obtaining economic benefits from growing sandalwood trees. This situation has made a significant contribution to the depletion of sandalwood resources in NTT.

Fortunately, the government recognised that the monopolistic nature of managing sandalwood resources had played a significant role in the demise of sandalwood and therefore introduced regulations that are favourable to individual ownership. In 1997, the governor of NTT issued a moratorium on sandalwood harvesting for 5 years, aimed at halting further degradation. This regulation eliminated income contributions received from the sale of sandalwood. One year prior to the ban, a sweeping operation was launched to collect illegally cut wood being stored by individuals. Almost 2,000 t of 'illegal' wood was collected during the operation and was earmarked for allocation to local industries to maintain their operations up to the year 2003. However, local reports indicate that the wood collected also included some freshly cut wood (ITTO 2013).

Since 2000, the management of sandalwood resources has been under the district government and each district can issue its own regulations. For instance, Timor Tengah Selatan (TTS) District issued Perda 25/2001, which specifically addresses the issues of sandalwood ownership and sustainability. Unfortunately, sandalwood resources in TTS District are hard to find, materials for the handicraft industry are scarce, and people with interests in planting sandalwood are still traumatised by past negative experiences. Similarly, the East Sumba (Sumba Timur) District issued Perda 19/2000. These Perdas were issued in response to the monopolistic nature of Perda 16/1986. The major shift in the new Perda is recognition of individual rights. Under this Perda, sandalwood trees that grow on private land, be they natural or planted, belong to the landowner.

Sandalwood resource base

Sandalwood is endemic in the NTT Province on the islands of Timor, Sumba, Alor, Solor, Pantar, Flores, Rote and others. The ideal conditions for the growth of sandalwood are at altitudes of between 50 and 1,200 mASL, and rainfall of between 625 and 1,625 mm/year, with between 9 and 10 dry months (Septiani et al. 2010). Sandalwood prefers shallow soils with good drainage, a clay texture, and of limestone or volcanic origin (Riswan and Soedarsono 2001). It also prefers good sunlight and does not require a lot of water.

Sandalwood is a hemiparasite, meaning it parasitises the roots of other species – collectively called host trees – with a haustorium adaptation on its own roots, without harming its hosts. Sandalwood trees rely on the host trees for nutrient supply, such as phosphorus, nitrogen and potassium (Kharisma and Suriamihardja 1988), and shade when young (Barrett and Fox 1994; Fox and Barrett 1995). Because of the hemiparasitic nature of the sandalwood tree, its cultivation requires a host plant to support its growth and development. More than 70 species have been identified as suitable host plants, but each type of host plant influences the growth and development of sandalwood differently (Lion and Thomas 2017).

Sustainability of sandalwood species in NTT depends on planted trees. Naturally regenerated trees from seed, which in the past were common, are now hard to find. Deterioration of habitat conditions due to human activity coupled with longer dry seasons and increased temperatures have made it more difficult for the natural regeneration of sandalwood trees.

An example of a successful sandalwood planting program can be seen at Desa Ponain Kecamatan Amarasi Kabupaten Kupang, some 60 km south of Kupang. Up until the early 1990s, Desa Ponain was known as a centre of sandalwood production, and large areas of sandalwood stands could be found there. Nowadays however, only a few trees may be found scattered throughout private lands. In 2007, through a government program, seedlings were distributed for free to local farmers, who planted the trees on their land. These trees are now growing well (Figure 5.2), and the farmers are optimistic about the future of their trees.

The species has been planted and is thriving in other parts of Indonesia, such as at Bali, Bondowoso and Jember in East Java, Gunung Kidul in Yogyakarta, Sulawesi and Maluku (Rahayu et al. 2002). However, it is not known how large the area of this planted sandalwood resource is. In Yogyakarta, sandalwood was first planted in 1968 using seeds from trees growing in Timor (Sukirno et al. 1987). Nowadays, sandalwood trees are found scattered in wide areas as seeds are distributed by birds and germinate naturally when conditions are favourable.

Existing natural stands

Naturally regenerated trees or stands are almost non-existent in NTT. The loss was caused by a past high annual allowable cut, and rampant illegal cutting. In 1997, a moratorium on sandalwood felling from forestland was imposed to protect the remaining trees. The sandalwood currently available in the market is mainly sourced from privately owned land or community lands (Figure 5.3).

In the past, the natural stands of sandalwood were largely found on the islands of Timor, Alor, Sumba, Solor, Lembata and Flores. Mismanagement of this fragile natural resource has led to the disappearance of the natural sandalwood stands from most of their prior areas of distribution. A survey conducted in 1997 reported that the sandalwood population remained in only four districts of Timor Island, namely Timor Tengah Utara (TTU), TTS, Belu and Kupang (Widiyatmika and Munandjar 2000). Although natural stands are now rare, there are scattered naturally regenerated trees that dot the landscape in NTT. Given the right conditions and with time, they can eventually form viable populations of trees.

Figure 5.2 Ten-year-old sandalwood trees planted on private land at Desa Ponain Kupang

Figure 5.3 An example of a single sandalwood tree (at centre) growing on private land

The islands of Alor and Sumba were known to have abundant natural sandalwood. In Alor, a seed production area of 1 ha was planted in 1980. This has become an important seed source in NTT. Unfortunately these trees are now susceptible to theft as they have attainted commercial maturity. Sumba was once known as Sandalwood Island because of its abundance of natural sandalwood stands.

Sandalwood has typically been more abundant in Indonesia's eastern compared with the western provinces. According to the national census of 2015, the NTT Province had a population of 5.1 million, distributed in 22 districts and one city.

On Timor Island, sandalwood trees were abundant in two districts (TTU and TTS), but it is likely they have been further reduced in recent years. On the other hand, human population in the two districts has increased by between 11 and 16% over the past 10 years.

Data from a 1998 inventory revealed that the natural population of sandalwood in NTT was 250,940, comprising 51,417 trees and 199,523 saplings, while in 1990 there were some 564,952, of which 176,949 were trees and 388,003 were saplings (Forestry Office of TTU [Dinas Kehutanan Kabupaten TTU] 2010). Meanwhile, the population of sandalwood in TTS based on an inventory conducted in 2010 was only 1,426 trees, compared with the results of a 1997 inventory of 112,710 trees (Forestry Office of TTS [Dinas Kehutanan Kabupaten TTS] 2010). These population reductions due to overexploitation caused the status of sandalwood to become rarer in the local, national, and even regional markets (Butarbutar and Faah 2008). The severity of sandalwood depletion has been reported by the International Tropical Timber Organization (ITTO 2013), which found about 85% of the sandalwood resources (trees and saplings) in Timor were lost between 1998 and 2010.

The Provincial Forest Service of NTT conducted a province-wide inventory of sandalwood trees every 5 years. The last inventory was conducted in 2005. Sandalwood is one of the few species for which the government conducts a regular inventory of the available resources. While it is important to know the extent of sandalwood resources that are still available, it is also a reflection of the general view that sandalwood is the property of the government.

Trade and industry

There are at least three products that use sandalwood as the raw material, namely: (1) oil extracted from the heartwood used for perfumery, cosmetics and aromatherapy; (2) powder used for incense; and (3) wood for furniture and handicraft. Sandalwood oil from West Timor has been exported mainly to the USA and Europe (France, Holland and the UK) (Badan Pengembangan Ekspor Nasional [BPEN] 1993). However, since 2004, as sandalwood raw materials have diminished, no sandalwood products have been exported from Indonesia.

Sandalwood oil in traditional medicine has been used as an antiseptic and for the treatment of headache and stomach-ache. It is also used in the perfume industry. The santalol content in the oil has a distinctive fragrance that has been highly valued for centuries. Sandalwood oil is one of the most expensive essential oils in the market, reflecting the nature of the raw material source and the limited supplies. The oil currently trades at between USD30,000 and USD85,000/t. The sandalwood oil industry is a major consumer of sandalwood raw materials. The largest and oldest oil-distilling factory is located in Kupang. When established in 1974, it had a processing capacity of about 800 t of wood per year (Rohadi et al. 2004).

The once important and valuable sandalwood commodity of NTT in the international market has all but disappeared. Figures from the days when sandalwood was abundant demonstrate the volume of timber harvested. For instance, Rohadi et al. (2000) reported that the intake of sandalwood for the industry in West Timor was around 4,000 t/year. The main industry in West Timor comprises an oil factory, and joss stick and handicraft manufacturing. All of the factories are located in Kupang, the capital of NTT.

Recent attempts by the authors to obtain permission to visit oil factories have been unsuccessful, suggesting that there may be a black market for sandalwood still operating.

Extension and awareness

Ineffective local government policies that tend to neglect community rights and thus discourage villagers from participating in the maintenance of sandalwood regeneration has been identified as one of the root problems of the declining resources of sandalwood in NTT (McWilliam and Andrew 2001; Rohadi et al. 2000). To recover the loss of sandalwood resources, participation of the local community is crucial. Local communities should receive a fair share of the returns, to reward them for their efforts and encourage them to cultivate sandalwood trees.

As new regulations that give more rights to people have been issued, extension work (including an awareness-raising program) must be carried out so that people are aware of the change in government policy. In some parts of NTT, people are still sensitised by their past criminalisation due to their failure to oblige with historical regulations on sandalwood. Without such extension, low planting rates of sandalwood on private land might still be expected. A recent study conducted as part of an ITTO Project in NTT (ITTO 2013) found that local communities in NTT have positive perceptions of sandalwood cultivation, due to their customary relationship with sandalwood. People would be confident to plant and look after sandalwood trees if the economic benefits were favourable.

Research and development

Genetic conservation and tree improvement

Given the growing concerns about the depletion of genetic resources of *S. album* in West Timor, the conservation of genetic resources is of the highest priority. Effendi et al. (1995) reported that four seed production areas (SPAs) have been identified in West Timor, but it is unclear if these SPAs still exist. Similarly, phenotypically selected plus trees have been identified in various districts across West Timor. In total, some 108 trees have been selected and used as materials for breeding and genetic improvement works (Effendi and Surata 1993).

In recent years, the Centre for Forest Biotechnology and Tree Improvement (CFBTI) had been conducting a study on the genetic aspects of sandalwood. Using DNA markers, we examined the genetic diversity of sandalwood from several populations on the islands of Alor, Timor and Sumba. Ex-situ genetic conservation of sandalwood was established in 2002 and 2005 at Gunung Kidul near Yogyakarta. A plot of 2.5 ha containing 18 provenances (10 of Timor, 3 of Sumba, 3 of Alor and 2 of land race Java) were planted (Yuliah et al. 2012). Seed collection from other distributions in Rote, Pantar and Solor has also been carried out and the genetic materials established as a genetic conservation plot.

Genetic diversity of these populations is high (Haryjanto and Liliek 2009; Rimbawanto et al. 2006), which is not surprising since sandalwood has a predominantly outcrossing reproductive system. Individuals with high santalol content (Haryjanto and Liliek 2017) have been clonally propagated and established in a clonal seed orchard (Haryjanto and Liliek 2016).

Suitability of growing sites

Although sandalwood is native to NTT, habitat conditions have changed due to human interventions. Therefore, if planting programs are to be successfully implemented, information on site suitability is needed. A study published in 2016 provided data and information on the land suitability for sandalwood (*S. album*) cultivation on Timor Island (Sumardi et al. 2016). The analysis showed areas suitable for development of sandalwood in five districts in Timor Island are as follows: Belu – 125,216 ha (51.32% of the district's total land area); TTU – 163,554 ha (61.26%); TTS – 278,818 ha (70.64%); Kupang – 263,677 ha (44.73%); and Kupang City – 8,994 ha (49.89%).

National plans and strategies

The Master Plan Sandalwood Development and Preservation NTT Province 2010–2030 was published in 2010, as a joint publication between the Agency for Agricultural Research and Development, the Ministry of Environment and Forestry and the Provincial Government of NTT. The plan details actions aimed at re-establishing sandalwood resources in NTT by 2030. The strategy focuses on the following issues:

1. Improvement of regulations to benefit and encourage the community to actively engage in a sandalwood planting program and ensure that the sandalwood trees will grow to their optimal harvest age.
2. A public education and awareness-raising program on the sustainable management of sandalwood resources, harvesting and marketing, and regulations pertaining to sandalwood cultivation and harvesting, and an industry levy.
3. Intensive cultivation of sandalwood including using seeds of known origin, tending and sustainable harvesting.
4. Improved utilisation to increase product value adding.
5. Transparency in trading and distribution.
6. Conservation of genetic resources for sustainability of the species.
7. Funding support.

The district and provincial governments have shown a strong commitment to implement a sandalwood planting program and have allocated funds for seedling production and planting. Public consultation regarding the regulations for sandalwood resource management is a continuing process, and the government has shown an inclination towards ensuring farmers will receive greater benefits than in the past.

Priority national activities

The focus of the sandalwood program is to regenerate sandalwood throughout the NTT Province by 2030. Hence both local and central governments are gearing up to achieve this goal.

Since 2010, the NTT Provincial Government has launched several sandalwood planting programs across the province. These include the Sandalwood Plantation (*Hutan Tanaman Cendana*/HTC), Sandalwood Family Action (*Gerakan Cendana Keluarga*/GCK) and Sandalwood School Action (*Gerakan Cendana Pelajar*/GCP) programs. Between 2010 and 2018, more than 3.3 million seedlings were distributed and planted in 22 districts. In addition, the regional Watershed Management Office in Kupang produced around 50,000 seedlings/year and distributed them free of charge to those wanting to plant sandalwood. The public are free to take any number of seedlings simply by showing their citizen identification.

The Ministry of Environment and Forestry supports the planting of sandalwood through the Centre for Watershed Management of Benain Noelmina in Kupang. The Ministry has allocated a budget to produce sandalwood seedlings for free distribution to people who want to plant sandalwood trees. The program has proven to be popular and has been ongoing for 5 years now.

As mentioned earlier, sandalwood trees are also being planted and are growing well in other parts of Indonesia, such as at Gunung Kidul and Kulon Progo in Yogyakarta, Bondowoso in East Java, Bali, Aceh (in Sumatra) and Sulawesi. These potentially suitable areas for sandalwood are worth further investigation and additional planting should be carried out in these areas. The climatic conditions in these areas are less extreme than in NTT and should therefore support better chances of plantation success.

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6 An account of the recent history of sandalwood in Australia

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Abstract

Australia's involvement in the sandalwood industry commenced in the early to mid-19th century by Australian merchants trading in sandalwood harvested from the Pacific islands. The harvesting and trading of Western Australian sandalwood (*Santalum spicatum*) in the mid-1840s all but ended the Australian trade in sandalwood from the Pacific islands. Almost 180 years on, Australia is the dominant supplier of sandalwood in the global market, most of the resource traded being wild-harvested Western Australian sandalwood as managed by the Western Australian Government. The first significant trial plantations of Indian sandalwood (*Santalum album*) and Western Australian sandalwood were established by the Western Australian Government in the mid-1980s. These successful comprehensive field trials led to the development of privately funded commercial Indian sandalwood plantations in the northern regions of Australia and commercial Western Australian sandalwood plantations in the southern region of Western Australia. The development and expansion of the two sandalwood industries in Australia over the last 20 years has been substantial. While the export trade of raw or semi-processed commodities continues to flourish, a strong focus has been directed towards product development and local value adding. In more recent years, the Western Australian Government's commercial interests and involvement in plantation research and development has reduced, whereas these areas in the private sector have expanded. Today, large commercial plantations of both species continue to be established, harvesting of the first commercially grown plantation resource has commenced and investment and development of processing facilities and technologies continues. The Australian-based sandalwood plantation industries attract a range of local and foreign investors across a range of entry levels. A firm market distinction between the two sandalwood species (*S. album* and *S. spicatum*) has always existed, furthermore, the distinction between the traditional wild-harvested and plantation-grown Western Australian sandalwood is clearly recognised. It is expected that Australia will continue to be a major provider of sandalwood products sourced from both wild and plantation resources for many years.

Distinction between the quality of *Santalum spicatum* wild-harvested wood and plantation-harvested wood

The *Santalum spicatum* population has a broad natural distribution across the majority of the southern half of the state of Western Australia and to a lesser extent across South Australia. Historically, most of the wild-harvested sandalwood was exported abroad for traditional cultural uses. In more recent years, since 1997, there has been a move towards the distillation of the aromatic oil from the wood, particularly by Australian oil producers for the fragrance industry. Today the valuable components of the oil have been further recognised and are used in a range of industries around the world, including essential oils, cosmetics, therapeutics and body care.

The oil is contained within the heartwood of the tree; this is more accurately described as oil-bearing wood. The amount of oil within the wood is expressed as a percentage weight concentration (% w/w). Higher oil-yielding wood is normally located within the roots and stump of the tree, and the yield ratio progressively decreases further into the branches of the tree. The presence of oil-bearing wood also steadily decreases above the base of the tree and the percentage of non-oil bearing sapwood increases.

The key fragrance component of sandalwood oil is influenced by the concentration of α-santalol and β-santalol. The higher the percentage of these components the more aromatic and usually sweeter the notes. The Australian Standard for *S. spicatum* oil (AS 2112-2003) requires an α-santalol content of greater than 15%. This standard is regularly achieved from oil extracted from the older wild-harvested trees – in many cases these trees will be greater than 70 years of age (Figure 6.1). Higher percentages of α-santalol are associated with heartwood from different sections of the tree; the roots, stump and lower section of the main stem are found to contain the highest percentage, whereas lower percentages of α-santalol are found above these sections.

In comparison to older, wild-harvested Western Australian sandalwood (*S. spicatum*), plantation-grown and harvested Western Australian sandalwood is found to be of a lower value in all markets. The lower value is directly associated with the lower percentage of oil-bearing wood and the lower percentage (w/w) ratio of α-santalol (Figure 6.2). To date, commercial plantations of *S. spicatum* have been harvested at between 15 to 20 years of age. It is understood that the oil concentration and quality in sandalwood trees increases with time, therefore, trees around the age of 15 years may begin to develop and yield commercial amounts of valuable oil. However, plantation profits at this age can be marginal. Plantations harvested at ages greater than 20 years have shown on average to have greater mean oil concentrations and greater mean α-santalol concentrations than those harvested around 15 years of age.

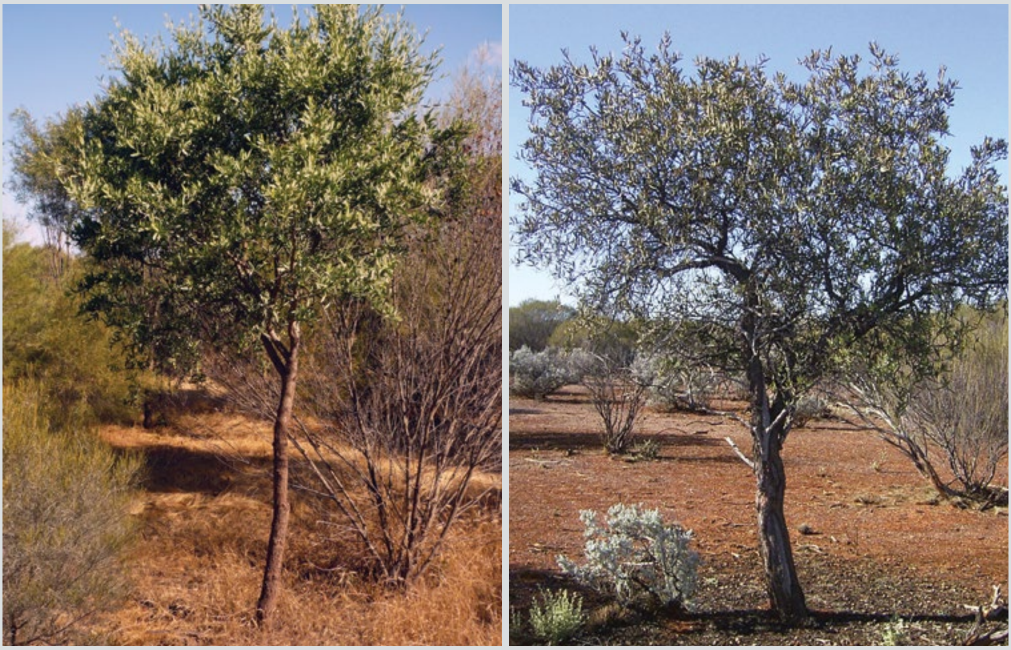
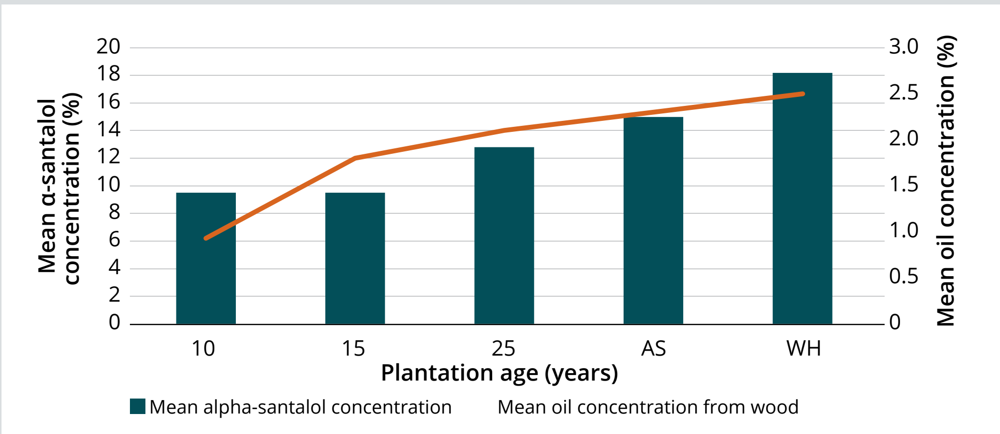


Figure 6.1 A 10-year-old plantation sandalwood tree (left) and wild sandalwood with an estimated age of 100 years (right)



AS = Australian Standard 2112-2003 (mean α-santalol percentage concentration in oil); WH = wild-harvested trees (average age approx. 85 years)

Figure 6.2 Mean oil concentration from combined roots, stumps and lower logs and mean α-santalol concentration from combined roots, stumps and lower logs

Note: The above data have been extrapolated from a Forest Products Commission field study (Brand and Pronk 2010) involving 64 harvested and processed Western Australian sandalwood (*S. spicatum*) plantation trees aged 8 to 26 years.

Discussion

Age has a significant effect on both the oil yield of oil-bearing wood and the mean concentration of α-santalol within the oil of Western Australian sandalwood trees. The Western Australian sandalwood industry has operated since the mid-1840s solely on the harvesting of wild trees that are at least 50 years old and a large percentage that are greater than 100 years of age. The commercial harvesting of Western Australian sandalwood plantations has commenced in recent years and in most cases the trees being harvested are 20 years old or younger. Based on the higher concentration of heartwood oils and the oil quality of wild-harvested wood, it is regarded as having greater commercial value than the plantation resource currently being harvested (Brand et al. 2007).

Commercial Western Australian sandalwood growers have identified the average lower oil yields and α-santalol concentrations typically associated with plantation-grown wood harvested younger than 25 years of age (Brand and Pronk 2010). The longstanding Western Australian sandalwood market is also aware of the differences between wild-harvested and plantation-grown sandalwood. As such, the plantation-based industry is developing a plantation-grown Western Australian sandalwood product standard.

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7 National sandalwood report for Timor-Leste

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Introduction

Timor-Leste is a small nation that occupies half of the island of Timor. Timor is a principal natural source of sandalwood (*Santalum album*). Wild populations of sandalwood on Timor have been exploited since the 1400s, first by the Chinese, then the Portuguese (1515–1974) and later Indonesians (1974–1999). There have been many cycles of boom and bust in the Timor sandalwood trade, with many colonial governors declaring the resource all but depleted as early as the 1800s, again in 1901 and as recently as 1977. Since the restoration of Timor-Leste's independence in 2002, there have been private and government initiatives to restore sandalwood within the Timorese landscape. The Timor-Leste National Government has established several plantations on the country's north and south coasts, and each year seedlings are grown in government nurseries for distribution.

There are estimated to be approximately 493,000 wild sandalwood trees in Timor-Leste, but many are currently immature and without the valuable heartwood. Trade in sandalwood and its products is prohibited in Timor-Leste, to allow the wild trees to develop and grow. Despite this trade ban, there is significant interest among Timorese to plant and grow sandalwood as an intergenerational asset. Since 2017, the Ministry of Agriculture and Fisheries (MAF) has commenced research into sandalwood growth and industry development, and this is contributing to the increase in seedling production throughout the country.

Resource base

Sandalwood resources in Timor-Leste are primarily wild stands, with a small number of government and household plantings. Farmers have never systematically planted sandalwood, and hence the majority of the sandalwood trees in Timor-Leste are the result of natural regeneration. Wild trees are dispersed across the island and distributed from sea level to more than 1,200 m elevation. Large and/or mature trees are confined to very isolated and rugged areas, away from roads.

A forest inventory across two districts of western Timor-Leste (Bobonaro and Covalima) found that two trees in every 1,000 are sandalwood trees (0.2%) (Marques et al. 2010). Mean density of all trees in the survey was 160/ha, equating to an average of one sandalwood tree per 3 ha of forest. Extrapolating this density across Timor-Leste (1.5 million ha) gives a coarse estimate of 493,000 sandalwood trees in the wild. During Indonesian occupation, sandalwood tree numbers dropped from 544,952 trees to 250,940 trees over a 10-year period (ITTO 2011), so a broad estimate of 493,000 trees is considered possible.

In the 2009 survey in Bobonaro and Covalima (Marques et al. 2010), no sandalwood trees with a diameter above 30 cm were recorded. This is consistent with a recent resource survey of 159 mature trees identified by local landowners across the country. In this recent sandalwood resource survey, average tree diameter at 1.3 m height was 15.6 cm, with the maximum diameter being 26.5 cm.

Government and non-government organisations have been producing and distributing sandalwood seedlings in Timor-Leste since 2002. More than 80,000 seedlings have been distributed since independence, with increasing numbers in more recent years. In November 2019, there were approximately 80,000 seedlings in government nurseries ready for distribution in the following wet season. In addition, there are more than 20,000 seedlings in non-government nurseries that will be ready for planting in December 2019.

The government established a sandalwood plantation on the south coast in Suai (Zumalai) in 2004 and a second plantation in Aidabaleten (Atabae) on the north coast in 2016. A third plantation of 50 ha is planned to be established at a second location on the south coast in 2019.

Trade and industry

Recent history

During Indonesian administration of Timor-Leste, the Indonesian company PT Scent distilled sandalwood oil (derived from wild sandalwood trees) in the capital Dili (Aditjondro 2000). Aditjondro summarises 'that the monopoly on the voracious exploitation of the sandalwood forests of Timor-Leste was controlled by a company, PT Denok, run by a relative of one of the leaders of the invasion'. In 1979, the principal shareholder of this company set-up another company dedicated to the export of sandalwood, namely, PT Scent Indonesia, and in 1 year of operation felled thousands of tons of sandalwood. This company, through the use of the Indonesian armed forces, forced the East Timorese to log the sandalwood, without regard to the age of the trees, even tearing out the roots of the trees, which contain the most concentrated aromatic oil. Criticism of this practice went unheeded in Jakarta and, in 1982, PT Scent Indonesia produced 240 tons of sandalwood timber and exported large amounts of sandalwood oil. This went on for at least another 8 years. The company invested Rp1.2 billion – the largest investment in East Timor – and employed 42 workers. In 1990, PT Scent Indonesia claimed to have produced 465 tons of sandalwood oil and powder worth Rp500 million.

The widespread and intense exploitation of wild sandalwood growing in Timor-Leste led to rapid falls in sandalwood production during the 1980s. In 1986, 328 tons of sandalwood timber, 300 kg of oil and 64.7 tons of powder were produced. Six years later, production fell to 118 tons of timber and 40 kg of oil and no powder. (Aditjondro as quoted by Warren Wright 2004). From 1990 to 1996, an average of 124 m^3 of sandalwood was harvested annually but by 1999 this had reduced to 40–50 t (McWilliam 2001). By the time of Timor-Leste's independence in 2002, commercial sources of sandalwood were considered exhausted.

Current trade

All sandalwood trade in Timor-Leste is currently prohibited, with no legal trade or export of sandalwood or sandalwood products permitted. The prohibition is in response to *S. album* being placed on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species as Vulnerable (Arunkumar et al. 2019), and the few mature trees left growing in the wild in Timor-Leste. The aim of the prohibition is to increase wild tree stocks, especially the number of mature trees available for future harvest. Despite this prohibition of sandalwood trade, there is an export black market operating in the country, with many tonnes of sandalwood being confiscated over the last 10 years. Most of the illegal trade is transported by road to neighbouring Indonesia, and just recently a shipping container full of illegally harvested sandalwood was seized by the Government of Timor-Leste.

Extension and awareness

All Timorese are aware of the native sandalwood tree, its importance to the nation and its history. Almost every village is aware of the existence of local sandalwood trees, and the need to protect them from being harvested (AI-Com 2019). In 2015, the government passed a resolution confirming the importance of sandalwood as an emblematic plant of national value.

The prominent national leader, Kay Rala Xanana Gusmão, was the prime minister in 2014 when Timor-Leste celebrated 500 years of Portuguese in the country. During Gusmão's official address, he recognised the historical and economic importance of sandalwood by stating, 'It is now 500 years since white man arrived here because of our sandalwood. Sandalwood was Timor-Leste's greatest wealth, and one which provoked the colonial (Portuguese) powers to invade.' (ETLJ 2014)

In November 2015, the Council of Ministers passed a resolution that promotes sandalwood planting activities in order to regulate its exploitation. Following on from this resolution, a national sandalwood day was launched on 13 January 2017 by the Directorate-General of Forests, Coffee and Industrial Plants from the MAF. This day is now celebrated annually on 13 January and is used to promote sandalwood as an emblematic national plant for Timor-Leste.

Despite the national awareness of sandalwood in Timor-Leste, many landowners consider sandalwood seedlings/trees to be difficult to grow. Many describe experiences of slow or non-germination of seed, death of seedlings in nurseries, and death of planted trees after several years of growth. This is not a new problem. In 1946, under the request of the governor Óscar Ruas, many sandalwood seedlings were prepared only to die at a very early age (Cinatti 1950). There is currently a large demand for sandalwood seedlings among local farmers. In baseline surveys conducted by the AI-Com program (https://ai-com.tl), more than 95% of farming households would like to grow sandalwood trees but lack the seeds and seedlings to do so.

Part of the perceived difficulty of growing sandalwood trees is a lack of appreciation that the tree is a hemiparasite, and that it grows best with other trees/shrubs for the sandalwood roots to host. To make this information available, in 2017 the MAF launched a book describing the appropriate hosts of sandalwood in both Tetun (local) and English languages (Page et al. 2017).

Research and development

Although the development of government-owned plantations in Timor-Leste commenced in 2002, sandalwood research is only just commencing in the country. The research has concentrated on three areas:

1. germination and nursery management;
2. smallholder production; and
3. germplasm collection.

Seed propagation

MAF researchers have confirmed the technology of using gibberellic acid to stimulate sandalwood germination in Timor-Leste. After a series of experiments, the ministry has recommended that sandalwood seed be soaked for 3 days in 250 ppm concentration gibberellic acid. Based on experiments, this results in three times the number of seedlings in one-third of the time.

Since the first successful germination trials in 2017, most of the local sandalwood seedling producers now use gibberellic acid to stimulate sandalwood germination. This has led to a dramatic increase in the number of sandalwood seedlings available in the country.

In 2018, the Global Climate Change Alliance Timor-Leste program produced 10,000 more seedlings in community nurseries than in previous years due to the rapid germination of sandalwood seedlings. In 2019, more than 100,000 seedlings were growing in government and non-government nurseries ready to be planted out in December. This is in comparison to approximately 10,000–20,000 seedlings produced 2 years ago, with the main prior limitation being slow and staggered germination.

Small-scale production

The MAF is also working with local farmers to define the best ways to grow sandalwood trees with smallholder farming households. Over the last 2 years, MAF researchers have established small tree lots (20 trees per household) with 70 farming households. Among these tree lots, there were large differences in tree survival and height growth 1 year after establishment. Some locations had 100% survival 12 months after planting, and others had only a few plants that survived. One critical factor was identified. The sites with the most ground covered by the pot host (*Alternanthera* spp.) had the highest survival. There was also a clear positive correlation between height of the sandalwood tree and level of growth of the host plant.

Germplasm collection

The MAF has commenced a germplasm collection of sandalwood in Timor-Leste. Seed has been collected from 10 locations and seedlings are being grown in a nursery on the country's south coast.

National plans and strategies

Each year, the National Directorate of Forestry and Watershed Management develops a national plan and associated strategies to promote forestry investment using sandalwood and other industrial trees. This has occurred since 2016, with the expectation that it will contribute to the country's future economic growth. Right now, the directorate is promoting planting sandalwood in the following areas: Atabae (150 ha, western part of Timor-Leste) and Zumalai (50 ha, southern part). Other industrial trees are being promoted in Dilor (150 ha, eastern part). These planting activities can potentially address the decline in sandalwood resources and associated loss of genetic diversity within this valuable species.

The Timor-Leste Strategic Development Plan 2011–2030 is an integrated package of strategic policies to be implemented in the short term (1–5 years), medium term (5–10 years) and long term (10–20 years), but it is more than just a set of targets. The Strategic Development Plan is about setting out a pathway to long-term, sustainable, inclusive development in Timor-Leste. Reforestation using sandalwood and the establishment of commercial plantings will provide rural employment in the short term and attractive financial returns to rural communities and other investors in the longer term. The successful implementation of Timor-Leste's Strategic Development Plan and strategies will require the active participation of the Timorese people and other stakeholders. Sandalwood in Timor-Leste has historical, economic, ecological, cultural and spiritual significance, and therefore, within national government actions on forest protection and expansion, sandalwood has been given the priority it deserves.

Acknowledgements

The authors would like to acknowledge the staff of the Division of Forestry, who continue to promote and develop sandalwood within Timor-Leste.

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Technical papers: Resource development and trade

8 Looking ahead – global sandalwood production and markets in 2040, and implications for Pacific island producers

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Abstract

Sandalwood has distinct, high-value end uses, which function to underpin its price and maintain demand in different market segments and regions. These uses and markets include the essential oil from its heartwood as an ingredient (providing woody base notes) in fine perfumes, exclusive natural body-care products and new pharmaceuticals, especially for European and North American markets; for solid furniture, carvings, traditional medicines and religious uses in China, Korea and Japan; for attars, funeral pyres and chewing tobaccos in India; and for customary uses in the Middle East.

The markets for sandalwood heartwood and oils have remained strong and continued to diversify since the first Pacific island sandalwood began to be exploited and exported to China over 200 years ago. The global sandalwood market remains buoyant, with recent sales of *Santalum album* oil at more than USD2,000/kg, and with heartwood being traded at more than USD100/kg.

This paper provides information on production and demand of sandalwood in 2040 for major sandalwood producer regions and markets including Australia, China, India, Indonesia and Timor-Leste, Japan and Korea, East Africa, Europe and UK, South Pacific (Fiji, Tonga, New Caledonia, Papua New Guinea, Vanuatu), the Middle East and North America (USA/Hawai'i and Canada).

The global market for sandalwood products – sustainably sourced from a growing plantation resource in Australia, Asia and the Pacific islands – is predicted to remain strong up to and beyond 2040. The high rate of increase in sandalwood prices in recent decades is unlikely to continue; this is due to both increased supply from increasingly better-managed plantations and the likelihood of technological innovations that will induce earlier and greater heartwood yields in planted sandalwood.

One company, Quintis Ltd., a sandalwood producer and processor managing a vast *S. album* plantation resource in northern Australia, has emerged as the globally dominant player in the international sandalwood market. It is estimated that Quintis will be harvesting around 700 ha of *S. album* plantation per year in 2040 producing 2,660 t of heartwood and generating about 90–95 t of *S. album* oil for export, which equates to 30–40% of the current global demand.

Introduction

Sandalwood has been highly esteemed in Asian cultures and religions for thousands of years, the traditional sandalwood sources being wild stands of East Indian sandalwood (*Santalum album*) in South India and eastern Indonesia. The valuable portion is the heartwood found in the basal part of the trunk and larger woody roots. Sandalwood is produced by many species in the genus *Santalum*, which includes about 16–17 described species and 14 varieties, and one extinct species. *Santalum* is naturally distributed throughout India, Indonesia, New Guinea, Australia and the Pacific islands.

The main species of international commerce are:

- *S. album* Linn. – native to Indonesia and India (and presumed naturalised in the Top End of northern Australia). This is the most highly regarded species in international commerce but is now cut out in its native habitat. Most of the future supply will be coming from plantations in northern Australia, India, Indonesia and other Asian countries.
- *Santalum spicatum* (R.Br.) A.DC. (Australian sandalwood) – native to south-western Australia. One of the most traded sandalwood species, by volume, due to well-controlled and sustainable harvesting. *S. spicatum* oil has low percentages of the preferred santalols and high levels of (E,E)-farnesol, and is best suited to incense sticks and carving.
- *Santalum austrocaledonicum* Vieill. (sandalwud) – native to New Caledonia and Vanuatu. Quality of oil varies with some populations – such as on Santo and Malekula in Vanuatu and Isle of Pines in New Caledonia – having high-quality oils with similar oil profiles to East Indian sandalwood. This species is most closely related to *Santalum leptocladum* Gand., which until recently was considered to be the southerly populations of *Santalum lanceolatum* (Harbaugh and Baldwin 2007; Harbaugh 2007).
- *Santalum yasi* Seem. (*yasi* or *ahi*) – native to Fiji, Tonga and Niue. Usually produces an excellent quality heartwood and an oil that meets the International Organization for Standardization (ISO) standard for East Indian sandalwood.
- *Santalum paniculatum* Hook. & Arn. (*'iliahi*) and *Santalum ellipticum* Gaudich. (*'iliahi alo'e*) – native to Hawai'i. The overall oil quality is satisfactory with some chemotypes being very good.

Minor species that have been important at different periods in the history of sandalwood exploitation and trade include:

- *Santalum macgregorii* F.v.Muell. (PNG sandalwood) – native to Papua New Guinea. The heartwood generally has a poor-quality oil profile with the exception of some trees in the Western Province (which may be a different species and related to *S. lanceolatum* on Cape York Peninsula, north Queensland).
- *Santalum insulare* Bertero ex A.DC. (Eastern Polynesian sandalwood) – native to French Polynesia and the Cook Islands. The overall oil quality is satisfactory, and some chemotypes have excellent oil quality.
- *Santalum lanceolatum* R.Br. (northern sandalwood) – native to northern Australia. The heartwood of this species is generally of an inferior oil quality with the exception of some trees on Cape York (which may have oil profiles closer to East Indian sandalwood).
- An inferior type of sandalwood is produced by several species in the related genus *Osyris*, which are shrubs found in East Africa and used as a substitute for *Santalum* sandalwoods.

Global sandalwood markets have been strong for centuries, but prospective smallholder and other growers are seeking more information on whether the current strong demand and prices will continue and how export/international markets will be impacted by the large sandalwood plantations being established in northern Australia, India, Indonesia, the Pacific and reportedly in other countries.

Methodology

The study involved a review of publicly available papers, reports, company prospectuses and other documents with information on the production of sandalwood from wild sources and plantations. This was supplemented by the direct knowledge of the author on the status of sandalwood in the South Pacific islands and northern Australia through numerous field visits over the past 30 years, and meetings with industry stakeholders. The demand projections were based largely on historical demand by different market segments in different countries where these are known or able to be estimated. Sandalwood industry experts were widely consulted for their views on production and markets during the development of this paper and their knowledge and considerations were integrated into these assessments.

Outlook for sandalwood production and markets in 2040

Australia

Production in 2040: Quintis plantations of *S. album* in northern Australia (c. 12,500 ha total in north-western Australia and the Top End of the Northern Territory) are expected to have 420 surviving stems at the final harvest at 14–16 years. The average yield is likely to be around 8–10 kg heartwood per tree at 25% moisture content with a yield of 3.7% oil (i.e. 3.8 t heartwood per hectare). It is estimated that 700 ha of *S. album* plantation will be harvested in 2040 producing 2,660 t of heartwood. If 95% of the Quintis harvest is distilled into oil @3.7% oil (with 5% of heartwood destined for Asia art/furniture market) this would generate 93 t of *S. album* oil for export. Santanol Pty Ltd (now owned by Mercer Int.) also has large areas of planted *S. album* in northern Australia, about 2,500 ha, but the earlier plantings were of poor quality. The two main Australia native sandalwood species, *S. spicatum* and *S. lanceolatum*, are expected to continue to be harvested from the wild, at similar to the current harvest rates, and supplemented by planted *S. spicatum* (22,000 ha planted in central-south Western Australia, but on long rotation and with a rather low oil yield, c. 1.5%).

Demand in 2040: The local demand for sandalwood products in Australia will remain minor (as a proportion of global use). The main consumption will be through imported value-added products incorporating sandalwood oil, such as perfumes, body-care products and medicines.

Summary: In 2040 almost the entire (>98%) Australian sandalwood production will be destined for export. The product, export market and price will vary depending on species and other factors. In 2040 Quintis and Santanol plantations in northern Australia will produce c. 100 t of oil, equivalent to more than 30% of the world market demand for high-quality sandalwood oil. Given the market dominance of the Australian plantation East Indian sandalwood oil, it is possible that other producers/suppliers of high-value sandalwood oil will be price takers if global supply exceeds demand. There is expected to be an oversupply of *S. spicatum* or Australian sandalwood oil in 2040, as the planted stands in Western Australia mature and are harvested.

Asia

China (including Taiwan)

Production in 2040: About 2,000 ha of *S. album* plantations have been developed in South China but heartwood has been slow to develop. Some of these have been interplanted with *Dalbergia*, which may cause problems later due to its heavy shading. Sandalwood Forest (Qingyuan) Co. Ltd in north-west Guangdong (started in 2012) has planted 200,000 sandalwood trees with plans to establish 6 million seedlings. The company is well organised and capitalised, but their plantations are expected to develop heartwood very slowly and be cut back to near ground level by annual frosts. It is estimated that by 2040 there will be c. 70 ha being harvested @6 t/ha (@30 years age) or 420 t (with 2% oil).

Demand in 2040: China's growing middle and upper class will need at least 100 t of oil per year for local medicines, perfumes and body-care products. Annual perfume sales in China of around USD4 billion are expected to increase four-fold by 2040 and many, perhaps the majority of these perfumes, will incorporate sandalwood oil into their formulations. China will remain a premium destination for carving logs and furniture, which is the most highly priced market segment for sandalwood logs. A conservative estimate of demand for solid sandalwood in 2040 is 1,000 t of heartwood per year.

Summary: China will minimally require an additional 5,000 t/year of plantation *S. album* heartwood to meet new and unmet demand for oil, carving logs, solid wood furniture and traditional medicines. The modest amount of heartwood from China's *S. album* plantations will be mainly used domestically for local handicrafts and incense products. China will continue to require and import substantial amounts of lower grade sandalwood products for incense products (including from *S. album* spent charge, *S. spicatum* powder and pre-grind, incense sticks).

India

Production in 2040: Padmanabha (2013) found that the annual official harvest of sandalwood was about 400 t, yet total production is about 2,000 t/year, with the difference due to illegal harvesting. In 2019 there was about 30,000 ha of *S. album* planted in India: these plantations are estimated to produce about 8 t heartwood per hectare on a 25 to 30-year rotation. It is estimated that there will be about 1,000 ha of 25 to 30-year-old sandalwood plantation harvested producing 8,000 t heartwood with an oil content of 2.5% oil, or 200 t oil. It is estimated that wild stands will produce 2,000 t heartwood with an oil content of 5% oil, or 100 t oil.

Demand in 2040: At least 250 t of oil. It is likely that the local *S. album* plantation wood will be mainly used domestically for agarbatti and funeral pyres (rather than oil production) and some oil, especially for soaps/attars.

Summary: India will likely be an importer of sandalwood heartwood and/or oil in 2040 but it is difficult to predict by what quantity due to uncertainties in the production, quality and maturation times of its recent plantations. The new plantations are mainly in non-traditional sandalwood growing areas and the impacts of sandalwood spike and other pests and diseases are unknown, and growth rates/heartwood development rates are uncertain.

Indonesia and Timor-Leste

Production in 2040: The main sandalwood production areas are in eastern Indonesia (Nusa Tenggara Timur (NTT), including West Timor, Flores and Sumba) with small wild populations in north Sumatra and central Java. Indonesia has vast areas of land that are potentially suitable for sandalwood cultivation, but the most suitable lands are needed for short-term crops/food production. Current and projected future sandalwood production is limited, due to previous unsupportive legislation, and relatively long rotations, which discourage planting by farmers in need of quick returns. There are major replanting programs in process, e.g. NTT government replanting program, with Kupang/NTT nurseries distributing 500,000 sandalwood seedlings per year (equivalent to about 1,000 ha of sandalwood) and 50 ha/year in Timor-Leste (with a national government aspiration to plant 1 million sandalwood trees per year). It is considered that there is currently less than 5,000 ha (equivalent) of planted *S. album* (mostly in low-productivity agroforestry systems) in Indonesia and Timor-Lest. Estimated yield is 6 t/ha at 30 years. It is estimated that 500 ha (equivalent) will be harvested in 2040 (@30 years) with a yield of 3,000 t.

Demand in 2040: Traditional use of sandalwood in religious ceremonies will continue, especially among Balinese Hindus. A small amount of sandalwood oil may be locally distilled for use in perfumes and body-care products.

Summary: The local demand for sandalwood and its oil is expected to remain modest, such that Indonesia (and Timor-Leste) will likely export most of their production in unprocessed form (i.e. about 3,000 t of *S. album* heartwood will be exported in 2040).

Asia (other countries)

Production in 2040: There are increasing areas of sandalwood plantations in Sri Lanka, Thailand, Malaysia and Vietnam, with several thousand hectares currently established. The heartwood yield is estimated to be 8 t/ha on a 25-year rotation. There will be limited sandalwood production in 2040, but production will increase thereafter. It is estimated that 800 t of heartwood will be produced in 2040 based on plantations already established in Sri Lanka (Subasinghe et al. 2013) and Thailand.

Demand in 2040: Sandalwood is extremely important in East, South-East and South Asian cultures and religions, with the first Buddha reputedly being carved out of sandalwood. It is mainly imported into East Asia in the form of powdered sandalwood, incense sticks and small logs for carving. Import data for Japan and South Korea is limited, but it is expected that current sandalwood demand will be maintained and increased for certain uses such as perfumes and traditional medicines. It is very difficult to predict future demand for sandalwood products in South-East Asian countries but it is likely that increased domestic demand (in perfumes, medicines, furniture, incense) will absorb increased domestic production.

Summary: In 2040, South Korea and Japan will continue to be large importers of sandalwood products. Increased demand for sandalwood products in other countries in South-East and East Asia will be mostly met by increased sandalwood production from new plantations in Sri Lanka, Thailand and Vietnam.

East Africa

Production in 2040: *Osyris* – a closely related genus to *Santalum* – naturally occurs in East Africa (Kenya, Tanzania, Somalia and Uganda). *Osyris* spp. have been exploited over the past two decades for a lower grade of sandalwood. It is predicted that all legal and most illegal sources of wild-harvested *Osyris* will have been overharvested such that there will be almost nil supply of this sandalwood substitute in 2040 from wild sources, and almost none from plantations due to its slow growth rate.

Demand in 2040: Currently there is a minimal demand for sandalwood products from Africa, but this is expected to change due to improving African economies and through sandalwood being a desired consumer product (body care and perfumes) by upper/middle classes.

Summary: *Osyris* species are slow-growing shrubs not well suited to commercial production of sandalwood, and the yield from planted sources will be limited in the medium to long term. There is reportedly interest in developing *S. album* plantations in Africa (Padmanabha, pers. comm., 2014), and the species would likely grow very well in several countries in East Africa, with appropriate hosting regimes. In 2040, East Africa and other African regions and countries (including the Republic of South Africa and Senegal) will be low level, net importers of sandalwood products.

Europe and UK

Production in 2040: No sandalwood is grown in Europe, although sandalwood is cultivated commercially in the French Territory of New Caledonia.

Demand in 2040: Europe and the UK will remain a major market for value-added sandalwood products, such as perfumes, soaps and body-care products. Historically 10–15 t of oil has been imported annually into Europe, and these imports are predicted to grow as reliable plantation sources are developed, which can be used to develop new high-value products, especially French perfumes.

Summary: In the EU and the UK, in 2040 the current demand for sandalwood ingredients and products will be maintained and increased for certain uses such as perfumes, aromatherapy and body-care products, with demand for high-quality sandalwood oil expected to increase to 20–30 t/year.

Pacific islands

From the beginning of the 19th century European traders began heavily exploiting sandalwood resources in the Pacific islands to supply the market for incense and carving wood in the Buddhist temples of China (Shineberg 1967). Ever since, the supply of sandalwood from the Pacific islands has fluctuated considerably (Thomson 2013), but in recent times it has averaged about 250 t/year. This is equivalent to less than 10% of the sandalwood being cut during the early 19th century (Shineberg 1967; Thomson and Doran 2010; Thomson 2013).

Fiji and Tonga

Production in 2040: In recent decades the total amount of *S. yasi* heartwood exported from Fiji and Tonga has been less than 100 t/year (Thomson et al. 2020). *S. yasi*, *S. album* and their hybrids are being planted on an increasing scale in Fiji including through the Ministry of Forestry's Sandalwood Development Programme (Bolatolu et al. 2019), and there has been greatly increased planting in Tonga over the past 5 years (Motuliki 2019). The estimated harvest of planted sandalwood in 2040 is 12,000 trees with a total yield of 300 t heartwood (with 3.5% of oil). The estimated yield from natural stands of *S. yasi* in Fiji and Tonga in 2040 is 65 t heartwood (with 5% oil).

Demand in 2040: In 2040 there will be limited local use and a fairly insignificant domestic market mainly for value-added sandalwood products, such as perfumes, soaps and body-care products for expatriate communities and carry-on export/tourist markets.

Summary: In 2040 the total production from Fiji and Tonga is estimated to be 365 t of sandalwood heartwood. Almost all of this wood will be exported, mainly in unprocessed form, likely to East Asia and the Middle East. As larger planted areas are harvested in both countries there will be more local value adding, especially conversion of heartwood into essential oil.

New Caledonia

Production in 2040: In New Caledonia the most recent inventories on Maré and Isle of Pines have demonstrated the presence of reasonable quantities of sandalwood that could be sustainably harvested based on an annual quota of heartwood. The replanting program for *S. austrocaledonicum* has historically been about 1–2 ha/year in the Southern Province. For Loyalty Islands, there are plans for smallholders to replant 30,000 sandalwood seedlings per year. This replanting is to be undertaken in association with the distillery on Maré.

Demand in 2040: Metropolitan France has been a major market for sandalwood oil from New Caledonia for incorporation into value-added sandalwood products, such as perfumes, soaps and body-care products. The supply of *S. austrocaledonicum* oil into Europe (>90% to France) from Loyalty Islands has been increasing but remained steady from 2016–18 at 8.6–8.7 t oil (with a declared value of USD5.7 million or USD650/kg).

Summary: In 2040, it is predicted that the demand for high-quality sandalwood oil will continue to grow in France to 15–20 t, with this demand rather elastic depending on the availability and price of sandalwood oil. It is expected that sandalwood production from any increased plantings in New Caledonia will be readily absorbed by the markets in France, including its Pacific territories, and elsewhere in Europe.

Papua New Guinea

Production in 2040: Harvesting of the native sandalwood species, *S. macgregorii*, commenced in the early 20th century. Ever since there have been widely fluctuating levels of heartwood exports, reaching in excess of 500 t in 2003, but with no recorded exports in recent years. The rather low-value heartwood of *S. macgregorii* has been mainly exported in unprocessed form to East Asia. There appears to have been only limited reported replanting of *S. macgregorii* in Papua New Guinea. In East New Britain, Amruqa has been establishing small-scale trial plantings since 2010 with high survival and moderately fast but variable growth rates. There is a need for more research and development on sandalwood in Papua New Guinea, especially for the *Santalum* entity in Western Province, which has a more desirable chemotype than *S. macgregorii* and which appears to be a different species.

Demand in 2040: There are no recorded important local uses, and future demand within Papua New Guinea will be low.

Summary: In 2040, production is likely to be negligible (<10 t of heartwood per year) due to past overharvesting of wild stands, coupled with limited replanting and slow growth, and frequent wildfire in its native habitats in the Central and Gulf provinces.

Vanuatu

Production in 2040: The quantity of sandalwood (*S. austrocaledonicum*) heartwood harvested and exported from Vanuatu has been the most consistent of any Pacific island country (due in large measure to effective regulation by the Department of Forests). However, exports have dropped in recent years due to the decline in wild stocks. Future sandalwood exports from Vanuatu will largely come from smallholder and commercial plantations. The sandalwood plantation area established in 2014 was about 1,400 ha with an annual planting rate of 20,000 sandalwood trees. South Pacific Sandalwood Ltd is the major commercial plantation grower.

The annual sustainable resource from native stands is likely to be 50 t, while smallholder growers are likely to produce 400 t of heartwood per year by 2040. If South Pacific Sandalwood Ltd were, in collaboration with local landowners/partners, to plant an additional 500,000 trees then the additional sandalwood heartwood production in 2040 from a 2020 planting of 100,000 trees (with survival of 95%) would be 95,000 × 20 kg/tree or 1,900 t.

Demand in 2040: There are limited local uses for sandalwood and an insignificant domestic market mainly for value-added sandalwood products, such as perfumes, soaps and body-care products.

Summary: In 2040, Vanuatu's heartwood production may increase 10-fold from historical levels to >2,000 t, mostly destined for export. There is a need to grow the international-market preferred (i.e. santalol-rich) chemotypes of *S. austrocaledonicum* from Santo and Malekula, while differentiating *S. austrocaledonicum* oil from that of *S. album*.

Middle East

Production in 2040: Currently no sandalwood is grown in the Middle East, and this is likely to remain the case due to the unfavourable climate (too dry and hot).

Demand in 2040: During the late 1980s and early 1990s, when India and Indonesia were the main producers of *S. album* oil, the Middle East (including United Arab Emirates and Oman) imported 4 t of oil per year, and it is expected that by 2040 demand will more than treble to >12 t oil per year.

Summary: In 2040, it is expected that demand for sandalwood oil and value-added products will remain strong. There will also be a continuing demand in the Kingdom of Saudi Arabia and the Gulf Arab States for sticks of heartwood to be burned at social events.

North America (USA and Canada)

Production in 2040: Hawaiʻi is the sole supplier of *S. ellipticum* and *S. paniculatum* wood and oil to the world sandalwood market. There has been widely variable production and export from 2010 to 2015, with sandalwood exports being around 250–600 t/year, mainly of *S. paniculatum* to China, Dubai and Sri Lanka. The recent export phase of sandalwood exports from Hawaiʻi appears to have almost ceased, due to dwindling available wild stands of trees of commercially exploitable size. The production from wild stands in Hawaiʻi is expected to be limited in future, possibly averaging up to 50–100 t heartwood per year if currently protected/little known stands are sustainably harvested. There is only modest commercial interest in replanting.

Demand in 2040: The USA has been a major market for value-added sandalwood products, such as perfumes, soaps and body-care products.

Summary: It is difficult to predict the amount of oil that Santalis Pharmaceuticals and other large users in the USA might require in future for incorporation into pharmaceuticals, body-care products and perfumes – but it could range up to hundreds of tonnes of oil per year.

Discussion

A major shift is underway in almost all traditional areas of sandalwood production, such that planted trees will replace wild-harvested sandalwood resources. This is due to the commercial extinction of sandalwood in almost all of its native occurrences, the main exceptions being *S. spicatum* in Western Australia and *S. austrocaledonicum* in New Caledonia due to a better regulated and monitored environment based on a realistic sustainable yield. At the same time, and over the past 25 years, there has been a considerable research and development effort to determine and document best practices in the cultivation of sandalwoods (propagation, establishment, host species and pruning regimes).

The transition from wild to planted resources is exemplified in the Pacific islands where there are now very few remaining, accessible mature sandalwood trees but rapidly growing smallholder sandalwood plantings. With the high prices on offer over the past two or three decades, there has been a scramble to locate and harvest the last remaining wild sandalwood in Fiji, Tonga and Vanuatu. This has sometimes led to wasteful 'checking' and cutting of immature trees, sandalwood theft – typically of individual mature trees – and an associated undocumented illegal trade in sandalwood products. In future it is expected that sandalwood production from wild stands in the Pacific islands will remain at low levels, totalling ≤100 t/year: trade in wild sandalwood will be predominantly from the traditionally better regulated supply of *S. austrocaledonicum* from Vanuatu and New Caledonia. However, the supply of sandalwood from the South Pacific islands will gradually increase as a result of mainly smallholder planted sandalwood stocks attaining maturity firstly in Vanuatu, then Fiji and Tonga.

It is difficult to quantify the size of the global market for sandalwood due to the lack of published and available trade data and also due to the scale of illegal trade, which is likely to be around 33% of the total market. The most reasonable estimate of the global sandalwood market in recent times is 6,320 t heartwood for the year 2011–12 (Coakley 2013). It is clear that the global demand for sandalwood remains strong and also that demand has considerably outstripped supply, especially for East Indian sandalwood over the past two or three decades. As a consequence, prices have continued to rise at rapid rates during the 2000s (e.g. the price for high-quality East Indian sandalwood oil recently reputedly reached USD3,000/kg for perfumes and new pharmaceutical uses, before dropping back to around USD2,000/kg).

In the near future (if not already), planted sources of *S. album*, *S. austrocaledonicum* and *S. yasi* will overtake and supplant wild sandalwood resources of the same species; likewise, this pattern will be repeated for *S. spicatum* over the next 10–15 years. The market outlook and prices for sandalwood of high quality (i.e. with high levels of santalols and which fits within the East Indian sandalwood ISO standard) are expected to remain strong for at least the next 10 years. The price elasticity for sandalwood products is rather high (i.e. demand would increase substantially if the price of sandalwood falls, due to latent high demand in several of its uses such as medicinal/body-care products). However, equally, the likelihood of a major, sudden and sustained drop in sandalwood price is low because the price is buffered and underpinned by its high-value uses in different regions (i.e. perfumes and attars, fragrant smoke, carving wood, medicinal and body-care products) in regions with strong economies such as Europe, North America and the Middle East and/or growing middle classes with higher disposable incomes such as China and India. Nevertheless, sandalwood is a luxury item whose price and demand would inevitably decline during any major global economic downturn.

It is expected that a whole range of new uses will be developed, and traditional uses will be re-established once more reliable and consistent supplies of high-quality sandalwood oil are generated through sustainably managed plantations. There is currently a substantial unmet demand to include sandalwood oil in high-range and mid-range perfumes, body-care products, aromatherapy, traditional eastern medicines, new pharmaceutical products, and top-of-the-range solid furniture. Such uses and associated increased demand from China, India and other Asian economies will underpin the price of better grades of sandalwood oil for the foreseeable future. It is, however, quite possible that species with inferior oil quality, such as *S. spicatum*, will struggle to maintain their market share in future, with lower grades of *S. album* products (including spent charge) and possibly also plantation *Aquilaria* displacing *S. spicatum* in agarbatti.

Synthetic santalols are expensive to produce and less demanded in the perfume sector and are unlikely to be a major source of replacement of natural santalols. However, other innovations may affect sandalwood production, including improved genetics and silviculture producing higher amounts of higher quality heartwood at a younger age, and new heartwood stimulation technologies.

Acknowledgements

This chapter has also been published as Thomson LAJ (2020) 'Looking ahead – global sandalwood production and markets in 2040, and implications for Pacific Island producers', *Australian Forestry*, 83(4):245–254.

The author acknowledges inputs provided by numerous informants in Fiji and elsewhere, including international and Pacific sandalwood industry experts (Dr Tony Page, Dr John Doran, Dr David Bush, Mr Tim Coakley, Mr Steve Bartrop and Mr Jonathon Naupa). The author acknowledges funding support from the Australian Centre for International Agricultural Research (ACIAR) for this collaboration between the Pacific Agribusiness Research in Development 2 (AGB-2014-057) and Domestication and breeding of sandalwood in Fiji and Tonga (FST/2016/158) projects.

Disclosure statement: The author is a scientific adviser and shareholder in Pacific Reforestation (Fiji) Ltd, which has small-scale plantings of *Santalum* in Fiji.

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9 Essential oil of *Santalum austrocaledonicum*: developing an international standard

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Abstract

Sandalwood oil is among the world's most popular essential oil products, being used in perfumery, aromatherapy and traditional/religious practice. Although International Organization for Standardization (ISO) standards have existed for *Santalum album* and *Santalum spicatum* (Western Australian sandalwood) for some time, there has to date been no formal standardisation of *Santalum austrocaledonicum* essential oil. Producers as well as authors regrading *S. austrocaledonicum* refer to the oil as meeting the ISO standard when in fact they are referring to the ISO standard for Indian sandalwood (*S. album*) oil, a different product.

Two distinct chemotypes are reported for *S. austrocaledonicum*, with possible sub-chemotypes. The main chemotypes are santalol (Vanuatu and New Caledonia) and nuciferol/lanceol (primarily Vanuatu). Variation in oil quality is influenced by genetic factors, the maturity of timber at the time of harvest, the part of the tree used and/or the influence of host species and other environmental factors on oil formation. Tentative components and composition parameters for oil of *S. austrocaledonicum* based on values provided from commercial production in New Caledonia include the following: α-bergamotol (3.0 to 8.0%), *Z*-α-santalol (38.0 to 45.0%), *Z*-β-santalol (12.0 to 17.0%), *Z*-nuciferol (1.4 to 21.4%), *Z*-γ-curcumen-12-ol (2.1 to 19.8%), *Z*-lanceol (4.0 to 13.0%), and epi-β-santalol (2.6 to 4.0%). Additional consultation with stakeholders in both New Caledonia and Vanuatu is required to further inform the development of the proposed standard.

Introduction – standards process

Quality standards for essential oils aim to provide a range of measurable parameters, which allow clear identification and evaluation of relative quality. These parameters are typically chemical and physical but include olfactory parameters such as aroma and appearance.

Standardisation of essentials oils is necessary to ensure safety, efficacy and fair trade. Essential oil standardisation is provided primarily by ISO (The International Organization for Standardization) and Pharmacopoeia such as the British/European Pharmacopoeia.

ISO is an independent, non-governmental organisation comprising members from the various national standards organisations of the 164 participating member countries. The ISO is the largest developer of voluntary international standards. The ISO:

- facilitates world trade by providing common standards between nations
- supports the creation of products and services that are safe, reliable and of good quality
- helps businesses increase productivity and reduce errors and waste
- enables comparison of products from different markets
- supports development of global fair trade
- provides consumer and end user safety by defining minimum standards through certification.

ISO is not an acronym but rather a name derived from the Greek 'isos', meaning equal. The ISO has a central secretariat based in Geneva, which administers over 250 technical committees. It is these committees that develop and review ISO standards.

Product standardisation is the process of maintaining uniformity and consistency among the different iterations of a particular good or service that are available in different markets.

For standardisation of essentials oils, it is necessary to:

- ensure safety – consumer confidence in authenticity and safe usage
- provide efficacy – correct composition and potency to be effective in application
- support fair trade – provide confidence in purchase and supply of the raw material.

The development process for ISO standards involves a range of defined steps, which are coordinated by the ISO secretariat and are implemented by the respective national committee leading a particular standard development project (ISO 2019).

There are six stages including:

1. proposal
2. preparatory
3. committee
4. enquiry
5. approval
6. publication.

The Swedish Civil Contingencies Agency in collaboration with ISO and the Swedish Institute for Standards provides the following information about the ISO standardisation process (https://www.isotc292online.org/projects/the-iso-standardization-process):

Proposal stage

This first step is to confirm that a new International Standard in the subject area is really needed. A new work item proposal (NWIP) is submitted to the committee for vote using Form 4.

The person being nominated as project leader is named on the Form.

Any complications around copyright, patents or conformity assessment are raised at this early stage.

Preparatory stage

A working group (WG) is set-up by the parent committee to prepare the working draft (WD). The WG is made up of experts and a Convenor (usually the Project Leader).

Successive WDs can be circulated until the experts are satisfied that they have developed the best solution they can. The draft is then forwarded to the WG's parent committee, who will decide which stage to go to next (Committee stage or Enquiry stage).

Committee stage

During this stage the draft from the WG is shared with the members of the parent committee.

If the committee uses this stage, the committee draft (CD) is circulated to the members of the committee, who then comment and vote using the Electronic Balloting Portal. Successive CDs can be circulated until consensus is reached on the technical content.

Enquiry stage

The Draft International Standard (DIS) is submitted to the ISO Central Secretariat (ISO/CS) by the Committee Manager. It is then circulated to all ISO members, who then have 12 weeks to vote and comment on it.

The DIS is approved if a two-thirds of the P-members (participating members) of the technical committee or subcommittee (TC/SC) are in favour and not more than one-quarter of the total number of votes cast are negative. If the DIS is approved and no technical changes are introduced in the draft, the project goes straight to publication. However, if technical changes are introduced, FDIS stage (Final Draft International Standard) is mandatory.

Approval stage

This stage is automatically skipped if the DIS has been approved and no technical changes are introduced. However, if the draft incorporates technical changes following comments at the DIS stage (even if the DIS has been approved), the FDIS stage becomes mandatory.

If this stage is used, the FDIS is submitted to the ISO/CS by the Committee Manager. The FDIS is then circulated to all ISO members for an 8-week vote.

The standard is approved if a two-thirds majority of the P-members of the TC/SC is in favour and not more than one-quarter of the total number of votes cast are negative.

Publication stage

At this stage the ISO/CS submits the final document for publication through the Submission Interface. But if the standard has passed through the Approval stage, the Manager may submit the Project Leader's responses to member body comments on the FDIS.

Only editorial corrections are made to the final text. It is published by the ISO/CS as an International Standard. Committee Managers and Project Leaders get a 2-week sign off period before the standard is published.

Chemotypic variation in *S. austrocaledonicum*

The process of standardisation requires a broad understanding of the range and diversity of products in trade, which can be difficult and/or expensive to attain. It also risks excluding variants to the mainstream production that occur naturally. For example, tea tree oil, the largest Australian essential oil, is representative of one of the three naturally occurring chemotypes of *Melaleuca alternifolia*. There is nothing wrong with the other two chemotypes, they were just never commercialised. This industry started out with wild-harvested material (bush cut) and has moved to broadacre production using clonal varieties with significantly higher yields than bush cut, and ease of production. Because wild harvesting was less specific, it was possible to have inclusion of other *M. alternifolia* chemotypes in harvest, and so parameters for components such as 1,8-cineole were broader. This breadth in the standard did, however, expose tea tree oil to adulteration. As such, the most recent revision of the ISO standard for tea tree oil (Essential oil of *Melaleuca,* terpinen-4-ol type (tea tree oil)) ISO 4730:2017 (ISO 2017) has tightened the range on 1,8-cineole and other parameters in an effort to exclude adulterated oil from being traded as tea tree oil.

Santalum austrocaledonicum grows naturally in New Caledonia and the Vanuatu archipelagos (Baldovini et al. 2011). It is one of severalPacific sandalwood oils (*Santalum yasi*, *Santalum insulare*, *Santalum paniculatum*) and is closely related to *Santalum lanceolatum* (north-east Australia), *Santalum macgregorii* (Papua New Guinea) and *Santalum album* (naturally occurring in Timor). *S. austrocaledonicum* occurs in three reported subvarieties: *austrocaledonicum*, *pilosulum* and *minutum* (Harbaugh and Baldwin 2007). As with other species of *Santalum*, it grows proximate to host species. Host species are typically nitrogen fixing with the sandalwood parasitising the host to draw additional nutrition.

In Vanuatu, *S. austrocaledonicum* is reported to have two distinct chemotypes with potential sub-chemotypes (Page et al. 2010). The diversity is possibly due to genetic divergence due to island biogeography. It is also possible that perceive differences occur due to the maturity of timber at time of harvest, the part of the tree that is used and the influence of host species on oil formation. Brand and Pronk (2011) describe variations in oil composition occurring in *Santalum spicatum*, with distinct differences between the root, lower truck, upper trunk and branches. The main chemotypes of *S. austrocaledonicum* are santalol (similar to varieties from New Caledonia) and nuciferol/lanceol. The main constituents of *S. austrocaledonicum* are α-santalol and β-santalol, *Z*-nuciferol, curcumen-12-ol, *Z*-lanceol, epi-β-santalol and α-bergamotol.

Developing an international standard for *S. austrocaledonicum*

With revisions of both *S. album* and *S. spicatum* underway it seems important to formalise a standard for *S. austrocaledonicum*. The generation of an ISO standard requires that a product be at a significant scale of global production. The creation of this standard was proposed by the Australian representatives at ISO and ISO Technical Committee 54 was in agreement that this was an important global product. *S. austrocaledonicum* is reported to be the third most traded sandalwood oil by volume. Some chemotypes have an oil composition very similar to Indian sandalwood (*S. album*), making it a desirable replacement product for *S. album*, which suffers through shortage of supply.

Sandalwood oil is among the world's most popular essential oil products, being used in perfumery, aromatherapy and traditional/religious practice. Although ISO standards have existed for *S. album* (ISO 2002) and *S. spicatum* (Western Australian sandalwood) (ISO 2009) for some time, there has to date been no formal standardisation of *S. austrocaledonicum* essential oil. Producers as well as authors refer to the oil of *S. austrocaledonicum* as meeting the ISO standard when in fact they are referring to the ISO standard for East Indian sandalwood (*S. album*) oil, a different product. This is in part due to ambiguity surrounding the ISO description of East Indian sandalwood as 'Sandalwood oil – Oil of *Santalum album*' and currently only including two major components (α-/β-santalols) in its chemical description.

To date, comprehensive information about *S. austrocaledonicum* oil is only available from production originating in New Caledonia, and in particular the Loyalty Islands. While oil production may be occurring in Vanuatu there has not been information available relating to commercially produced oil that can be drawn upon to include in the current draft ISO standard. There are several significant commercial plantations of *S. austrocaledonicum* in Vanuatu that will reach their commercial potential over the coming decades. The majority of natural mature stands in Vanuatu have been depleted through unsustainable harvesting practices originally in the 1800s and again more recently in the early 2000s.

The oil composition of these commercial stands may have influence over parameters defined for essential oil of *S. austrocaledonicum* in future revisions of an ISO standard for this oil (Table 9.1). Importantly, the process of standardisation is to facilitate trade by providing confidence in the authenticity of a product. As such it is necessary to allow for changes and modifications to standards over time to reflect changes in knowledge and production of a defined product.

Acknowledgements

Dr Daniel Joulain, President, SCBZ Conseil, for contributing comprehensive raw data of physical and chemical characteristics of *S. austrocaledonicum* from The Loyalty Islands, New Caledonia.

Table 9.1 Tentative list of components and composition parameters for oil of *S. austrocaledonicum* based on values provided from commercial production in New Caledonia

Component	Minimum (%)	Maximum (%)
α-bergamotol	3.0	8.0
Z-α-santalol	38.0	45.0
Z-β-santalol	12.0	17.0
Z-nuciferol	1.4	21.4
Z-γ-curcumen-12-ol	2.1	19.8
Z-lanceol	4.0	13.0
epi-β-santalol	2.6	4.0

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10 Product specifications for tropical planted sandalwood to facilitate transparent commerce and trade

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Abstract

The sandalwood trade provides an important source of income for many smallholders in the Pacific and over the past decade many have been making a transition from wild-harvested to planted sandalwood. Given their investment in planting sandalwood, many resource owners are seeking to optimise commercial returns from sales. Grower knowledge of sandalwood products and their associated prices is an essential element for the scheduling of harvesting and sales negotiation with traders. However, this knowledge is not widespread among resource owners and there is little public information available to guide them. A transparent grading system is also essential to facilitate central and/or internet marketing of sandalwood products. As a first step to address these issues, this document represents a standardised system for the grading of smallholder planted sandalwood products.

This product grading system is based on size of product and tree structure (roots, stumps, stems and branches). It contains grades across four broad product classes: (1) specialty; (2) typical; (3) immature wood (sapwood) and faulty heartwood; and (4) by-products.

Specialty heartwood products command the highest prices and are produced in older trees greater than 20 years. These include carving logs and butts and decorative natural pieces such as burls and wood forms used for display. The international price of the carving log provides the basis for which typical sandalwood grades can be valued.

Typical sandalwood grades are based on an expected heartwood oil gradient, where the concentration and quality are greatest in the stump (butt) and associated major roots and progressively declines upward through the primary stem and branches. Five typical grades are proposed and specified including roots, butts (large and small), logs, small logs and heartwood pieces. A pricing index is proposed for these grades based on the roots and butts being 60% of the value of a carving log. Heartwood pieces are considered to have a variable price and are not included in this pricing index.

Immature and faulty sandalwood products include sapwood and diseased, degraded and improperly formed heartwood products. Such immature and faulty products have low commercial value and prices are by agreement between producer and trader.

The processing by-product is second cutting chips that are derived from the final process of de-sapping. This process is typically undertaken by the trader following purchase from the supplier.

Introduction

Sandalwood is a tree that produces a valuable oil-rich fragrant heartwood that has a high demand within international markets. Sandalwood has been used since antiquity and is revered for its fragrant properties as well as its association with spiritual rites. Oil is extracted from the heartwood for use in perfumes, while the heartwood in larger pieces is used for carving and in smaller pieces for the manufacture of incense products. To facilitate the international trade in sandalwood oil, a product standard has been developed for East Indian sandalwood (ISO 2002). This standard has often been used to broadly assess the quality of other sandalwood species. A grading system for wood products to align the domestic and international trade of sandalwood is required (Coakley 2013), particularly as sandalwood products are increasingly derived from planted sources.

As wild sources of sandalwood have been exhausted around the world, many countries have been making a transition to planted sandalwood. This transition has been challenging because the wild resources have been exhausted prior to the full maturity of the planted resources. Typically, wild sandalwood trees have been harvested at ages greater than 30 years and have significant volumes of high-grade heartwood. In comparison, many planted trees are being harvested at up to 15 years and therefore the volume and quality of heartwood from planted sandalwood is lower than wild wood. This has resulted in price reductions for planted sandalwood products that has caused concern among producers. Sandalwood growers are therefore seeking a greater understanding of their products to help inform their marketplace negotiations. Similarly, for traders, a grading system can help facilitate more efficient communication with their suppliers and potentially reduce the risks associated with long-distance negotiations and trade.

Grading systems and product standards provide an important foundation for trade and commerce. They contain information that is recorded in a specific and documented form and contribute towards improved communication and understanding across a variety of settings. Grading systems for biological products are particularly important because of their inherently high variability. For agricultural products in the USA, nearly 600 grade standards have been established for some 230 agricultural commodities (Barth and Ferriero 2013). Such standards assist trading between buyers and sellers based upon agreed definitions of quality. Product grading systems are developed iteratively over time with inputs from producers, traders, retailers, consumers and other industry stakeholders.

The aim of this short technical document is to provide a simplified and visually based grading system for planted sandalwood that can be easily understood and implemented by producers and buyers.

Oil properties

The value of wood products from sandalwood is dependent upon the concentration (amount) and quality (fragrance) of the oil contained within.

- **Oil concentration** in commercial heartwood can range from 1 to 8%, and typically those with higher concentrations will have a stronger fragrance. The strength of the fragrance is, however, a highly subjective assessment and therefore it can be misleading to use it as a reliable indicator of wood value.
- **Oil quality** is assessed by the type of aroma/scent that the sandalwood produces. While all sandalwood has a similar scent, there are subtle differences that regular consumers can detect. The quality of the scent is directly related to amount of santalols contained in the oil, which is broadly described as a 'soft and woody' aroma. There are quality standards for oil composition for both *Santalum album* (ISO 2002) and *Santalum spicatum* (AS 2003). While there is no standard published for other sandalwood species, a draft for *Santalum austrocaledonicum* has been recently presented to industry stakeholders (Dowell 2020).

The proportion of santalol is influenced by the species (Doran and Brophy 2005; Baldovini et al. 2011; Braun et al. 2014), native provenance (Page et al. 2010), tree age (Brand and Pronk 2011), and tree organ (i.e. roots, stems, branches) (Moretta 2001; Coakley and Hettiarachchi 2009). Knowledge of these influencing factors is critical for rationalising processing and marketing of sandalwood products. For instance, while much sandalwood product does not necessarily meet the international standard for East Indian sandalwood oil, it can still be utilised in similar products to the aforementioned oil and in agarbatti/incense products that are less lucrative than high-quality oils, but still have significant market value.

Determining the concentration and percentage of santalol in a piece of wood requires specialised laboratory equipment (gas chromatography) and/or highly trained experts in the field of fragrance. Near-infrared (NIR) technology has been demonstrated to be a viable technology for rapid determination of sandalwood oil concentration and composition within heartwood and oil samples (Wedding et al. 2008; Kuriakose and Joe 2012; Kuriakose and Joe 2013). With advances in the portability of NIR (dos Santos et al. 2013; Ellis et al. 2015; Pasquini 2018), the technology could potentially be developed for field deployment to determine the relative quality of heartwood during trade. At this stage however, a grading system would need to be robust enough to ensure products can be fairly graded in the field without technology interventions.

Heartwood and oil

Yield and oil composition varies between wood type or tree parts (roots, butt, trunk and branches) (Figure 10.1), with the highest oil and santalol concentrations found in the major roots and butts, which decrease vertically up the tree to the branches (Moretta 2001; Baldovini et al. 2011; Braun et al. 2014). The age (maturity) of the tree also has a significant effect on heartwood quality, with older and larger trees typically producing greater volumes of heartwood with higher oil concentration and santalol content than small young trees (Subasinghe et al. 2013). As a tree ages, the size (diameter) of the heartwood within the tree increases so that a greater volume of heartwood can be found in older trees (Page et al. 2010).

Positive correlation between stem basal diameter and heartwood diameter has been recorded across most commercial sandalwood species including *S. album* (Brand et al. 2012; Kumar et al. 2012), *S. austrocaledonicum* (Page et al. 2010), *Santalum yasi* (Bush et al. 2020), *Santalum macgregorii* (Page et al. 2020) and *S. spicatum* (Brand and Pronk 2011). Historically the minimum harvestable size of wild *S. austrocaledonicum* trees were individuals that have a stem diameter of 15 cm at 50 cm above ground level (Lui 2003). Such a limit is required to ensure trees have sufficient heartwood, oil concentration and oil quality.

Tree age also has a positive influence on heartwood oil concentration and quality (Brand and Pronk 2011). Because of this, sandalwood harvested from plantations may not be as easily graded based on wild-harvest grading systems and may need to consider factors such as tree age and oil concentration and quality. However, subjective field assessment of both oil concentration and oil quality is unreliable and not recommended for grading sandalwood by resource owners and buying agents.

Branches (small logs)

Heartwood is found in the upper part of the trunk of younger trees and branches of trees older than 20 years. They typically have the least amount of heartwood and lowest concentration of oil of all plant parts.

Trunk (logs)

Most heartwood is found towards the base of the trunk and decreases with trunk height.

Stump (butt)

The most oil-rich heartwood is located in the stump.

Roots

The main roots can also contain heartwood but, like branches, heartwood in roots is mainly found in older trees.

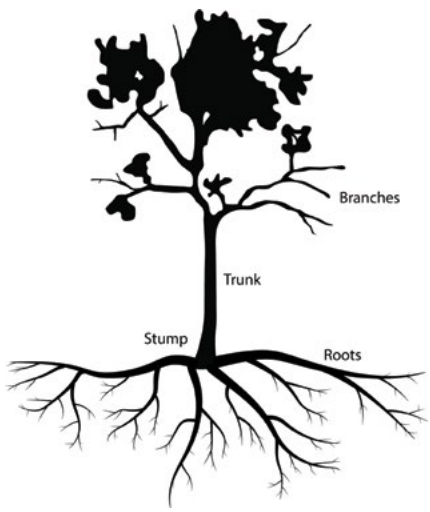

Figure 10.1 Heartwood oil is contained within the roots, stumps, trunks and main branches of a sandalwood tree

Sandalwood grading

Both oil concentration and total santalol content of heartwood oils have been consistently found to be elevated in the basal parts of the tree and decline with height above the ground for *S. album* (Brand et al. 2012; Subasinghe et al. 2013), *S. spicatum* (Moretta 2001; Brand and Pronk 2011) and *S. yasi* (Doran et al. 2005). It is therefore logical that a grading system reflects this natural variation within individual trees. Product grades currently used for the trade for *S. yasi* include three separate specifications based on trees with an age of between 20 and 25 years. These grades include: (1) butts including the stem up to 70 cm above ground level; (2) trunk to branches; and (3) sapwood and other minor heartwood pieces (Bolatolu et al. 2019). These grades do not include any size descriptors and are assumed to be for de-sapped heartwood products. For wild-harvest *S. spicatum*, Brand and Pronk (2011) described five grades including the butt (base of the tree from 150 mmAGL to the below-ground root crown), roots, and stems and branches grouped on their diameter and length: 1st grade (small-end diameter ≥40 mm, length ≥300 mm), 2nd grade (small-end diameter ≥20 mm, length ≥150 mm) and 3rd grade (maximum large-end diameter = 20 mm).

Grading of *S. austrocaledonicum* is set out by the Department of Forests as three grades in the annual service announcement for the harvesting and trading seasons. While the minimum price is included for each grade, descriptions of the grades are absent. Bourne (2019) suggested that the four-grade system is not used by traders of sandalwood in Vanuatu and described a five-grade system: (1) A – trunk and roots (large); (2) B – trunk and roots (small); (3) C – sickwood; (4) D – poles; and (5) E – chips.

Product grading system

The sandalwood grading system is based on the tree structure and includes four primary categories, each with their own grades (Figure 10.2).

- **Specialty** – Produced mainly in older trees greater than 20 years and are valued for their ornamental and decorative features. Carving logs are large logs without significant faults that are of sufficient size for an artist to carve into a decorative piece. Specialty grades also include naturally occurring features in the timber such as burls or wood forms that can be highlighted in natural showpieces. The pricing of specialty grades is often determined through negotiation between buyer and seller.
- **Typical** – Most commonly produced commercial grades across most tree age classes.
- **Faulty** – Diseased, degraded or improperly formed heartwood products. These faulty pieces are of low value and their faulty status annuls any grading based on tree origin.
- **By-products** – Derived through the process of de-sapping the sandalwood. Pure sapwood derived from de-sapping has limited commercial value.

In *S. spicatum*, product grades are influenced by whether the tree was living or dead at the time of harvest. Deadwood is derived from a tree that has died from fires, loss of hosts, grazing and drought (Coakley 2013) and generally without significant degradation (i.e. water, rotten or sickwood). Deadwood represents about 30% of the annual harvest in *S. spicatum* (Coakley 2007). For tropical sandalwood species, the availability of undegraded deadwood is limited and therefore this grading system is based on trees that are alive at harvest.

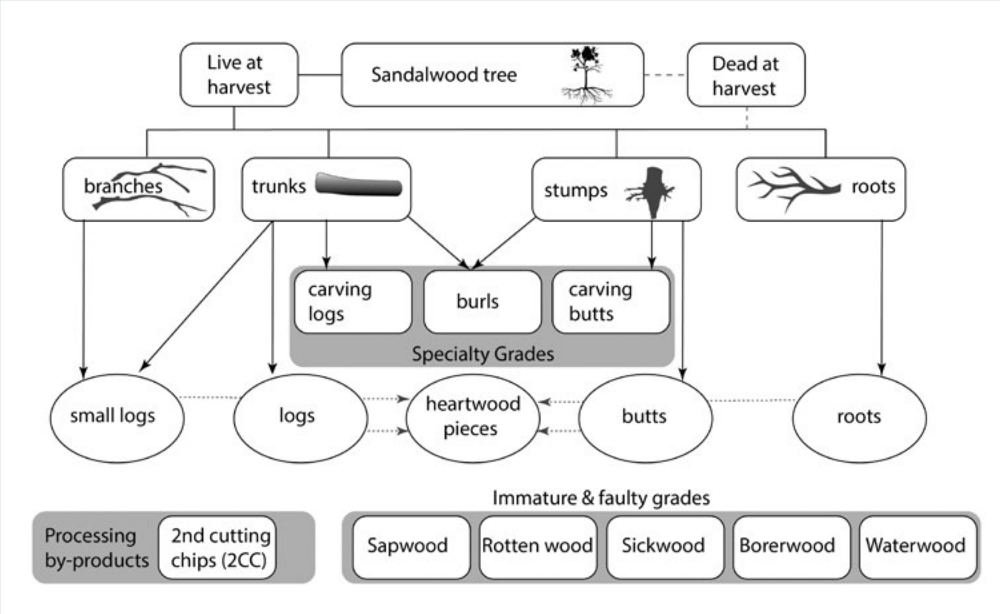

Figure 10.2 Sandalwood products are based on the tree structure and include four product categories: (1) specialty; (2) typical (within ovals); (3) faulty; and (4) by-products

Note: Dashed lines are connections that are not common in tropical sandalwood species. Dotted lines indicate that heartwood pieces can be derived from any source of the tree.

Typical sandalwood grades

A simplified five-grade system is proposed for the **typical sandalwood** category.

- **Butts** – Stump section separated from the roots and the trunk log with all sapwood removed. The length of the trunk section is no more than 15 cm above ground level. They are further classed as small (<10 cm trunk section at ground level – Figure 10.3) and large (>10 cm trunk section at ground level – Figure 10.4). Small-sized sandalwood butts are often associated with immature trees and thus the oil concentration and commercial value is considerably less than large-sized butts.
- **Roots** – Solid roots with all sapwood removed (Figure 10.5).
- **Logs** – De-sapped large-diameter sections of branch (rarely) and trunk heartwood 30–100 cm long and >10 cm diameter at smallest end (Figure 10.6).
- **Small logs** – De-sapped small-diameter sections of branch and trunk heartwood 30–100 cm long and 3.5–10 cm diameter at smallest end (Figure 10.7).
- **Heartwood pieces** – A single grade for pure heartwood pieces, fragments, small branches and debris. Small pieces of heartwood that do not conform to any specialty, typical or faulty grades (Figure 10.8).

Figure 10.3 Large sandalwood butts/stumps with trunk sections of greater than 10 cm at ground level

Figure 10.4 Small sandalwood butts/stumps with trunk sections of less than 10 cm at ground level

Figure 10.5 Solid roots with all sapwood removed

Figure 10.6 Logs – de-sapped, large-diameter sections of trunk heartwood 30–100 cm long and >10 cm diameter at smallest end

Figure 10.7 Small logs – de-sapped, small-diameter sections of branch and trunk heartwood 30–100 cm long and 3.5–10 cm diameter at smallest end

Figure 10.8 Heartwood pieces – a single grade for pure heartwood pieces, fragments, small branches and debris that do not conform to any specialty, typical or faulty grade

Processing by-product

- **Second cutting chips** – A by-product of the second stage of de-sapping, that is often undertaken by traders (Figure 10.9).

Immature and faulty sandalwood grades

An additional four grades describe immature and faulty heartwood products. These products have low commercial value.

- **Sapwood** – The wood of an immature tree that lacks any notable heartwood (Figure 10.10). Sapwood is the low-value, white-coloured outer layer of wood in mature trees that lacks oil and is also a by-product of the process of de-sapping. Sapwood is abundant in young trees and is also found in the branches of mature sandalwood trees.
- **Rotten wood** – Heartwood with significant areas of degradation, usually associated with water entry into the wood and/or disease entry (Figure 10.11).
- **Sickwood** – The heartwood of a tree that has been affected by disease, most notably soil-borne fungal diseases such as *Phytophthora* spp. and *Phellinus* spp. (Figure 10.12). Typically, the central core of the tree is infected and becomes degraded.
- **Waterwood** – Sandalwood with incomplete, uneven or wounded heartwood development (transition wood) or heartwood that has been damaged (Figure 10.13). This product is suspected to be associated with cyclone damage. It is known as waterwood, as resource owners describe it having a high wood water content at the time of harvest.

Specialty heartwood

Three grades describe the specialty heartwood products:

- **Carving logs** – De-sapped, totally clean heartwood logs with a smooth surface and a minimum diameter at the smallest end of 10 cm. The minimum length is 30 cm and the maximum length is 1,200 cm. Must be near circular in cross-section and have no hollows, cracks or knots, and be entire (Figure 10.14). All sapwood and transition wood must be removed so there is only good heartwood. Ends need to be sealed with a clear end sealer product (Coakley 2007).
- **Carving butts** – Decorative art pieces of the buttwood. The value of a decorative carving butt is determined by agreement between producer and buyer.
- **Burls** – Rare pieces of heartwood where the grain has grown in a deformed manner (Figure 10.15). The deformations form decorative patterns that can be used for art and carving pieces. Burls can be formed by biological infections that don't cause wood rot. The price for burl pieces would be through agreement between producer and buyer.

Figure 10.9 Second cutting chips – a by-product of final de-sapping after the bark has been removed; typically contains a 1:1 proportion of heartwood and sapwood

Figure 10.10 Sapwood – the outer layers of a mature tree or wood of an immature tree that lacks any notable heartwood

Figure 10.11 Rotten wood – heartwood with significant areas of degradation associated with water or disease entry into the wood

Figure 10.12 Sickwood – the heartwood of a tree that has been affected by disease, most notably soil-borne fungal diseases such as *Phytophthora* spp. and *Phellinus* spp.

Figure 10.13 Waterwood – sandalwood with incomplete, uneven or wounded heartwood development (transition wood) or heartwood that has been damaged

Note: This product is suspected to be associated with cyclone damage.

Figure 10.14 Carving logs de-sapped (left), totally clean heartwood logs, near circular in cross-section, with a smooth surface and no hollows, cracks or knots (right)

Figure 10.15 Burls are outgrowths on the sandalwood stem (left) and form rare decorative pieces of wood (right)

Processed product

- **Heartwood chips** – Heartwood that is chipped into a consistent size specification (grade) that is used in distillation of oils (Figure 10.16).
- **Heartwood powder** – Heartwood that is ground into powder that is used in the manufacture of joss sticks and other incense products (Figure 10.17).
- **Heartwood oils** – Fragrant oil that is liberated from the heartwood by a range of means including solvent extraction, water or steam distillation, or supercritical fluid extraction (Figure 10.18).

Acknowledgements

This production of this document was generously funded under the Australian Centre for International Agricultural Research (ACIAR) project FST/2016/154. The inputs of various growers, traders, processors and marketers is kindly acknowledged, including Santal Valley, Summit Estate and Wescorp.

Figure 10.16 Heartwood is milled to a consistent size specification (grade) of 3–5 mm, which is then used for extraction of oil

Figure 10.17 Heartwood is milled into a fine powder so that it can be used in the manufacture of joss sticks and other incense products

Figure 10.18 Sandalwood oils are extracted from the heartwood and come in a range of colours (from light straw colour to dark honey brown). Heartwood with a high oil content (>3%) and high levels of α-santalol and β-santalol is used for oil extraction.

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11 Participatory value chain study for yasi sandalwood (*Santalum yasi*) in Fiji

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Abstract

Santalum yasi (*yasi* sandalwood) was first exploited in Fiji in the early 1800s and has been periodically heavily harvested ever since. *S. yasi* produces one of the most valuable sandalwoods, being high in α- and β-santalols and typically meeting the East Indian sandalwood (*Santalum album*) International Organization for Standardization (ISO) standard. Wild *S. yasi* stands are near commercial extinction and are being replaced by rapidly increasing smallholder plantings throughout the Fiji archipelago.

A value chain study is presented for *S. yasi* in Fiji over a period of 35 years (1984–2018). This study was undertaken during 2018–19, in a participatory manner, through interviewing and consulting with the key value actors including resource owners, *S. yasi* growers, buyers, local buyers and processors, international buyers and processors, and the Fiji Government's Ministry of Forestry. The study's focus was on the main *S. yasi* producing and processing islands of Viti Levu, Vanua Levu, Kadavu and the Lau Group.

The *S. yasi* value chain has operated in a suboptimal way with inadequate returns to resource owners and growers and the Fiji Government, failure to develop a local *S. yasi* value-adding industry and, until recently, a lack of *S. yasi* replanting. Key findings were: (1) the lack of recognition and development for *S. yasi* in the international marketplace, owing to its substitution for *S. album* that adversely impacts all actors along the value chain; and (2) there is an opportunity for branding based on *S. yasi*'s natural properties and competitiveness. Recommendations to improve the *S. yasi* value chain functioning, both short term and long term, are provided for *S. yasi* resource owners/iTaukei and smallholder growers, Fiji Ministry of Forestry, and sandalwood buyers, processors and exporters.

Due to its high value and non-perishability, *S. yasi* has a major and unique potential to contribute cash income to Fijian communities in remote island archipelagos. Fiji is well-placed to develop a highly competitive and sustainable *S. yasi* sandalwood industry delivering greater returns to resource owners, growers and processors through the development of high-quality plantings, creation of a *S. yasi* branding strategy, development of local value adding and/or through cooperation with major perfume houses and body-care product companies.

Keywords: Fiji, sandalwood, *Santalum yasi*, value chain study

Introduction

Sandalwood has a near-unique potential to provide a source of revenue for remote island communities in Pacific Island nation archipelagos, associated with the high value of its heartwood and its non-perishable nature (Thomson 2006). Indeed, sandalwood (*Santalum* spp.) has long been important in the economy of several Pacific Island nations, including Fiji. In the early 1800s there were major trade imbalances developing between China and Great Britain, due largely to Britain's newly acquired taste for tea drinking: sandalwood was one of the few commodities of high value that China was interested in trading with the West (Shineberg 1967). The first South Pacific sandalwood species to be exploited in the early 1800s was *Santalum yasi* in Fiji, with the species being largely cut out by 1816 (Shineberg 1967). Since that time there have been periods of more intense exploitation, usually at intervals of several decades, due to the long recovery period for wild populations. This is associated with both its slow growth rate and the near-total removal of larger, heavy seed-bearing trees. In more recent decades, Fiji sandalwood was heavily cut in 1985–88 (918 t heartwood exported, Bulai 1995) and 2006–08 (511 t heartwood exported, Thomson 2013).

Most species of valuable sandalwoods (including East Indian sandalwood – *Santalum album*, *Santalum austrocaledonicum* and *S. yasi*) are 'commercially extinct' in their native habitats, with a global trend towards planted stands replacing wild-harvested sandalwood as the main source of sandalwood. Significant plantations have now been established in the Pacific islands including Vanuatu (Page et al. 2012), Fiji (Bolatolu et al. 2019) and Tonga (Motuliki 2019), and elsewhere including northern Australia (Done 2007) and South Asia (e.g. Subasinghe et al. 2013). This pattern is also being observed in Fiji, where there has been a proliferation of sandalwood planting since the early 2000s. The interest and capacity of individual smallholders, home gardeners, communities and private companies in Fiji to grow sandalwood as a long-term investment derives from:

- a continuing sandalwood research and development program by the Ministry of Forestry, supported by its development partners and private sector including the German Agency for Technical Cooperation (GTZ), Commonwealth Scientific and Industrial Research Organisation (CSIRO)/South Pacific Regional Initiative on Forest Genetic Resources (SPRIG), Pacific Community (SPC), Australian Centre for International

Agricultural Research (ACIAR) and Pacific Reforestation (Fiji) Ltd (Jiko 1993; Bulai 1995, 2007; Dayal 2012; Bush et al. 2020)

- market forces, i.e. the ever-increasing price paid for *S. yasi* heartwood in Fiji (up from FJD3–4/kg in the mid-1980s (Bulai 1995) to FJD100/kg in 2019)
- Ministry of Forestry's extension programs, especially its Sandalwood Development Programme (Bolatolu et al. 2019).

While sandalwood prices have been on an ever-increasing upward trajectory, skyrocketing since wild sources neared exhaustion (in the 2000s), there is a need to work with and better inform current and prospective sandalwood growers in Fiji. In particular, Fiji's sandalwood growers need to be made better aware of the global sandalwood market, sources of future production and competition to better inform their investment, plantation development and management decisions.

The paper reports on a value chain study of the Fiji sandalwood industry with the objectives of providing a thorough documentation of value chain participation, providing greater transparency for all stakeholders, and identifying weakness and opportunities in the chain to more sustainably improve returns to all involved.

Methodology

There is an extraordinary diversity of value chain analyses (VCA), approaches and methodologies. For this study we have used a simplified VCA that has been developed and specifically adapted for use in the Pacific islands by the Pacific Island Farmers Organisation Network (PIFON) (MacGregor and Stice 2014). A participatory VCA study was conducted during 2019 and 2020 on the islands of Viti Levu, Vanua Levu, Kadavu, Lau Group and Rotuma involving interviews and *talanoa* (informal discussions and storytelling) with industry stakeholders – harvesters, nurseries, growers, buyers, processors – as well as through correspondence and contact with sandalwood exporters and end users/consumers.

The six steps in the PIFON VCA are:

1. drawing a value chain map;
2. populating the map with facts and figures;
3. identifying what each stakeholder/actor contributes to the final product and the returns they receive;
4. assessing the market (market analysis);
5. assessing strengths and weaknesses along the chain and identifying ways to take advantage of strengths and minimise weaknesses; and
6. developing a plan to improve the value chain. The findings of the Fiji sandalwood VCA were then tabulated.

Results

The results of the Fijian *S. yasi* VCA are presented as tables and figures (Tables 11.1–11.5 and Figures 11.1–11.2) for each of the steps (Steps 1–6). Participatory analysis was highly effective for definition of the value chain structure including identification of major actors and gaps and opportunities towards the top of the chain involving processing and marketing. Some data gaps remain, particularly in quantifying the inputs of some actors, most notably the growers. This makes quantification of benefits to them less certain. The VCA in its present form does not extend to nursery and seed production, though these are sources of significant value for some smallholders. Gathering more detailed data in these aspects is a future priority.

Step 1: Drawing a value chain map

Table 11.1 Listing of actors involved in the value chain

Main actors (those who buy and sell the product as it moves along the chain)	Supporting actors (those who provide services to facilitate the movement of the product along the chain)
Sandalwood resource owners/harvesters – principally Fijian villagers from Kadavu, Vanua Levu (Bua and Macuata), Viti Levu (Nausori Highlands) and Lau (Ono-I-Lau and Lakeba)	**Local transport operators –** vehicles and boats
Buyers/local processors – Victor Zutshi/Aromatic Oils (Fiji) Ltd based in Lautoka; Jeff Allen (now in Vanuatu); Blue Ocean Marine Ltd, Suva; GoldHold Co Ltd, Labasa; Wee Kong Marine Product and Exporters Co., Suva	**Government of Fiji agencies –** iTaukei Land Trust Board (formerly Native Lands Trust Board) and Fiji Ministry of Forestry (approval to cut and sell sandalwood)
International buyers/exporters/processors – including JJ Yu (Taiwan Timber Co (Fiji) Ltd); Kuo Ping Ku (Taiwan Pine Cedar Wood Enterprise); Jonathon Naupa and associates (Tropical Rainforest Aromatics, Vanuatu)	
Consumers – sandalwood products from Fiji-sourced *S. yasi* – Asia (PR China and Hong Kong, Taiwan, South Korea, Japan, Singapore and Vietnam); Middle East (Dubai and Kingdom of Saudi Arabia); and Australia	

Step 2: Putting facts and figures into the map

GoF regulatory agencies FFD & TLTB
Local transport providers
During the 1980s and 1990s the Native Lands Trust Board collected a Sandalwood Regeneration Levy (10% of price paid) for replanting but it did not take place, apart from a trial planting on Kadavu. FFD had limited involvement in regulation aside from impounding sandalwood that had been illegally procured

Fiji yasi resource owners:
They also harvest the trees, remove the sapwood and sell to buyers, usually in their village. The quantity of heartwood harvested fluctuated dramatically between 1984 and 2018 with maximum of 285 t in 1986 and 306 t in 2008 and an average yield of 52 t

GoF regulatory agencies FFD & TLTB
Local transport providers

Buyers/local processors:
From 2008 to 2010 *S. yasi* was procured and steam distilled by Aromatic Oils (Fiji) Ltd in Lautoka. In 2011, 1,330 kg *S. yasi* oil was exported at FJD1,180/kg

International buyers/exporters/processors:
The main buyers of *S. yasi* during the 1980s and 1990s were Taiwan Pine Cedar Wood Enterprise and Taiwan Timber Co (Fiji) Ltd. Buyers from these companies or their local agents/brokers (and other companies) would visit Fijian villages and buy cleaned heartwood. The *S. yasi* heartwood price fluctuated, increasing from FJD3–8/kg during the 1980s, to FJD13/kg in early 1991, FJD45–56/kg in 2009–11 and FJD100/kg in 2018. The heartwood was then exported mainly to East Asia and the Middle East for further processing or sale (for oil, incense sticks, carving wood)

International freight agencies

International consumers of value-added Fiji yasi products (mainly in East Asia and the Middle East):
The main consumers of Fiji *S. yasi* were for carving and incense sticks in East Asia and heartwood for incense pieces in the Middle East. The price paid by end consumers is not recorded but likely to be 3 to 4 times the price that was paid to the resource owners/harvesters

International freight agencies

GoF = Government of Fiji; FFD = Fiji Forestry Department; TLTB = iTaukei Land Trust Board

Figure 11.1 Fiji *S. yasi* value chain from 1984 to 2018

Step 3: Identifying what each actor contributes to the final product and the returns they receive

Table 11.2 Actors, actor contributions and cost of those contributions, actor rewards and actor risks

Actor (participant in the value chain)	Actor contributions to the final product	Cost of actor contributions	Actor rewards (share of the final selling price to the consumer)	Actor risk
Smallholder establishment and tending	Establishment of trees and tending for 15–25 years.	Not well studied but may entail 2 weeks' work per tree for small plantings with efficiencies for larger scale plantings.	Likely approximately 30% of the price paid by the final customer.	Main risks are planting sandalwood trees too closely, lack of long-term hosts, cyclones and theft.
Resource owner/ harvesting and de-sapping	Identify mature *S. yasi* trees containing heartwood and harvest trees including main roots. The lighter-coloured sapwood is then removed (de-sapped) using large knives (usually cane knives or machetes). The de-sapped heartwood is then stored and dried ready for sale.	Not well studied and documented, and the labour inputs will vary greatly from tree to tree with the least remote and largest trees providing much better returns for effort (for cutting, digging, local transport – often hand-carried or on horse for most of the distance back to the village, and de-sapping). For a small/medium-sized tree with 20 kg of heartwood, it takes approximately one person a day to cut and dig up roots and another 1–2 days to transport back to the village and de-sap. Resource owners need increased awareness and capacity building from the buyers, including on type/ choice of de-sapping, length of heartwood required (1–3 m per length), and other attributes.	Approximately 15–30% of the price paid by the final customer (with increasing proportional reward in later years).	Minimal risks as the market for *S. yasi* sandalwood was strong from 1984 to 2018. Main risk if inexperienced and/or poorly informed landowners cut immature *S. yasi*, which is a waste of labour and diminishes future returns. Theft of trees is an additional significant risk, especially where plantations are remote.

Table 11.2 Actors, actor contributions and cost of those contributions, actor rewards and actor risks *(continued)*

Actor (participant in the value chain)	Actor contributions to the final product	Cost of actor contributions	Actor rewards (share of the final selling price to the consumer)	Actor risk
Local buyer/ processors	Provide advance finance for local buyers (agents) to scout out *S. yasi* in rural areas, later return to procure *S. yasi* and then transport heartwood to distilleries in Lautoka and Suva. Verifies that the procured product is *S. yas*i, steam distils the oils, ± rectify oil, and markets oil internationally.	The costs of the actor's contribution are payments to agents/buyers, including finance to buy *S. yasi*, and all costs associated with distillation and marketing of *S. yasi* oil.	Approximately 25–50% of the price paid by the final customer (but can be much higher where individual trees/large logs are auctioned on the internet). The Ministry of Forestry is trying to regulate and control the activities of agents because in some cases they substantially reduce the returns to resource owners.	Key risk is that inexperienced buyers or agents can procure immature *S. yasi* and/or wood of other species and/or pay too high a price for inferior wood. Processing risks where inexperienced local processors are unable to distil a high-quality oil and/or input (energy) costs for producing oil are greater than the value of the oil; with the latter being influenced by oil yield and quality.
International buyers/ exporters/ processors	Buy *S. yasi* heartwood in the village, sort different *S. yasi* grades and market internationally.	The main costs are associated with product inspection and transport to/from sandalwood producing areas/villages and purchase of *S. yasi* heartwood, and then all costs associated with marketing and export (which may be to a parent company based in Taiwan, Vanuatu or elsewhere).	As above.	A risk is that travel may be undertaken by buyers to production areas, but insufficient *S. yasi* is able to be procured to cover costs. Risk of poor-quality and/or false sandalwood products being concealed within consignments.

Table 11.2 Actors, actor contributions and cost of those contributions, actor rewards and actor risks *(continued)*

Actor (participant in the value chain)	Actor contributions to the final product	Cost of actor contributions	Actor rewards (share of the final selling price to the consumer)	Actor risk
Processors utilising *S. yasi* oil and heartwood powder in their products for sale into overseas markets	Value adding to Fiji *S. yasi* product, through incorporation into perfumes, attars, body-care products and incense sticks.	*S. yasi* oil is likely to have been used as a direct substitute for East Indian sandalwood oil in perfumes and other products. Variable cost depending on end product involved.	Variable, e.g. 20–30%.	Production of *S. yasi* oil was very limited between 1984 and 2018. Not viable to develop specific products incorporating or largely based on *S. yasi* oil due to lack of sustainable supply.
Retailers of products incorporating *S. yasi* in overseas markets	Provide a retail outlet where consumers can access pieces of *S. yasi* heartwood, including carved items, and value-added products containing *S. yasi* heartwood powder or oil.	Variable depending on location and retailer's overheads – sandalwood and derived/ value-added products being sold into different markets (including local markets, department stores, internet).	Typically, at least 25% of the final value of the *S. yasi* incorporated into the product being sold (but will be highly variable depending on product).	Limited risk – sandalwood products are in high demand and non-perishable. Inexperienced retailers may be sold adulterated sandalwood oil.

Step 3: Proportional product share of the final selling price for the various actors

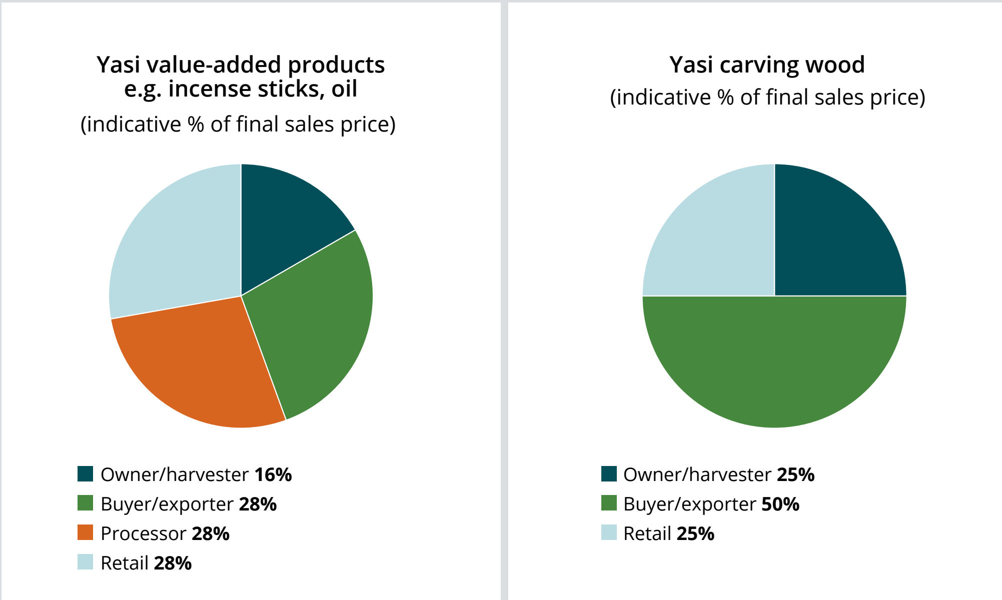

Figure 11.2 Proportion of final product sales price for various actors for *S. yasi* carving wood and other value-added products

Step 4: Assessing the market

Table 11.3 Consumer preferences and performance of value chain in meeting those preferences

What buyers and consumers care about	Performance of value chain in meeting demand scored from 1 (low) – 10 (high) and why
Heartwood composition – the oil yield and composition (for most end uses including oil distillation, use in incense sticks).	10 – Most important criterion for sandalwood distillers as it determines the percentage yield of oil from <1 to 8% oil content. The quality is equally important – oils meeting the ISO standard for East Indian sandalwood oil (ISO 3518:2002) are preferred. The value of an oil for perfume may be substantially impacted by its minor fragrant constituents (as much as by its α-santalol and β-santalol content) and also negatively impacted by undesirable minor constituents that may give 'off-characteristics' to fragrance, which give rise to allergic responses such as contact dermatitis or are listed as undesirable in product pharmacopoeia.
Oil quality (santalol content, absence of irritants (E,E)-farnesol, adulteration). Note: While *S. yasi* oil will generally qualify for ISO 3518:2002 for East Indian sandalwood oil, it will be useful to produce an official monograph detailing all the information on *S. yasi* oil and make it available for international buyers and end users.	10 – Oil quality/composition is the prime consideration for perfumers and manufacturers of body-care products incorporating sandalwood oil. Higher santalol contents are desired, ideally meeting the current ISO standard, viz. 41–55% α-santalol and 16–24% β-santalol, along with presence of minor fragrant compounds that can impart a unique fragrance (and absence of irritants). The presence of adulterants will considerably downgrade the value of sandalwood oil (or make it unsaleable), as will the presence of (E,E)-farnesol (a skin allergen recognised by the Scientific Committee on Consumer Safety of the European Commission). Note: Some samples of *S. yasi* oil appear to have a level of farnesol (1%) that is still too high to allow their use in non-allergenic fine fragrances. Sandalwood industry experts are concerned with the hybrid. The F1 *S. yasi* × *S. album* produces a high-quality oil, but further crossing/inbreeding may make the hybrid unpredictable, both in terms of performance and its oil yield and composition. Sandalwood traders believe that it will be in Fijian and Tongan growers' interests to keep the local *S. yasi* as pure as possible, so that it can continue to be arguably the best sandalwood species performer in the world.

Table 11.3 Consumer preferences and performance of value chain in meeting those preferences *(continued)*

What buyers and consumers care about	Performance of value chain in meeting demand scored from 1 (low) – 10 (high) and why
Mislabelling of exported sandalwood – both other genera including cevua (*Vavaea* spp.), *Exocarpus vitiensis* and also other *Santalum* species (notably *S. austrocaledonicum* from Vanuatu).	10 – Sandalwood buyers expect that *S. yasi* products from Fiji are derived from the pure species (although *S. yasi* hybrids with *S. album* will produce a similar and almost indistinguishable heartwood). Other Fijian timbers that produce a fragrant heartwood such as cevua (*Vavaea* spp.) should never be substituted for *S. yasi* as this has the potential to seriously downgrade the future markets and value of all sandalwood supplied from Fiji. Between 2012 and 2018, less than half of the wood exported under the name 'sandalwood' from Fiji was *S. yasi* (or *S. yasi* hybrids). Twenty per cent of sandalwood exports was of another inferior *Santalum* species (*S. austrocaledonicum*), which had been imported from Vanuatu for re-export, 21% was *Vavaea* species and 13% was *Exocarpus vitiensis*. Cevua has minor value as a fragrant timber export but should never be allowed to be exported under the label 'sandalwood'.
Straightness, diameter and proportion of heartwood – for carving wood.	9 – Highest value market for sandalwood including *S. yasi* is the carving markets in East (and South) Asia. The heartwood oil composition and yield is less important than the piece size, shape and figure and it should have a very high proportion of heartwood.
Sustainability of production.	3–5 – Sustainability of production was only of limited importance in earlier times but has been of increasing importance, especially for the sandalwood oil and body-care product market. Here, continued availability of raw product is a prerequisite for new product development and marketing.
Certification (legally sourced, fair trade, organic).	3 – Segments of the international sandalwood market, especially consumers of high-value perfumes and body-care products, are becoming increasingly conscious of buying only from legally sourced sandalwood sources, with preference for sandalwood products that are able to be certified organic and fair trade.

Step 5: Assessing strengths and weaknesses along the chain and identifying potential actions

Table 11.4 Actors, actor strengths and weaknesses and actions needed to improve participation in value chain

Actor (participant in the value chain)	Strengths and opportunities	Weaknesses and threats	Action needed
Resource owner/ harvesting and de-sapping	• The owners of *S. yasi* are typically those involved in its harvest and sale, which provides a greater level of interest in the trees and their protection. • Wide dispersal of benefits from sandalwood production among owners and their families (who may undertake de-sapping in village). • Major opportunities for Fiji sandalwood producers are in: (1) lowering their production costs cf. large-scale Australian grower *S. album* Quintis; (2) primarily organic methods of production; (3) niche – cottage, tribal, fair trade – marketing with associated livelihood story opportunities; and (4) sustainable agroforestry production.	• Sapwood and offcuts with heartwood often go unutilised and left in the village or bush. • Some resource owners are not fully aware of quality grades and are potentially underpaid for their sandalwood. • Sandalwood owners not fully informed of the economic merits of utilising high-quality genetic stock and of growing trees into larger sizes with a higher proportion of heartwood. Unaware of techniques to manage sandalwood regeneration to increase survival and growth rates, and imperative of proper hosting regimes to grow sandalwood commercially in both agroforestry plantations and in home gardens. • Risk that *mataqali* members may prematurely harvest *S. yasi* for their own financial gain (with loss of future income to *mataqali*). • Some harvesters are harvesting other genera/species that is erroneously being exported as sandalwood. • Sandalwood trading is a risky business due to sometimes corrupt supply chains. Therefore, buyers often don't pay the grower a fair price reflecting the value of the product.	• Better education of *S. yasi* growers and owners on growing and managing *S. yasi*, especially the need for: (1) utilising superior genetic material (i.e. either pure *S. yasi* or F1 *S. yasi*: *S. album* hybrids, which has preferably derived from seed orchards or clones of mother trees of known superior oil composition); and (2) proper host: *S. yasi* ratios and inclusion of several effective hosts, including *Calliandra*, *Acacia*, *Casuarina*, *Flueggea*, *Citrus* and others. • Equity in forestry extension delivery to enable greater participation in planting and ensure benefits are shared among *mataqali* to reduce opportunistic/premature harvesting. • Development of local industry to process sandalwood offcuts into powder for use by incense manufacturers in Asia. • Development of standardised grading system for sandalwood products that is accessible to resource owners. • Investigate development of separate markets for products such as cevua (*Vavaea* spp.), which while not sandalwood, does contain potentially valuable aromatics.

Table 11.4 Actors, actor strengths and weaknesses and actions needed to improve participation in value chain *(continued)*

Actor (participant in the value chain)	Strengths and opportunities	Weaknesses and threats	Action needed
Local growers/ buyers/ processors	• Oil extracted from *S. yasi* meets the ISO standards for *S. album*. • While *S. yasi* trees produce acceptable heartwood at 17–20 years, the best heartwood is produced on trees that are 25 years or older. • There is an opportunity for lower value sandalwood to be graded and chipped at a central point for greater utilisation of the tree. It is then desirable to grind the chip into 10–12 mm pieces for marketing into the lucrative agarbatti/ incense markets.	• The local processing industry has limited knowledge of best practices for buying *S. yasi* and processing it into oil, and limited knowledge and understanding of sandalwood uses, consumers and markets. • Corrupted supply chains result in poor product quality, product substitution and undersupply. • It is too expensive to set-up powder processing for the lower value parts of the tree (plus fire risk if not done carefully).	• Educate local buyers and processors on the size and traits of sandalwood that indicate the tree is ready to be harvested. Link local buyers and processors to major markets and buyers of sandalwood and develop a better understanding of the global marketplace and threats (from other sandalwood producing regions and synthetics). • Government and local stakeholders consider modes of aggregating supply to address issues of supply chain transparency, product legality and the international marketing for *S. yasi*. • Improve 'branding' of *S. yasi* sandalwood as a high-value, indigenous species that provides livelihood benefits for local landowners.

Table 11.4 Actors, actor strengths and weaknesses and actions needed to improve participation in value chain *(continued)*

Actor (participant in the value chain)	Strengths and opportunities	Weaknesses and threats	Action needed
	• A greater proportion of the economic and employment benefits from *S. yasi* industry stay in Fiji (and Tonga) when there is expanded downstream processing of sandalwood.		• *S. yasi* 'cottage' plantations for oil: due to the future market conditions for sandalwood oil it is not recommended to produce oil from *S. yasi* unless a processor has a firm contract to supply an end user and the 'story' and promotion is highlighting that it is *S. yasi* oil, not *S. album* or their hybrids. The branding story can be extremely positive and only promoting *S. yasi* oil and products. DōTERRA are undertaking a similar campaign for Hawai'i's endemic sandalwood (*S. paniculatum*) oil. • In future if Fiji plans to proceed with *S. yasi* oil production, then this will be best undertaken through either a cooperative or 'single desk' operator.
International traders (buyers and exporters)	• Knowledge of global sandalwood industry and markets, including how to grade *S. yasi* to maximise value.	• Lack of commitment to development of a competitive and sustainable *S. yasi* industry in Fiji, driven by commercial imperative to make short-term profits through maximising exploitation of the resource.	• Better regulate and monitor international buyers of *S. yasi* with an objective of replanting sandalwood to replace those harvested (e.g. five seedlings planted and maintained for every tree harvested). This might be addressed through a reintroduced *S. yasi* reforestation levy that is directed for use by the Sandalwood Development Programme and/or local organisations with a capacity to deliver.

Table 11.4 Actors, actor strengths and weaknesses and actions needed to improve participation in value chain *(continued)*

Actor (participant in the value chain)	Strengths and opportunities	Weaknesses and threats	Action needed
International competition: growers/ processors of high-quality sandalwood, especially in northern Australia	• Key strengths for northern Australia sandalwood producers are access to large areas of suitable (irrigated) freehold land for sandalwood culture, and established links (including supply contracts) with major global users of sandalwood oil (including USA-based Young Living, the largest essential oil company in the world; French perfumers; Nestle subsidiary; and Lush Cosmetics).	• If Quintis and other large-scale *S. album* plantations in northern Australia continue with their current harvesting schedules, there will likely be an oversupply of *S. album* oil in the market by 2022. This is likely to put downward pressure on prices, assuming the market size remains stable. However, a more stable supply from these larger sources may stimulate market growth and/or opportunities to develop high-value niche products including *S. yasi*. • The current price for plantation *S. album* oil in volume is around USD2,500/kg. Industry insiders expect this to drop below USD1,800/kg by 2022. There is a possibility for it to fall as low as USD1,200/kg. • The quality of the oil produced from young industrial plantations is significantly lower than that of wild-harvested sandalwood. Quintis is now harvesting trees at 15 years of age; there would be oil yield and quality advantages in waiting at least another 5–10 years.	• Differentiate, through effective branding and marketing, *S. yasi* oil and products from plantation *S. album* oil and body-care products. • Accent on quality and reliability requires regulation of harvesting, especially of younger material with underdeveloped heartwood. Substitution of non-sandalwood aromatics for *S. yasi* must be stopped. • Cooperation among government and local industry stakeholders to improve local supply chain transparency, product legality and supply aggregation to access international markets that value sustainability/ niche/organic/quality aspects of essential oil products.

Table 11.4 Actors, actor strengths and weaknesses and actions needed to improve participation in value chain *(continued)*

Actor (participant in the value chain)	Strengths and opportunities	Weaknesses and threats	Action needed
		• Due to the cost of maintaining industrial *S. album* plantations, it is not cost effective to maintain longer rotations (up to 30 years) and therefore industry insiders expect that sandalwood managed investment schemes in northern Australia may decline (rather than expand) in future. • Heartwood formation in young, planted *S. album* is small from the butt to up the trunk for about 1–2 m and the sapwood generally makes up 70–80% of the log. The growing companies are including secondary heartwood in their reporting, which is not considered valuable or desired for carving logs. Some survey participants believe Australian *S. album* growers will not be able to produce desirable carving logs for another 15 years. • Without continuity of supply at scale there is limited prospect for *S. yasi* to take advantage of its marketing (niche/organic) opportunity.	

Table 11.4 Actors, actor strengths and weaknesses and actions needed to improve participation in value chain *(continued)*

Actor (participant in the value chain)	Strengths and opportunities	Weaknesses and threats	Action needed
Overseas processors and users of *S. yasi* as ingredient	• Understanding of sandalwood product markets and consumer preferences. Opportunity to substitute *S. yasi* for *S. album* (but loss of identity of Fiji product).	• As above. • The end markets for sandalwood timber in Asia and the Middle East cannot differentiate between *S. yasi* and *S. album*. Therefore *S. yasi* is primarily sold as *S. album* at '*album*' prices. This reduces the prospects for differentiating and branding *S. yasi*.	• Education and marketing campaign to make overseas sandalwood processors and users more aware of *S. yasi* and the attributes of its oil. • Wild *S. album* is continually reducing and will be replaced by *S. yasi* and plantation timbers. *S. album* logs coming from industrial plantations (~15 years old) are unlikely to resemble wild-harvested *S. album*. It is therefore possible that *S. yasi* logs for the next period will be the most sought after and have the most consistent supply. Therefore, it is a good opportunity for *S. yasi* to be branded and gain recognition in the marketplace. • Fiji Government and industry stakeholders need to consider methods to limit substitution of *S. album* with *S. yasi*. Physical burning a 'Y' into the end of each log or something similar and associated market awareness. There is a need for a centralised marketing body that could achieve this.

Table 11.4 Actors, actor strengths and weaknesses and actions needed to improve participation in value chain *(continued)*

Actor (participant in the value chain)	Strengths and opportunities	Weaknesses and threats	Action needed
Fiji Government – Ministry of Forestry	• Have a mandate to regulate sandalwood development and trade in Fiji. • Involved in *S. yasi* research and development since mid-1990s including collaborating in AusAID-SPRIG and ACIAR research projects to conserve, improve and better utilise *S. yasi*. Implementation of the Sandalwood Development Programme to increase plantings of *S. yasi* throughout Fiji.	• Weak regulatory function and inadequate legislation to protect and advance the *S. yasi* industry in Fiji.	• New legislation and increased training and funding of Fiji Ministry of Forestry, including for research and development, policy development and enhanced regulatory functions.
Retailers of *S. yasi* products in overseas markets	• Understanding of sandalwood products markets and consumer preferences. • Opportunity to substitute *S. yasi* for *S. album* (but loss of identity of Fiji product).	• Major threat from cheaper sources of plantation *S. album* oil, especially from plantations in north-western Australia. • Consumers have few avenues for accessing reliable independent information regarding *S. yasi* as a sustainable/niche/organic/quality product.	• Education and marketing campaign to make overseas sandalwood processors and users more aware of *S. yasi* and the attributes of its oil.

Table 11.5 Actors, and short-term and long-term plans to improve value chains

Actor	Short-term plan	Long-term plan
Sandalwood resource owners/ iTaukei	• Locate and map sandalwood regeneration – undertake measures to protect sandalwood, especially from fire and theft. Undertake thinning and reduce canopy cover of neighbouring trees to allow more sunlight to reach *S. yasi*. • Protect (tabu) scattered mature *S. yasi* seed trees from harvest to ensure future natural regeneration.	• Plant more *S. yasi* throughout the natural stands, including to increase seed sources. • Global positioning system (GPS), measure and tag (microchip or other durable tag) sandalwood that is >10 cm diameter at ground level. • Better plan *S. yasi* utilisation together with iTaukei Land Trust Board, Ministry of Forestry and sandalwood buyers.
Sandalwood smallholder growers	• Thin overstocked *S. yasi* plantings and infill plant with recommended short, intermediate and longer-term hosts to improve quality and productivity of the *S. yasi*. • Undertake inventory of planted stock either by age or size (diameter at ground level). Provide information to Ministry of Forestry to assist with planning of the future utilisation and value adding/processing of *S. yasi* resource.	• Establish better-designed agroforestry plantings using high-quality pure *S. yasi* germplasm (produced by Ministry of Forestry through ACIAR FST/2016/158) and *S. yasi* × *S. album* hybrids in wetter areas (where *S. yasi* does not naturally occur).
Fiji Government – Ministry of Forestry	• Implement *S. yasi* sandalwood harvesting regulations. • Implement less destructive heartwood checking procedures to avoid early tree mortality/heartwood defects when tree trunks are carelessly checked with cane knife/axe. • Ensure that immature sandalwood is not harvested or that young wild trees 'checked' with cane knife, and that other species are not substituted as *S. yasi* or sandalwood. • Produce and distribute high-quality *S. yasi* and *S. yasi* hybrid germplasm. • Produce and distribute *S. yasi* extension materials. • Focus *S. yasi* extension activities on outer islands (including Lau Group, Rotuma, Lomaiviti Group and islands off north coast of Vanua Levu) where villagers have few other viable commercial cash-generating crops.	• Develop *S. yasi* industry plan in collaboration with all stakeholders (esp. resource owners and private sector), including canvassing options for transparent and legal supply mechanism for aggregating and marketing *S. yasi*. • Publish accurate reports on the *S. yasi* resources in Fiji to facilitate private sector investment in processing/ value adding. • Contribute to orderly development of the industry to ensure that excess processing equipment is not established (which will be unviable and put unsustainable harvesting pressure on both native and planted *S. yasi* resources).

Table 11.5 Actors, and short-term and long-term plans to improve value chains *(continued)*

Actor	Short-term plan	Long-term plan
Sandalwood buyers	• Improve communication with resource owners, sandalwood growers and harvesters to ensure that immature sandalwood is not harvested. • Encourage resources owners to replant and protect some seed trees from harvest to ensure future viability of the industry.	• Provide information to resource owners and growers on the size and quality of sandalwood that is needed (taking into account changing market conditions and buyer preferences).
Sandalwood processors	• Make sure only mature sandalwood is harvested and brought to factories. • Develop laboratory facilities (or link with overseas laboratories) to test sandalwood and make sure that it meets relevant standards, e.g. low (E,E)-farnesol, high α-santalols and β-santalols, etc.	• Develop and promote Fiji *S. yasi* sandalwood products as a unique and distinctive brand (this objective may be pursued with Tongan sandalwood growers and processors). • Install processing facilities that match the projected availability/supply of sandalwood resources.
Sandalwood exporters	• Ensure that only genuine mature *S. yasi* heartwood is being exported. • Undertake market research to ensure that exporters are obtaining the highest price for different types and grades of products.	• Feed information back to growers and processors on the products being demanded in the international market (and changing demands and prices).

Discussion

The heartwood of *S. yasi* has vast, currently almost untapped potential to provide sustainable long-term income for smallholders in Fiji, an especially valuable commodity for remote communities where shipping and transport costs are often prohibitive to most other traded items. However, realisation of this potential will require much greater collaboration – sharing of relevant information and benefits – of those involved in the *S. yasi* value chain. A more functional value chain will benefit both *S. yasi* resource owners, smallholder growers, processors and those involved in value adding and marketing as well as the Fiji Government and populace through increased employment and export revenue. The current sharing of proceeds from the sale of *S. yasi* back to producers/resource owners, harvester and growers, while not unreasonable (estimated at 20–25%), ought to be increased as a proportionately greater return to *S. yasi* growers and producers in order to send the right market signal and encourage greater culture of *S. yasi* and long-term benefits to Fiji and its peoples.

Some of the important actions identified in this study to enhance the *S. yasi* industry and to improve functioning and equity in the value chain were:

- Increase planting of *S. yasi* throughout the natural stands, including to increase seed sources, and managing the natural regeneration of *S. yasi* (through pruning/thinning neighbouring trees to increase sunlight) to shorten time to seed production and harvest and increase the volume and quality of heartwood from native stands.
- Focus *S. yasi* extension activities on outer islands (including Lau Group, Rotuma, Lomaiviti Group and islands off the north coast of Vanua Levu) where villagers have few other viable commercial cash-generating crops.
- GPS, measure and tag (microchip or other durable tag) wild sandalwood that are >10 cm diameter at ground level to improve protection and management of the resource.
- Develop and implement *S. yasi* sandalwood harvesting regulations.
- Better plan *S. yasi* utilisation – resource owners and growers with iTaukei Land Trust Board, Ministry of Forestry and sandalwood buyers.
- Establish better-designed agroforestry plantings using high-quality pure *S. yasi* germplasm.
- Ensure only mature *S. yasi* – with a reasonable proportion of heartwood – is harvested, appropriately branded and exported (and there is no substitution with wood of other genera and species).
- Develop and promote Fiji *S. yasi* sandalwood products with its own unique and distinctive brand.
- Provide feedback information to growers and processors on the type and quality of *S. yasi* products being demanded in the international market.
- Government of Fiji to develop a *S. yasi* industry plan in collaboration with all stakeholders to promote orderly development and ensure that processing capacity matches the quantities of *S. yasi* heartwood available for processing.

The *S. yasi* value chain includes resource owners/harvesters, agents/buyers/local processors, international buyers/exporters/processors and end consumers as well as supporting actors notably regulating agencies (iTaukei Land Trust Board, Ministry of Forestry) and those involved in transport/supply chain logistics. Due to the long period – between 20 and 40 years – between planting/regeneration of *S. yasi* and its harvest, and the periodic nature of more intense harvests, there has been a lack of continuity of knowledge and relationships between the actors in the *S. yasi* chain. Historically this turnover in *S. yasi* value chain actors, an associated lack of goodwill and interest in building trust, a loss of iTaukei/*S. yasi* resource owner memory, and misunderstandings of what is required by the *S. yasi* buyers/market has diminished the functioning, worth and reputation of the *S. yasi* value chain in Fiji. There is a clear need for the Government of Fiji, through its Ministry of Forestry, to become more involved – through greater education, research and development, extension, industry planning and regulation – in the *S. yasi* value chain to ensure its potential to improve the livelihoods of Fijian rural smallholders is realised. While competition among and between *S. yasi* buyers and processors is a laudable objective – excessive competition can be counterproductive – the industry plan needs to be carefully and appropriately calibrated such that the value of Fiji's relatively modest and limited sandalwood resource is maximised.

S. yasi produces a high-quality heartwood oil that meets the international standard for East Indian sandalwood. It therefore competes well in the international marketplace, but product recognition suffers as it is tacitly substituted for *S. album*. This substitution reduces the market presence of *S. yasi* and the potential for developing a unique high-value branding for *S. yasi* oil and products. This branding will become more important as young (~15–20 years) *S. album* from overseas industrial plantations becomes more prominent in the marketplace. Though comparatively high volumes of plantation-grown East Indian sandalwood from Australia are likely to place downward pressure on sandalwood prices, there is an opportunity to create a differentiated niche for *S. yasi* (and other Pacific sandalwoods). It is possible that the Australian product will have the effect of commoditising East Indian sandalwood and its products, possibly leading to overall market growth. The *S. yasi* brand can be built upon the market perception of its exotic Pacific provenance, competitive advantages related to fragrance quality (especially its high β-santalol content), market-perceived and actual natural and organic production methods, and the benefits that accrue to Indigenous Fijian (and Tongan) producers.

The development of *S. yasi* market presence and branding is an issue that requires cooperation and coordination among all supply chain actors. Some of the key challenges to be addressed are:

- reduce/eliminate harvesting of immature trees by resource and woodlot owners (resource owners/harvesters, local buyers/processors, government)
- eliminate substitution of *S. yasi* with inferior wood such as *Vavaea* and *Exocarpos* through education and developing alternative markets for the substitutes (resource owners/harvesters, local buyers/processors, government)
- quantify current and future resources to permit business investment (resource owners/harvesters, government)
- develop options for aggregating legal supply for sale to international buyers (all actors).

Conclusions

Due to its high value and non-perishability, *S. yasi* has a major and unique potential to contribute cash income to Fijian communities in remote island archipelagos. Fiji is well-placed to develop a highly competitive, sustainable *S. yasi* sandalwood industry delivering greater returns to resource owners, growers and processors through the development of high-quality plantings, creation of a *S. yasi* branding strategy, development of local value adding and/or value adding through cooperation with major perfume houses and body-care products companies.

Acknowledgements

This chapter was published in modified form in Thomson LAJ, Bush D and Lesubula M (2020) 'Participatory value chain study for yasi sandalwood (*Santalum yasi*) in Fiji', *Australian Forestry*, 83(4):227–237.

The authors greatly acknowledge the Fiji Ministry of Forestry and inputs provided by numerous informants in Fiji and elsewhere, including international and Pacific sandalwood experts (Dr Tony Page, Dr John Doran, Mr Tim Coakley and Mr Jonathon Naupa). We acknowledge funding support from ACIAR for this collaboration between the Pacific Agribusiness Research in Development 2 (AGB/2014/057) and Domestication and breeding of sandalwood in Fiji and Tonga (FST/2016/158) projects.

Disclosure statement: The senior author is a scientific adviser and shareholder in Pacific Reforestation (Fiji) Ltd, which has small-scale plantings of *Santalum* in Fiji.

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12 Growing sandalwood in partnership with Erromango Islanders

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Abstract

Erromango is a rugged and isolated island. It has limited transport links and opportunities for engaging in the formal economy. While the people of Erromango are very resilient, because of remoteness, service delivery can be a challenge for government. The islanders live in villages scattered around a rugged and exposed coast. Sandalwood harvesting and trading has been the main commercial activity of the island since European contact in the early 1800s but the endemic resource is now depleted.

Sandalwood still offers the people of Erromango a path for livelihood improvement and island development. This paper describes two phases of commercial investment in joint venture sandalwood plantings on the island.

Introduction

Since European contact the history of Erromango has been volatile and punctuated by commercial exploitation, religious conversion and disease. In the early 1800s sandalwood (*Santalum austrocaledonicum*) was discovered and unscrupulous traders used any means to secure sandalwood loads to trade with China. Soon after, missionaries arrived and profoundly changed traditional society and culture. Also, at this time many islanders were taken as indentured workers to the sugarcane fields of Australia. European diseases, for which the islanders had no immunity, took many lives such that the population had reduced from an estimated 5,000 pre-European contact to about 500 by 1870 (Lightner and Naupa 2005). Today the population is approximately 2,500 and growing rapidly with 50% of the population under the age of 20 years. The main income source on the island has always been from harvesting wild sandalwood but by the early 2000s the endemic resource was all but depleted.

Sandalwood investment partnerships with landowners

Three agriculturalists including myself arrived in Williams Bay in 2004 on the west coast of Erromango. The group found the poverty so confronting that a decision was made by the group to explore options to assist the islanders. Erromango is considered the home of sandalwood and developing commercial options for the species suited the mantra and experience of the islanders. The local species is also well suited to the rugged terrain and climate of Erromango.

Two phases of investment have been made on Erromango to plant sandalwood as a commercial activity. The first phase comprised joint ventures (JVs) with customary landowners, and the second phase sought JVs with family groups who did not have legal access to customary land.

Landowner joint ventures

In 2005, meetings were held with customary landowners to propose the concept of JV commercial sandalwood lots. From those meetings 13 landowners were identified, and each signed a JV agreement. The growers were paid to fence several hectares, clear the plots of vegetation, plant sandalwood at 3 m × 3 m or 3 m × 4 m spacings and tend to silviculture. The plantings were established over a 7-year period from 2004 to 2011. Growers were provided with annual management fees to maintain silviculture and security of the planting. Periodically, inventories and growth assessments were conducted by the investing group. To date those trees planted adjacent to hosts have thrived while others have languished. Also, the performance of the JV partners varied considerably, with some easily planting 1,000 or more trees while others planted very few.

Lessons learned:

1. The planting regime was far too intensive; a spacing of 5 m × 5 m is more appropriate.
2. There were insufficient hosts to promote ideal sandalwood growth. Host trees were subsequently planted but results have not been outstanding.
3. With trees exposed to wind and despite continual apical dominance pruning, it is difficult to achieve a 2 or 3 m straight trunk.
4. Planting large numbers of trees on old garden areas where vine growth is predominant ensures weed tending to 'release' the sandalwood will be a never-ending job.
5. Tree inventories were challenging because trees were not planted on a systematic grid.
6. Severe Tropical Cyclone Pam passed over the island when the oldest trees were 9 years old. All trees were stripped of leaves and those in exposed plantings suffered damaged stems and roots. A severe drought followed in West Erromango and increased losses to a high of 20%. Trees planted in sheltered contours were defoliated but suffered only minor structural damage.
7. The trees that survived Severe Tropical Cyclone Pam were stressed and produced copious quantities of seed. Unfortunately, the seeds produced for the next two seasons had poor germination.
8. Interestingly, direct seeded trees did not suffer serious root damage during the cyclone. This method, while ideal on isolated blocks, was not revisited primarily because of the time required to monitor germination.
9. To mitigate future cyclone effects, it is recommended that the canopy be pruned to reduce total leaf area by as much as 80%.

Sandalwood partnerships with non-customary landowners

In 2014, the New Zealand Ministry of Foreign Affairs and Trade (MFAT) announced a new fund where businesses with appropriate international experience could apply to develop difficult 'out of reach' projects. A new company was formed that applied for funding to assist families and single parents (especially women) to grow sandalwood. MFAT approved the project in 2015, with company shareholders providing 33% of the funding for 5 years after which MFAT would withdraw. The company would then fund the project until harvesting began. A health and safety manual was prepared and all workers underwent induction and training courses. The project has a strong focus on gender equity, family work and communications as well as budgetary advice.

The number of qualifying groups was originally 125 but this has now increased to 190, with each group responsible for an average of 500 trees (McLean 2013). Landless family groups, the customary landowner and the company sign a JV agreement, which is then lodged with the Vanuatu Department of Forests for registering as a plantation. After sale of harvested wood the customary owner receives the standard forestry royalty, and the company and the family group share the net returns equally on an undivided basis. The silviculture costs up to point of sale are contributed by the company and are not taken from harvest returns but from the paid-out company share. Planting will cease in June 2020 and the target is to establish 80,000 sandalwood trees.

From previous growing experience and reflecting on the impact of Severe Tropical Cyclone Pam, new planting criteria were developed. The planting area would not be cleared, rather, 2-m wide strips would be cleared every 5 m leaving virtually all endemic vegetation. Branches of remaining trees were trimmed so that newly planted seedlings were not overly shaded. Seedlings were planted every 5 m along those rows, giving a standard population of 400 trees/ha. This planting regime has many advantages over previously used methods:

1. The cost of initial clearing has significantly reduced (by approx. 60%), particularly where there is dense vegetation.
2. Recently planted seedlings have shade and shelter from hosts and are less prone to dry and windy conditions.
3. Sandalwood seedlings have many beneficial hosts, which is evidenced by outstanding early growth rates.
4. Releasing (clearing vines, etc.) costs have been significantly reduced.
5. Tree counts are easily made, and missing/dying/dead trees are easily identified and replaced.
6. Host trees may significantly reduce any future cyclone damage by providing wind protection.

Acknowledgements

Valuable support has been received from the MP for Erromango Mr Tomkor Netvunei, the Ministry of Agriculture, Livestock, Forestry, Fisheries and Biosecurity and the Ministry of Infrastructure and Public Utilities, the Tafea Provincial Government, the Erromango Council of Chiefs, village chiefs and family groups.

Most importantly, the foresight in developing the program and subsequent support by all MFAT staff must receive a very special acknowledgement and thank you from all involved.

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13 Challenges for sandalwood plantation development in tropical Australia

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Quintis, Australia

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Abstract

The Australian plantation sandalwood company Quintis has recently been through a period of rapid estate expansion. Over a 6-year period from 2012 to 2018, the company established over 7,000 ha of Indian sandalwood plantation. Establishing a commercial-size plantation of Indian sandalwood outside of the well-tried region of the Ord River Irrigation Area (ORIA) has been a long process of research and due diligence on many areas throughout northern Australia. Quintis has now established new plantations in the Burdekin area of northern Queensland and in the Top End of the Northern Territory. Quintis is the largest commercial grower of sandalwood in Australia and to expand their estate there was a requirement to look for new sites where sandalwood plantations could be successfully established. The social, environmental and silvicultural challenges for successful establishment have varied between sites.

About the company

Quintis operated in the east Kimberley region of northern Western Australia for 18 years as Tropical Forestry Services, and their first commercial plantings of Indian sandalwood were established in 1999 in the Ord River Irrigation Area (ORIA). Tropical Forestry Services was rebranded as Quintis in 2017 and the company currently has around 5,300 ha of irrigated Indian sandalwood in the ORIA.

Since 2012, there has been a rapid expansion into new areas of production, located in Katherine and Douglas Daly regions of the Northern Territory (approx. 5,800 ha) and in the Burdekin region of north Queensland (1,600 ha) (Figure 13.1).

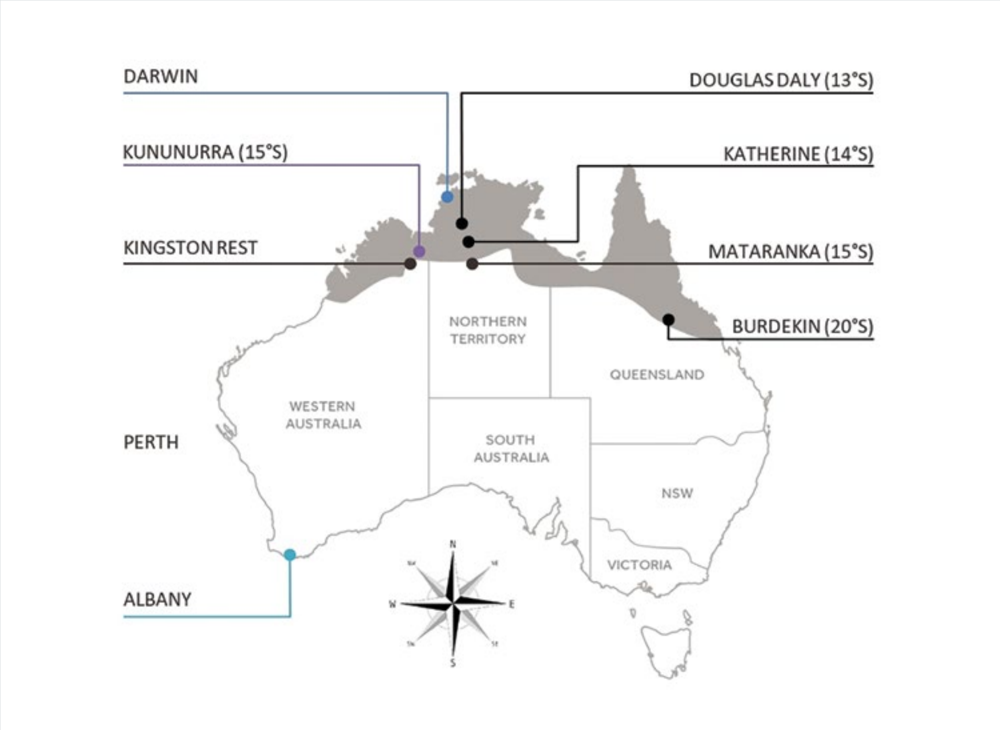

Figure 13.1 Location of Quintis plantations and facilities

Note: Black dots are plantation estates, dark blue dot is Northern head office (Darwin), purple dot is Kununurra Estate and primary processing centre and light blue dot is the oil processing facility in Albany.

Quintis has large-scale seedling production nurseries in Katherine and Kununurra (Western Australia) and uses local external contract nurseries to grow seedlings. The company now employs around 200 people permanently across Australia, and up to 300 casual workers during the planting season.

Harvested logs are processed on-site at Kununurra and then chips are sent to the processing facility in Albany, Western Australia. Until now, this facility has primarily processed Australian sandalwood (*Santalum spicatum*) into value-added products.

Value-added products are sold throughout Australia and exported overseas under the Mount Romance brand. They are also sold through Quintis' retail stores in Albany, Kununurra and Broome.

Quintis is currently working on development of new products from *Santalum album* that can fit within the Mount Romance range.

About the trees

Indian sandalwood is a hemiparasitic tree that requires a host, or a range of hosts, to grow. In its natural environment it grows in close association with a range of overtopping species, providing a semi-shaded environment when young (Barret and Fox 1994). In a Quintis plantation regime, sandalwood is also grown with many host species providing partial shade when young under intensive irrigation. The range of host species used by Quintis are:

- *Sesbania formosa* – a short-term tree host planted in close proximity to the sandalwood. This tree normally dies after 2–4 years as a result of being parasitised by the sandalwood.
- *Acacia trachycarpa* – a medium-term host that usually lives for around 5 years.
- *Senna siamea* – a vigorous tree when not hosted. The effect from being hosted by the sandalwood is gradual reduced vigour and it generally no longer requires canopy management after age 5. No value at the end of the rotation from a harvest perspective.
- *Dalbergia latifolia* and *Dalbergia lanceolaria* – good long-term host species with potential for value (i.e. timber) at the end of the rotation.
- *Cathormion umbellatum* – a native across tropical Australia, it is a slow-growing host. It has a good growth rate when older as it matches the growth rate of the sandalwood and does not require pruning or hedging.

There are currently other host species being trialled for different locations to determine the suitability of species for each specific site.

A DNA DArT-seq analysis of the Quintis sandalwood breeding population has shown that it has been predominantly sourced from central India. However, approximately 30% is from other Indian provenances.

Plantation expansion

At establishment, the tree stocking per hectare is high, with initial sandalwood stocking in most configurations at 505 stems per hectare and a further 350 long-term hosts per hectare. Also, for the first 3 to 5 years, there are a further 505 short-term hosts per hectare.

With so many species involved and growing the plantations under an irrigation regime, the plantations require intensive management over the first 5 years. For many years, many tasks were manual and therefore high numbers of workers were required, particularly during the early years. Recent developments have led to more of these tasks being mechanised. Tasks include:

- Land preparation – The land is generally laser-levelled before drainage works and irrigation are installed. The land preparation is for row cropping rather than for traditional forestry.
- Establishment – Tree-planting sites are marked, and seedlings are hand-planted at a specific spacing and configuration.
- Irrigation – Trees are either drip irrigated, or flood irrigated. Irrigation design is developed in collaboration with professional consultants.
- Weed control – This is initially a very manual task, involving chipping, spot spraying and hand-weeding undertaken by large groups of workers. The use of tree guards has reduced this workload in favour of chemical weed control. Cultivation and spraying are also used between tree rows.
- Pruning – All sandalwood trees are hand-pruned several times over the first 4 years of the rotation.
- Seed collection – Seed is hand-collected and cleaned.

Finding suitable areas

Indian sandalwood is a tropical species that is well suited to parts of northern Australia (Done et al. 2005). The tree itself will grow well on a range of soil types but prefers well-drained soils. The range of soils is from light-medium clays through to the lighter loams. Because of its parasitic nature, host tree species must also accompany the sandalwood trees, so the host species must also be matched to the conditions and soil types. The plantation may consist of up to five host species and it can be quite difficult to find a site that is suited to them all.

Since 2012, Quintis has spent considerable time and resources in finding suitable areas to grow sandalwood across northern Australia. The main reasons for this are:

- land resource pressure due to other crops competing for limited land and water. There is very little area left in the ORIA that is suitable to grow sandalwood
- having several plantation sites reduces the risks of cyclones, flooding, fire and pests
- the effects of climate change, including increased extremes in temperature and rainfall events
- the strong demand and forecast increasing price for sandalwood oil (Clark 2006).

There are many factors that need to be considered when selecting a site for an Indian sandalwood plantation. These include:

- climate (temperature and humidity)
- rainfall
- soil type
- water availability for irrigation
- cyclone risk
- termite risk
- scale of plantable areas.

Satisfying all of these factors means that much of northern Australia is considered unsuitable and finding reasonably large areas to establish plantations has been a real challenge for Quintis.

Extensive due diligence of different areas was completed, starting with high-level selection of certain regions based on geography and access to water, followed by more intensive research on climate, land areas and soil types. Site visits and extensive soil testing were completed over 2 years in several locations across both the Northern Territory and north Queensland to select the most suitable areas based on satisfaction of the above-noted criteria.

The areas that Quintis has selected in Queensland are the areas surrounding the towns of Dalbeg and Millaroo, which are adjacent to the upper Burdekin River. The predominant crop in the area, as with most of the Burdekin region, is sugarcane.

The areas in the Northern Territory are in the Katherine and the Daly district regions. Previously, these areas have predominantly been used for cattle farming. The soils are generally sandy clay loams and water supply is from underground aquifers.

Challenges for suitable areas in Australia

Water supply

There are relatively few areas in northern Australia where water is available for irrigation and where it is inexpensive. The Ord and Burdekin are arguably the most secure water supplies in northern Australia and almost never have allocation restrictions. There are very few others. The security over water is not only to overcome risk associated with growing the plantations but also to satisfy investors who have their own criteria to mitigate risk.

Climate

The most suitable climates in Australia are coastal but the coastline of northern Australia is prone to cyclones during the wet season. Getting far enough away from the coast for protection without substantially reducing rainfall or temperature (too cold) decreases the land availability considerably. Millaroo, the closest coastal plantation, is approximately 60 km from the coast.

Also, many areas in tropical Australia are subject to flooding. Much of the Burdekin delta falls into this category. Dalbeg is located on the upper region of the Burdekin River and has a very high riverbank. There are no known cases of flooding from the river itself. Localised flooding has been mitigated by drainage works within the plantation area.

Soil type

Although sandalwood has been shown to grow on a range of soil types, a major constraint for successful establishment and survival is drainage. The sites must drain well both from the overland flow and through the soil profile. Quintis has been very selective about soil types and spends considerable effort on drainage planning in the plantation design.

Scale

In order to set-up a new operation, some scale was required. There are many small pockets of land in suitable areas but finding larger parcels that satisfy all of the above-noted conditions means that the pool of land to choose from is much reduced. The current plantation area established in the Burdekin is 1,600 ha, in Katherine it is 2,430 ha, and in the Douglas Daly it is 2,660 ha. All plantation sites still have some room for expansion.

Local regulations

Converting farmland into plantations is subject to different levels of regulation depending on location and council area. In the ORIA, sandalwood is classified the same as horticulture and requires no formal applications to convert from field crops or tree crops to sandalwood plantations. In the Burdekin Shire, an application for a material change of land use is required and must be approved by the local council. Some councils may not allow this conversion and the code assessment process may be such that other stakeholders can have input or protest the changes. All of the land that Quintis has purchased in the Burdekin has been successfully changed from sugar production to forestry through the Burdekin Shire Council's code assessment process.

Challenges in the selected areas with new plantations

Location

The Dalbeg and Millaroo areas have some unique qualities, which ultimately led to Quintis purchasing land in these two areas. Within the irrigation scheme, these sites are the furthest from the coast that still have access to irrigation water from the Burdekin River, supplied through open channels and pipelines. Dalbeg has a large percentage of river silt soils graduating through to medium clays. The drainage is excellent compared to other areas. As these areas are on the fringe of the irrigation area, this means that the plantations are somewhat separated from the bulk of the farming area, reducing the competition for land and conflict with other farming enterprises.

Summers at both the Queensland and Northern Territory sites are usually moist and hot, with temperatures reaching the low 40 °C. The winters can be cool, and the Queensland site has had at least three light frosts since establishment, with some damage resulting from this observed on the host trees, in particular *S. siamea* and *C. umbelatum*. This was one suspected risk before expanding into the area, but the effects were unknown. The damage to the host trees was only slight and has not been long lasting. The sandalwood themselves have shown no ill effects from the cold weather except slower growth rates when compared with trees in the ORIA. It is anticipated that before the end of the rotation, these trees will catch up and be at least equal to if not larger than trees of the same age in the ORIA.

Most of the Burdekin irrigation area is close to the coast and prone to cyclones. The delta area of the farming area is also prone to flooding. In the Northern Territory, the key risk is the availability of water. As most of the water supply comes from aquifers, sites away from the aquifer are unsuited to plantation establishment.

The oldest plantations in Queensland and the Northern Territory were planted in 2012. Since then, there have been no cyclones near the Northern Territory plantations; however, this is not the case for the Queensland plantings.

On 28 March 2017, Severe Tropical Cyclone Debbie passed over the Whitsunday Islands as a Category 4, with winds of 165 km/hour. The cyclone weakened to Category 3 before making landfall at Airlie Beach with winds of 150 km/hour.

The cyclone tracked 50 km south of the plantations as a Category 2, with the plantation recording wind speeds of over 100 km/hour. In the blocks that had transitioned to the long-term hosts, there was little to no damage from the high winds other than occasional broken branches. However, in the youngest plantings, established the previous year, a high proportion of the sandalwood trees were leaning at a 45° or greater angle.

Fortunately, these plantations were able to be recovered by either staking the leaning trees or cutting the tree off low and letting a coppice shoot grow as the new main stem.

Soils and drainage

The Burdekin area has many soil types, and many are heavy cracking clays (alluvial soils) and sodic soils. Around 40% of soils are classified as sodic, mostly duplexes. With high rainfall, these sodic soils disperse and drainage through the profile is compromised. The topography is also very flat in many places, so when the region is in flood, many parts of the Burdekin remain waterlogged for prolonged periods. This would be detrimental to a sandalwood plantation, so most of the irrigation area was ruled out on this basis alone.

The soils of the Northern Territory are generally good for plantation establishment. Most are sandy clay loams to well-drained light clays. For most sites, the land is flat and well drained, with little to no flooding issues. The plantation sites are 130 km (Douglas Daly) and 230 km (Katherine) from the coast, so the cyclone risk is low. There is some competition for the best land from industries such as mango and more recently cotton.

Pest and disease

There is an unknown pest and disease risk when establishing new plantations of any species in areas where they have never been grown before. From experience in growing sandalwood plantations in the ORIA, it was expected that there would be some pest and disease issues to deal with. However, the mixed species nature of the plantations makes them reasonably resilient to any single pest event. That said, as the plantation size has increased, there have been observations of increased populations of key pests. The development of methods for monitoring and management of these key pests has been critical in the success of our plantations. The giant northern termite (*Mastotermes darwiniensis*) is an example of one of the key pests for which such methods have been developed.

Fire

For almost all the new plantation sites, particularly in the Northern Territory, there is significant risk from wildfires. Annually during the dry season, these fires burn in from the surrounding native vegetation, usually started by lightning strikes or by out-of-control burning off.

There is a priority placed on maintaining a secure fireproof boundary around the plantations, with regular maintenance of firebreaks both external and internal, and annual controlled burning of surrounding fuel. However, there has been the occasional fire within plantations caused by either lightning strike or by a silvicultural operation like slashing or mulching. All plantations have fire-fighting equipment and trained staff on stand-by for such occasions.

Research

Extensive research into establishment silviculture has been necessary to ensure the successful establishment of the plantations at the new sites.

With new sites, there are different weed spectrums that require different management and control strategies. The control of weeds within a young plantation is critical for good establishment. The research into cost-effective methods to control problem weeds has included: (1) investigating potential herbicides and application methods; (2) sowing dryland pasture grasses and other groundcovers; (3) using cost-effective weed control systems (e.g. cultivation, weed matting and mulching) and using tree guards and grow tubes.

The trialling of new long-term host species, particularly for new sites, continues. Although we consider the existing suite of hosts to be adequate for the new sites, we are still searching for new potential hosts.

A key area of research for Quintis is tree improvement. The company realises the potential gains from producing all production seedlings from seed orchards. The breeding population consists of over 100 families for which the genetic relationships to other families has been analysed. Considerable effort has gone into improving the genetic material available for planting with over 30 ha of clonal and seedling seed orchards being established across Queensland and the Northern Territory.

As we are now planting sandalwood plantations across a wide range of soil types with varying degrees of nutritional status, better understanding of the nutritional requirements for sandalwood long-term hosts is critical for sustainable growth of the company's current and future plantations. All potential plantation sites have the soil both chemically and physically examined prior to development. Several nutrition trials have been established to determine optimal fertiliser application regimes.

Looking to the future

Quintis has continued planting at the new plantation sites in the Northern Territory and north Queensland since 2012, with over 7,000 ha of sandalwood plantation now successfully established at these sites. There have been some small setbacks, but generally the plantations have established and are growing as well as previous plantations. Most of the plantings have now transitioned to their long-term hosts and are coming to a stage where stand manipulation may be required. Research trials have shown advantages to sandalwood growth in stand manipulation either by host thinning or crown reduction. We are also investigating the benefits of mid-rotation fertiliser additions.

Although not on the new sites, the harvesting of Quintis' oldest sandalwood plantations in the ORIA means there are now sites available for second rotation plantings. These plantings are expected to provide us with a range of new challenges going forward.

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14 Community sandalwood initiatives in Girabu, Kairuku and Iokea in the Central and Gulf provinces of Papua New Guinea

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Abstract

Historically sandalwood (*Santalum macgregorii*) has been harvested from wild stands in Papua New Guinea with little to no replanting, which has resulted in severely depleted natural resources. To address this decline in sandalwood numbers we have worked in three areas along the southern coast of the Central (Girabu and Kairuku) and the Gulf provinces (Iokea) to stimulate local replanting of this important species. A clan-based single agroforestry planting was implemented in Girabu and Iokea. Good survival and growth was demonstrated in Girabu where the land was ploughed and grass regrowth and fire were actively controlled. In Iokea, the sandalwood survival and grow was reduced from the re-establishment kunai grass (*Imperata cylindrica*) and two grass fires that swept through the planting. In Kairuku, a family-based approach was taken where nuclear families established small numbers of sandalwood around the homestead or within garden areas. These trees were planted so as to improve local seed supply for use in establishing more substantial woodlots. Extension workshops and activities in these areas has built capacity and confidence among landowners to establish their own independent plantings. We conclude that this work represents some of the first sandalwood plantings established along the southern coastal areas of Papua New Guinea. As these woodlots begin to produce seed there is potential for further expansion in these and nearby communities. Achieving this will help re-establish this once abundant resource with positive impacts on sandalwood conservation and smallholder livelihoods.

Background

In Papua New Guinea, *Santalum macgregorii* grows naturally in the country's Southern Region, particularly in the lowland areas of the Western, Gulf and Central provinces. In these areas, *S. macgregorii* occurs in habitats ranging from open eucalypt woodlands to savannah grasslands, at altitudes from 3 m above sea level (ASL) in the Gulf Province to as high as 787 mASL in Varirata National Park in the Central Province.

Harvesting of sandalwood in Papua New Guinea began over 100 years ago in 1890 and has continued intermittently ever since. It was reported by Paul (1990) that the country's sandalwood trade ended in 1975 due to overcutting, but recent trips to the Central and Gulf provinces indicated people were still harvesting and selling the product in 1997.

Today, Papua New Guinea continues to trade sandalwood harvested specifically from some parts of Kairuku-Hiri District and the Gulf Province as accessibility through the road constructions linking Kerema town to Port Moresby has paved the way for isolated areas to bring their product to traders. In fact, Papua New Guinea's sandalwood exports increased from 7,143 kg in 2011 to 24,300 kg in 2012 due to the improved road access to remote villages in the Gulf Province that have sandalwood growing on their land. In contrast, most areas in the Central Province no longer trade sandalwood.

Current situation

Due to *S. macgregorii*'s fragrant wood (with a high oil content), which is in high demand in Asian markets, natural sandalwood stands in Papua New Guinea have been heavily depleted over the last 20 years. This has created an unfortunate circumstance as the country's sandalwood exports depend entirely on the natural stands. Population pressure for fuelwood and building materials, shifting cultivation and frequent grass burning during dry seasons have further contributed to habitat destruction. Thus, there has been much destruction of sandalwood seedlings and young trees that otherwise would form the next crop of trees for future harvests.

Many of the villages that once boasted large areas of sandalwood no longer sell sandalwood today because the resource has become depleted. The depletion of the natural sandalwood stands has resulted in the loss of income for many landowners who usually depend on sandalwood as an alternative income stream. This has been an important source of revenue for the rural communities, helping to improve the livelihoods of many landowners.

Soon, there will likely be no more mature trees to produce seed to support natural recruitment. A lack of forest management knowledge and skills in the rural communities and a lack of understanding about sustainable community forest management have been the major contributing factors leading to the unsustainable harvesting of *S. macgregorii* by landowners. These unsustainable practices have resulted in the overharvesting and depletion of the natural stands of *S. macgregorii* in the Central and Gulf provinces.

This problem has created a situation where Papua New Guinea will lose export earnings from sandalwood as the country's export quantity is reduced due to reductions in the natural sandalwood stands and many historical production areas will no longer have resources to continue production. As a result, once the existing natural sandalwood stands are completely exhausted, Papua New Guinea will no longer export sandalwood. This will result in a loss of employment and income for the rural communities and loss of export income for the country.

Initial community engagement and establishment of a sandalwood project in the Central and Gulf provinces

In 2014, a sandalwood initiative for Papua New Guinea began to gain ground with the Papua New Guinea Forest Authority (PNGFA) undertaking initial consultation meetings with the Central and Gulf provincial governments. This included meetings with the three district administrations and the provincial governments. These meetings were then followed by community consultation meetings with several communities in Rigo, Kairuku-Hiri and Malalaua districts that have sandalwood naturally growing on their land. Communities with the potential to host sandalwood plantings were identified, resulting in the establishment of the three model project sites/areas in the two provinces under a Papua New Guinea Forest Authority Sandalwood Project.

Following the establishment of the sandalwood project a meeting between the PNGFA officers and the Australian Centre for International Agricultural Research (ACIAR) Country Office (manager and the assistant manager) took place in which a Sandalwood Concept Note was forwarded. This led to Dr Tony Page visiting and meeting with PNGFA officers in Port Moresby and the quick disbursement of funds from the then ACIAR project FST/2007/078 to continue that project's initiatives/groundwork and develop an outline for further funding support. This led to the development of the current ACIAR Papua New Guinea Sandalwood Project (FST/2014/069), which has expanded its activities.

Development of sandalwood demonstrations

Under the current ACIAR Papua New Guinea Sandalwood Project, the three model sites/areas were formalised following consultation meetings with several communities in the areas where sandalwood grows naturally in the Central and Gulf provinces. Specifically, these areas are Girabu in Rigo District, Iokea in Malalaua District and Kairuku in Kairuku-Hiri District.

Over 2 ha of sandalwood has been planted at the model sites in Girabu and Iokea, while several individuals and families are engaged to grow sandalwood in Kairuku. These model sites are discussed in the following sections.

Girabu Model Site 1: Rigo District, Central Province

Project site land ownership

Land ownership rights for this site are vested with the clan, as is the case with many Melanesian countries. Clear ownership rights over the land was a prerequisite for the project to be established, to avoid disputes of any sort that would hinder the progress of the project activities into the future. The project site will be registered under an Incorporated Land Group (ILG Act) for the clan that owns the land. Registration of this ILG has been challenging because of the requirements for birth certificates of all landowners within the ILG.

Seedling production

A project site nursery was constructed and improved with the instalment of a 5,000-L water tank and shade structure. Seedlings were produced from seed collections from local natural trees and some additional collections were sourced from Kairuku. Seeds were treated with gibberellic acid (0.1%) to improve germination and resulting seedlings were raised in polybags in ground beds. The herbaceous plant *Alternanthera nana* was used as a pot host and introduced when the seedlings were at the 4–5 leaf stage.

Sandalwood agroforestry

A 1-ha sandalwood (*S. macgregorii*) agroforestry demonstration plot was planted within a 5-ha customary land allocation. The entire 5 ha was not established due to labour shortages within the clan that own half of the allocated land. The 1-ha plot was ploughed in 2015 using a community-owned tractor to allow for vegetable production to benefit the landowners in the short to medium term. Rows of vegetables, namely corn, cucumber, yam, aibika, watermelon, sweet potato and peanut were planted on the site followed by banana, pineapples, pawpaw and cassava (Figure 14.1). Some of the vegetables were harvested for consumption while others were sold at the market, bringing some income to the family. Currently, the production and marketing of pineapples continues to provide an opportunity for the landowners to earn money for a few more years while tending to their sandalwood. Money earned has ranged from K2,000 to K3,000 from the sale of corn, cucumber, watermelon and pineapples.

Figure 14.1 Sandalwood being grown with corn, yam and peanut (left) and pineapple (right) at the Girabu Model Site

From December 2016 and for the next 7 months, sandalwood seedlings were planted among the vegetables at the project site. With the spacing designed at 5 m × 5 m, we had 13 rows of sandalwood and planted a total of 221 sandalwood trees. We included 6 rows of *Cassia fistula* and 6 rows of *Leucaena leucocephala*, giving a total of 204 host trees planted in the project area.

Extension into surrounding communities

Communities surrounding Girabu, namely Gobuia, Londairi, Wasuma and Gomore have been visited and over 1,000 sandalwood seeds were supplied and germinated by these communities. This informal extension-based training has increased local interest in planting sandalwood, resulting in increased demand for sandalwood seed and seedlings.

Iokea Model Site 2: Malalaua District, Gulf Province

Project site land ownership

The project engagement with the Iokea site built upon a relationship established between the Gulf Province and a customary landowner group in the village of Iokea. This relationship was developed independently of the Iokea ward administration and as such the project worked directly with the Hasu Clan customary landowners. Wider community engagement occurred through the provision of seedlings for the sandalwood planting and technical workshops for sandalwood planting.

Seedling production

Sandalwood seed/seedlings were sourced from the multiple mother/seed trees growing within the Iokea village. Community members participated by commercial supply of sandalwood seeds/seedlings to the project through a structure established by the Gulf Provincial Extension Officers and the Hasu Clan. Seeds were germinated without the aid of gibberellic acid pretreatment in basic germination trays. Seedlings were produced by individuals in small temporary nurseries as polybag stock in ground beds with low shade structures. The use of *A. nana* pot hosts was adopted by about half of the supplying nurseries. Potting media was dark, free-draining sand. The project provided and installed a 9,000-L water tank within the Hasu Clan nursery to harvest rainwater and cater for the nursery's irrigation requirements.

Sandalwood agroforestry

The Hasu Clan development site was mapped at over 70 ha and a 1-ha block within this site was prepared in 2015 for planting sandalwood. Given the ease of sourcing seeds, Iokea was the first of the project sites to plant sandalwood seedlings in April 2015 with over 300 sandalwood trees planted. The spacing was designed as 6 m × 3 m, with a plant spacing of 3 m within rows and 6 m between rows. After every four sandalwood trees a host was planted, and the 1-ha plot was designed to accommodate over 500 trees (Figure 14.2).

A total of 500 sandalwood trees were planted on the project site in April 2015 (300) and June 2016 (200). Although the site was suitable for agriculture, it was not ploughed due to mechanical issues with the tractor. Instead, the landowners manually cultivated an area within the site and planted some peanuts, cassava, sweet potato and pineapples, but only for the first crop before the site was overgrown with kunai grass (*Imperata cylindrica*).

These vegetables were used for own consumption and no records of sale were recorded by the landowners. The combination of dry conditions and re-establishment of kunai grass had a significant effect on growth and survival and by May 2017, 192 trees had been successfully established on-site. A small grass fire moved through the site in October 2017 resulting in 59% mortality of the 192 remaining young trees (Page 2017).

Community extension

A 2-day extension workshop was held in Iokea with 40 participants from four villages. Topics covered included: (1) sandalwood products and markets; (2) seed collection and processing; (3) potting media; (4) potting seedlings; (5) nursery management; (6) hosts; and (7) planting establishment and management. The workshop was structured with formal lessons, group discussions and field and practical demonstrations (Page and Oa 2017).

Figure 14.2 Sandalwood and host trees planted at the Iokea Model Site

Kairuku Project Area, Model Site 3: Kairuku-Hiri District, Central Province

The Kairuku Project Area covers several villages within Kairuku District in the Central Province. The villages covered are Biotou, Rapa, Babiko, Ipaipana, Mou, Nikura, Vanuamai and Eboa. These villages host several seed trees, either within household backyards or elsewhere on their land.

Project site land ownership

Within the Kairuku Project Area an individual family-based approach to planting sandalwood was undertaken, which contrasted with the clan-based approach of Girabu and Iokea. The family approach involved nuclear families establishing small sandalwood blocks using seeds either produced from their own mother trees or supplied by the project.

The Kairuku Project Area is interesting for determining how well different approaches will work with the sandalwood or other related forestry projects. This will provide insights for implementing related community projects in the future. The pros and cons would be an experience for the project to learn from, to replicate the positive outcomes in other projects in other areas.

In the Kairuku Project Area, we deal directly with interested individuals and families who come forward seeking assistance. We take on board their interests and concerns and during our site visits, we pass on our technical knowledge and we work directly with them to achieve their goals.

Seedling production

A common nursery has been established in Biotou, a central location in Kairuku. This nursery is a base for acquiring seeds and producing seedlings for the participants and to serve the area with the required nursery tasks as and when required. The project has also assisted families with technical input and equipment (polybags and shade cloth) to establish micro nurseries for self-supply of sandalwood seedlings.

Sandalwood agroforestry

Instead of having one common site for the Kairuku Project Area, there are multiple smaller plantings within a family's homestead or agricultural blocks. The plantings in the homestead are typically planted along boundaries or as ornamental specimens close to the house. These plantings are suitable for families that have limited seed and experience because the trees are easily maintained, and seeds easily collected when the trees become productive. Sandalwood is also being established in small garden plots with a diversity of crops including pineapple, manioc, guava, banana, yam, citrus, mango, breadfruit, betelnut and moringa (Figure 14.3).

Figure 14.3 Sandalwood planted within the homestead (left) and garden area (right) in the Kairuku Project Area

Extension into surrounding communities

A workshop was organised for Kairuku in November 2017, and 95 people attended from six villages. Topics covered included:

1. sandalwood products and markets
2. seed collection and processing
3. potting media
4. potting seedlings
5. nursery management
6. hosts
7. planting establishment and management.

The workshop was structured with formal lessons, group discussions and field and practical demonstrations (Page and Oa 2017). This has equipped many people who attended the workshop with the knowledge and skills to participate in the project.

Challenges and problems

1. Risk of fire is very high at the project sites, specifically in savannah/grassland areas.
2. Labour issues are common at all project areas.
3. Cooperation by clan members is an issue, determining the work that can be completed in the project areas.
4. Landowners taking ownership of the projects at each site is problematic.
5. There is a lack of water during dry seasons in the project areas.
6. The importance of host trees has been given a low priority by the site owners.
7. Complexity of and delays in the Integrated Land Group registration for clan-based project sites has been a challenge.
8. There is a high risk of wind blowing down planted trees, especially in open savannah/grassland areas.

Recommendations

1. People should be encouraged to grow sandalwood among the food crops in their gardens.
2. Firebreak creation to be a priority task for sandalwood plantations established in all savannah or grassland areas.
3. Brush cutters are an option for the project sites in savannah/grassland areas to maintain weeds and firebreaks.
4. The importance of host trees should continue to be emphasised, which will be very important as the sandalwood trees grow.
5. Lead farmers should be identified in each community to advocate sandalwood plantations.
6. Options of workable approaches should be determined after consultation meetings are held.
7. Model site nurseries should be upgraded and better resourced.
8. Collaborations with provincial governments needs exploring for project expansion.
9. Windbreaks need to be established to protect the sandalwood trees against strong winds.

Acknowledgements

Aspects of this paper were published in Rome G, Turia R, Oa L, Page T, Applegate G and Saliau C (2020) 'Sandalwood trade and development in Papua New Guinea', *Australian Forestry*, 83(4):208–215.

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15 Selection, breeding and development of Cape York sandalwood

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Abstract

Northern sandalwood (*Santalum lanceolatum* R.Br.) was harvested to near extinction in the Cape York Peninsula (CYP) and the species has not recovered. Some of the remnant trees have desirable oil profiles (high α-santalol and β-santalol). Hence, a breeding program has been initiated to develop the species to allow it to be planted back into the wild and also to provide improved germplasm that can be used to establish plantations on Indigenous land in the CYP. Microsatellite markers indicated that the populations of *S. lanceolatum* in the Northern Peninsula Area of the CYP had low levels of genetic diversity and were highly clonal (over 50% of trees sampled were clones). This may explain the low levels of fruit set in the wild. This molecular study supported the tree improvement program's focus of capturing only a few trees from each remnant stand across the region. Grafted clonal sandalwood seed orchards have abundant flowering and produce ample seed, allowing the establishment of two progeny trials in the northern CYP.

Two-year survival in these trials was excellent (96%) in an irrigated trial and moderate in an unirrigated trial (78%). Growth in the irrigated trial was also better with sandalwood trees averaging 2.01 m height and 2.4 cm diameter at breast height over bark (DBHOB). The fastest growing family in this trial averaged 2.61 m height and 3.3 cm DBHOB at this measure. In contrast, the unirrigated trial averaged 1.75 m height and 0.9 cm DBHOB, with the fastest growing family in this trial averaging 2.25 m height and 1.3 cm DBHOB. The four 'best growth' families in each trial, at this young age, were not the same, suggesting that selection strategies for these contrasting environments should focus on different families.

Impediments to the development of sandalwood plantations based on this resource are also discussed.

Keywords: clones, genetic diversity, progeny trial, risk, *Santalum lanceolatum*

Introduction

Santalum lanceolatum is a tall shrub or small tree up to 7 m with an air-dried wood density of 930–950 kg/m^3 (Applegate et al. 1990; Weiss 1997). *S. lanceolatum* generally has low concentrations of heartwood oil: 1–4% air-dried weight (Jones and Smith 1929, 1931; Weiss 1997). The oil is considered to be poor quality, given the low levels of the preferred α-santalol and β-santalol oils (0.6–2.6 and 2.0–4.3%, respectively). In addition, it has large proportions of the less preferred *Z*-lanceol (20–90%) (Doran et al. 2005). In contrast, *Santalum album* heartwood is reported to contain 4.5–6.5% heartwood oil with high levels of α-santalol and β-santalol (42.3 and 16.1%, respectively) and low levels of *Z*-lanceol (1.8%; Doran et al. 2005). The international standard for sandalwood oil derived from *S. album* (the benchmark species for sandalwood oil) requires α-santalol and β-santalol exceeding 41 and 16%, respectively (ISO 3518:2002). Most commercial species of sandalwood, for example *Santalum austrocaledonicum* (New Caledonia/Vanuatu), *Santalum insulare* (French Polynesia/Pitcairn Island/Cook Islands), *Santalum yasi* (Fiji/Tonga) and *Santalum macgregorii* (Papua New Guinea) have trees with oil profiles that meet this standard. Based on this, *S. lanceolatum* is regarded as a species with low-quality heartwood and oil.

In a recent study, Page et al. (2007) found significant variation across seven Cape York Peninsula (CYP) sandalwood populations in oil content with some populations having low oil concentrations (0.64%) typically attributed to *S. lanceolatum*, whereas a northern CYP population had trees with a mean oil concentration of 4.1% (range 0.1–8.2%). In addition, some of the *S. lanceolatum* trees sampled had oil quality profiles that met the international standard for *S. album* oil (ISO 3518:2002). Their study revealed a significant opportunity for the development of this species as a commercially viable tree crop. However, the species is considered to be regionally rare, as it has not recovered from overharvesting between 1865 and 1937, hence wild harvest is not feasible. In partnership and with approval of the Traditional Owners in the Northern Peninsula Area (NPA), a conservation and domestication program targeting high oil genotypes of *S. lanceolatum* has subsequently been initiated (Lee et al. 2019). Lee et al. (2019) documented the grafting of 20 wild trees from the NPA, including nine with superior oil profiles. These trees have produced seed and two small progeny trials have been established. This report summarises the continued development of the northern sandalwood, with respect to: (1) genetic diversity within and between populations in the NPA; (2) growth for the trees in progeny trials; and (3) risks and impediments associated with growing sandalwood trees in the NPA.

Materials and methods

Microsatellite marker study

Leaf samples were collected from five remnant populations of *S. lanceolatum* in the NPA (Bamaga, Injinoo, Muttee Heads, Seisia and Somerset: 156 samples) and two outgroup populations near Mareeba (approximately 750 km south-southeast of the closest NPA population: Rocky Creek and Price Creek, 23 samples). Leaf samples were collected with informed consent from the Traditional Owners, dried on silica gel in resealable storage bags and stored at room temperature prior to DNA extraction. Total genomic DNA was extracted and isolated using a DNeasy Plant Mini Kit (Qiagen, Valencia, California, USA) following the manufacturer's instructions. Twelve polymorphic microsatellite markers were used to investigate the genetic variation, population structure and the clonality of five remnant populations of *S. lanceolatum* in the NPA, as detailed in Brunton (2019).

Progeny – demonstration trials

Two sandalwood progeny trials have been established in the NPA near Bamaga: 10.89°S 142.39°E, and 20 mASL. Soils at both progeny trials are described as ferruginous laterites (Briggs and Philip 1995). Mean annual rainfall at Bamaga is 1,791 mm with a distinct 5-month dry, with less than 30 mm of rainfall per month between June and October. These trials were established as randomised complete block designs with single tree plots with 4–6 replicates of 19 families (each family is made up of bulked open-pollinated seed from multiple ramets of a single clone). These trials are small as the size of the trials were limited by land availability. The progeny trials also served as demonstration plantings of the species for the community. High school staff and students and Community Development Program workers assisted with the establishment of these plantings. The larger trial near the Northern Peninsula Area State College has been periodically irrigated with town water as needed. The trial established at the Bamaga Farm is unirrigated. Height, diameter at breast height over bark (DBHOB) and damage by pests, diseases and cattle were recorded as appropriate at age 2 years.

Results and discussion

Genetic diversity and clonality

The 12 microsatellite markers revealed low levels of genetic diversity (e.g. A_R = 2.964 and H_E = 0.415; Table 15.1) in the NPA *S. lanceolatum* populations, which is typical of plants in northern Australia that have suffered extreme range contractions, likely due to climate oscillations and the expanding arid zone approximately 2 million years ago (Broadhurst et al. 2017). This is likely to have been exacerbated by the overharvesting of the species that occurred between 1865 and 1937. The genetic diversity is lower than that observed for 17 populations of *S. austrocaledonicum* from New Caledonia (H_E = 0.66; Bottin et al. 2005), but similar to the diversity found in a microsatellite study of *S. yasi* (H_E = 0.42) in Fiji and Tonga (Bush et al. 2016). Both of these species have been overexploited in the wild like *S. lanceolatum*. The level of inbreeding (F = 0.078) between populations was low compared to that observed by Bush et al. (2016) for *S. album* (F = 0.47), *S. yasi* (F = 0.39) and *S. austrocaledonicum* (F = 0.55). Similarly, the inbreeding coefficient in the NPA sandalwood populations (F_{IS} = –0.054) was low, indicating only minor levels of within population inbreeding.

Table 15.1 Mean genetic diversity measures from the Northern Peninsula Area *S. lanceolatum*

n	N_A	A_R	PA_R	H_O	H_E	F	F_{IS}
177	4.83	2.964	0.242	0.458	0.415	0.078	−0.054

n = number of individuals; N_A = mean number of alleles per locus; A_R = allelic richness; PA_R = private allelic richness; H_O = observed heterozygosity; H_E = expected heterozygosity; F = between population inbreeding coefficient; F_{IS} = individual within a subpopulation inbreeding coefficient

Source: Summarised from Brunton (2019)

There was extensive clonality in the NPA sandalwood populations with over 50% of the trees across all populations being identified as clones. This high level of clonality may explain the low levels of seed production in the wild. This high level of clones within and between the disjunct populations of sandalwood in the NPA also indicates a conservative approach is required when selecting trees for inclusion in the domestication and breeding program. This was the approach adopted (Lee et al. 2019).

Progeny – demonstration trials

Two-year survival in the irrigated progeny trial was excellent (96%) and moderate in the unirrigated trial (78%). Growth in the irrigated trial was also better, with sandalwood trees averaging 2.01 m height and 2.4 cm DBHOB. The fastest growing family in this trial averaged 2.61 m height and 3.3 cm DBHOB at this measure. In contrast, *S. lanceolatum* trees in the unirrigated trial averaged 1.75 m height and 0.9 cm DBHOB, with the fastest growing family in this trial averaging 2.25 m height and 1.3 cm DBHOB. Across the two trials, the best growth families varied with families 22, 40, 185 and 994 having superior growth at age 2 on the irrigated site whereas families 8 and 25 were the better performing families on the unirrigated site. Six families had similar height and diameter growth across both trials (Figure 15.1). Trees with good growth in each trial are shown in Figure 15.2. The slower growth of the unirrigated sandalwood trees is not unexpected given the 5-month dry season. The growth rates of these unirrigated trees, however, appears to be similar to that observed for *S. austrocaledonicum* in Vanuatu, where the better-managed sandalwood groves had a mean basal area increment of 1–1.8 cm (Page et al. 2012).

Risks to plantation establishment

Growing trees in their natural environment has risks and in the NPA demonstration trial sites there have been several generalist herbivore insects including grasshoppers, leaf hoppers and cup moths observed on the sandalwood plants. However, by far the biggest risk for plantation development and conservation plantings are fire and cattle damage. Lee et al. (2019) reported that 19% of the wild trees in the NPA had been killed by fire during the last 8 years. Fire continues to be a major risk for the species. Cattle were excluded from the progeny trials by barbed wire fences, however, they broke into the irrigated trial area, probably in pursuit of green grass during the dry season, and damaged 18.5% of the sandalwood trees. Both trials were also impacted by Severe Tropical Cyclone Trevor in March 2019, but this did not visually damage the young *S. lanceolatum* trees. Conversely, many of the intermediate host trees (*Acacia simsii*) were blown over during the storm.

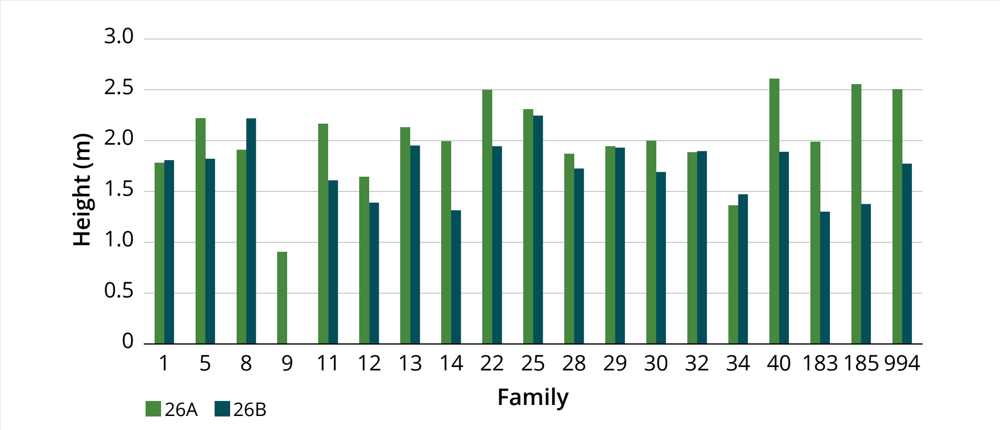

Figure 15.1 Two-year height growth in progeny trials (26A and 26B) after 2 years at Bamaga

Note: A total of 18 identified sandalwood families were tested (*x*-axis). Family 9 was only measured in trial 26A.

Figure 15.2 Two-year-old *S. lanceolatum* trees in the irrigated (left) and unirrigated (right) trials at Bamaga

Impediments for sandalwood development on the Cape York Peninsula

On CYP, any sandalwood plantation would be established on communally owned land, in contrast to Vanuatu and many other Pacific islands where they are established by individual family units as small agroforestry woodlots where trees are planted among or adjacent to other garden and cash crops (Page et al. 2010). Hence, any CYP sandalwood industry development would be for the whole community rather than benefiting a family unit. This requires consensus by the Traditional Owners that sandalwood is what they want to grow on their land, and it also means the scale of the plantings needs to be larger than those established by family units in the Pacific. This in turn means we would need to attract investors to fund this sort of development, as the Indigenous groups and corporations do not have money that they can tie up for 15–25 years. The Gudang Yadhaykena Group have contacted a range of potential investors to obtain funding to start a sandalwood industry using this germplasm. We have discussed and shared our results with these investors, however, the lack of scale of the plantings and the young age of these trials means that economic modelling of plantations developed with newly domesticated species is unreliable. Hence, to reduce this impediment we need to establish larger demonstration plantings/trials that will enable economic modelling and provide proof of concept of the potential of this species in the region.

Other impediments that need to be addressed include: (1) identification of more high oil trees to include in the breeding population; (2) data on growth rates, oil yields and heartwood formation through time; (3) knowledge of host species for long-term plantation development in the region and optimal silviculture for the species; (4) potential to use the CYP sandalwood in agroforestry systems; and (5) knowledge of the value of the timber/oils from these trees.

Conclusions

The genetic diversity of the northern sandalwood populations is relatively low and much of the material in the natural stands is clonal, hence a conservative approach is required when selecting trees for inclusion in either a breeding program or for inclusion in conservation plantings. The growth of the sandalwood in the young trials is good, with trees growing faster in the irrigated trial than the unirrigated trial. This growth is similar to that observed in other sandalwood species elsewhere. Risks and impediments to sandalwood development in the CYP include fire and cattle, lack of scale of the plantings and inadequate knowledge to guide economic modelling due to the young age of the trials. This can be addressed by establishing larger scale demonstration plantings and collecting additional data through time.

Acknowledgements

Funding by the Australian Centre for International Agricultural Research (ACIAR) project FST/2008/010 and continued under ACIAR project FST/2014/069, University of the Sunshine Coast and in-kind from the Department of Agriculture and Fisheries is greatly appreciated. These projects are well led by Tony Page (University of the Sunshine Coast). Assistance from John Oostenbrink to plant the trials and for grafting of the trees; the Traditional Owners of the northern Cape York, particularly members of the Apudthuma Land Trust, especially Sandra Woosup, the Ipima Ikaya Aboriginal Corporation RNTBC and members of the Gudang/Yadhaykenu Group, especially Alex Wymarra and Muen Lifu Uncle Shorty, are appreciated. We would like to thank the staff (particularly Harrison Atu, Jody Warbrick and Simon Dunning) and students at the Northern Peninsula Area State College.

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16 Conservation, domestication and breeding of *Santalum yasi* in Fiji and Tonga

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Abstract

The domestication and breeding of *Santalum yasi* presents some special challenges. Like other sandalwood species, *S. yasi* has been overexploited in its native range and is now found in fragmented natural stands that lack genetic diversity. It is a slow-growing species, and hemiparasitic, meaning that it relies on links through root haustoria to other plants to supplement its own photosynthetic output. Though the species is widely cultivated in its natural range in both Fiji and Tonga, only a very small number of trial plantings exist. Establishment of well-designed trials is an early priority for domestication. These will need to be carefully designed with respect to host selection so that host–sandalwood interactions can be assessed, in addition to the usual trial design considerations.

Molecular genetic studies of the species have shown that while overall genetic diversity is still at least moderate, individual stands lack diversity. An emerging potential threat to the species is the widespread planting and natural hybridisation with exotic Indian sandalwood, *Santalum album*.

Conservation of the remaining genetic resources of *S. yasi* is a high priority both for preservation of the species and to ensure that there is a sufficiently broad breeding base from which future selections can be made. In addition to the establishment of gene bank plantings and trials that can be used to carry out selections, the establishment of seed orchards based on a mix of genotypes from throughout the natural range is required. These seed orchards can be used to produce genetically diverse seed crops for wide deployment to villages, and to private and industrial growers. Genetically diverse commercial plantings made close to fragmented natural stands have the potential to provide pollen flow to remnant trees, increasing outcrossing rates and genetic diversity.

The presence of host–sandalwood interactions suggests that a long development time is required before heartwood assessments can be made.

Keywords: genetic conservation, heartwood, santalol, tree breeding

Introduction

The sandalwood genus and *Santalum yasi*

The sandalwoods (*Santalum* spp.) are a genus of hemiparasitic trees that, collectively, have a natural range from southern Australia extending north to Indonesia, Sri Lanka and India and east into the Pacific Ocean ranging from Hawai'i in the north to the Juan Fernández Islands in the south-east.

Santalum yasi is an important cultural and economic plant in Fiji, where it is known as *yasi dina* and in Tonga where it is called *ahi*. The natural range extends from Niue and 'Eua, a southern island in the Tongan group, through Tongatapu, Ha'apai, Vava'u and Niuas (Tonga), west and north through parts of Fiji: the Lau Group, to Bua and Macuata provinces (western Vanua Levu), Udu Peninsula (north-east Vanua Levu), Kadavu and Nausori Highlands (western Viti Levu) (Figure 16.1).

S. yasi is a small-to-medium, long-lived tree, often with a multi-stemmed habit (Thomson et al. 2018). It has been extensively exploited and populations are now highly fragmented – a fate shared with many other sandalwood species (Brennan and Merlin 1991). Bush and Thomson (2018) consider that it should be Red Listed as Endangered under International Union for Conservation of Nature (IUCN) Red List of Threatened Species criteria. In Tonga, harvest and export of *ahi* is now subject to control (Motuliki 2020), though illegal cutting is an ongoing problem throughout the natural range. The lower bole may reach diameters of up to 50 cm after 40–50 years, though trees of this age and size are now rare, especially in the wild (Bush et al. 2016; Huish et al. 2015). Most stands show evidence of regenerative stress (Huish et al. 2015) and molecular marker studies have shown they also lack genetic diversity and may be inbred (Bush et al. 2016).

S. yasi occurs in lowland, drier, and more open forest types in Fiji, Niue and Tonga. It grows well when planted with suitable host plants in home gardens and in smallholder agroforestry and mixed indigenous forest stands. Under suitable growing conditions it may attain harvestable size in about 25 years (20–25 cm diameter at the base with substantial heartwood development). It would appear that, like *Santalum austrocaledonicum* (Page et al. 2012), *S. yasi* grows at around 1 cm of basal diameter per year (on average) throughout Fiji and Tonga (Figure 16.2). This information can be used as a rule of thumb to gauge the age of trees based on their basal diameter.

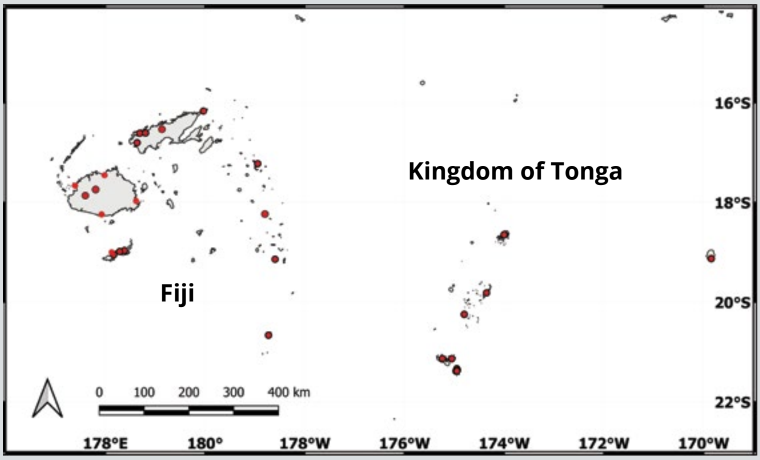

Figure 16.1 Natural distribution of *S. yasi* in Fiji and Tonga

Source: Thomson et al. 2018

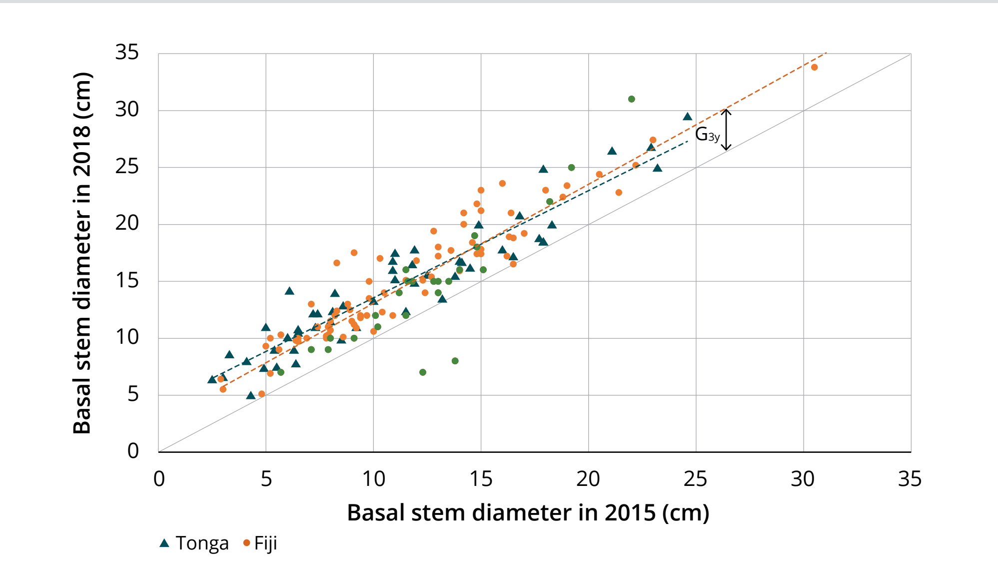

Figure 16.2 Growth of trees of mostly unknown age measured in 2015 and re-measured in 2018 in Fiji and Tonga

Note: The vertical distance G_{3y} measured between the diagonal and the lines of best fit for Fiji and Tonga is the diameter growth over the ~3-year measurement period. It is approximately 3 cm, corresponding to around 1 cm of diameter growth per year. Solid green circles indicate trees from Vunimaqo gene bank on Viti Levu, Fiji. These trees were planted in 2002 and were 16 years old in 2018. Their average growth rate was 0.9 cm/year, ranging from 0.4 to 1.2 cm/year.

Government departments in both Tonga and Fiji advise growers to harvest sandalwood after at least 20 years. However, due to the temptation or necessity to generate earlier cash income, trees are commonly harvested at around 15 years, at which time only a modest amount of heartwood will usually have developed (Bush et al. 2020a). A survey of trees in Fiji and Tonga undertaken in 2018 indicates that harvest at this age risks losing substantial income, with incomplete heartwood development evident (Figure 16.3).

Genetic diversity

The overall genetic diversity of *S. yasi* has been assessed as moderate using microsatellite markers (Bush et al. 2016). There is significant population differentiation among the Fijian and Tongan subpopulations (overall F_{ST} = 11%), with some differences among Kadavu, Vanua Levu and Viti Levu, while subpopulations from the different Tongan Island groups ('Eua, Tongatapu, Ha'apai and Vava'u) as well as the Fijian Lau Island Group are similar.

Despite the finding of moderate overall diversity, inbreeding within subpopulations appears to be elevated. Inbreeding commonly results in reduced survival and growth rates among forest tree species. It is assumed that the inbreeding is the result of fragmentation of wild stands and cultivated plantings established using seeds from a narrow genetic base – typically the remaining local trees that are good bearers of seed crops. Establishment of *S. yasi* seed orchards using unrelated selections may therefore result in gains through increased outcrossing.

Though the DNA marker studies have shown significant genetic differentiation

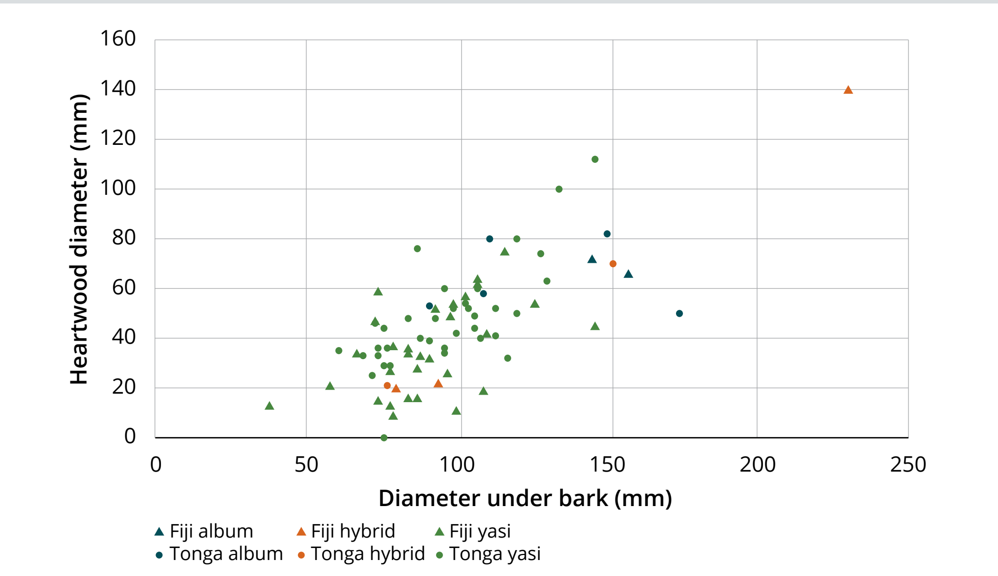

Figure 16.3 Heartwood development in trees of various sizes sampled at around 30–40 cm above ground

Note: These are many of the same trees sampled to produce Figure 16.2, with diameter over bark between 5 and 30 cm, averaging around 15 cm.

among subpopulations, little is currently known about how this translates to differences in traits of commercial interest, viz. wood, oil, growth, and disease and cyclone-resistance traits. However, it is evident that different populations of *S. yasi* have become adapted to broadly contrasting environmental conditions. In terms of heartwood development and oil content, there is considerable variation between individuals growing in the wild, but field trials are needed to determine the relative importance of genotype, age, environment and interactions on heartwood development (Bush et al. 2020a).

Breeding and hybridisation

Like other sandalwood species, the breeding system of *S. yasi* is thought to be a mixed mating system. However, this has not been formally studied and is not certain given the varying and sometimes contradictory information on the breeding system of other *Santalum* species. This is another area of research that needs to be more fully investigated. In practical terms, however, it is assumed that at least some individuals will be capable of self-fertilisation, and that orchards should be designed to minimise this and the risk of selfed mating ('selfing'), which is the most severe form of inbreeding.

Spontaneous hybrids between *S. yasi* and *Santalum album* are common where they are planted together. The first-generation (F_1) hybrids can be readily identified both morphologically and using DNA markers (Bush et al. 2016). These hybrids are reputed to grow more vigorously than pure *S. yasi*, especially on wetter sites, though quantitative data that demonstrate this are lacking. The quality of the essential oil from the heartwood of the hybrids appears to be similar to that of *S. yasi* and *S. album*, both of which are excellent (Bush et al. 2020a). Introgression of *S. album* genes into the *S. ya*si population is a potentially threatening process that could lead to loss of the genetic identity of the native species – a phenomenon that has been documented in other forest tree taxa (e.g. Burgess and Husband 2006).

Though an available option, hybrid breeding is not planned to be undertaken in the short to medium term. This is primarily to preserve the natural *S. yasi* gene pool. However, a secondary reason is that development of a product that is differentiated from *S. album* is desired. It is hoped a market niche for *S. yasi* can be developed because, while similar to *S. album*, the *S. yasi* oil profile tends to have a higher proportion of β-santalol (Bush et al. 2020a; Doran et al. 2005). Furthermore, provenance, in this case the 'exotic Pacific', often adds significant value in the market placement of luxury goods (Thomson et al. 2020).

Minimising interactions with host plants

As *S. yasi* establishes a root connection with its hosts via root haustoria, there is a significant potential for the host to influence the growth and potentially other traits of the sandalwood. This presents a special challenge for genetic improvement programmes because in addition to the usual effect of site–genotype interactions on genetic parameter estimation, there will be additional *S. yasi* genotype–host interactions that need to be accounted for. To minimise these genotype–genotype interactions, a small set of host species that are consistent within and between trials should be used. Ideally, these hosts should be clonally propagated so that their genetic diversity is minimised (Bush et al. 2020b). *Alternanthera nana* is an ideal pot host as it is easily vegetatively propagated, while there are many suitable intermediate and long-term hosts suitable for *S. yasi* (see Thomson et al. 2018; Page et al. 2012).

Wood and essential oil characteristics

Carving logs, incense production and sandalwood oil are the three main commercial uses of *S. yasi*. In addition, the heartwood oil holds special cultural significance in both Fiji and Tonga (Thomson 2006).

Essential oil extracted from the heartwood from the lower stem and main roots contains α-santalol–rich essential oil. Thomson et al. (2018) give figures of 34–40% α-santalol and 29–31% β-santalol akin to the oil of *S. album*, the industry benchmark. Recent analyses of cores taken from trees in 'Eua and Tongatapu gave 41 and 25% for α-santalol and β-santalol, respectively.

Sandalwood oil trait heritability has not been assessed in any species. However, it is probable that the heritability of oil traits will be high, based on generally high heritability of plant chemistry traits (e.g. leaf oils, heartwood chemical properties) in other tree species. It is also likely that there will be less genotype–environment interaction on wood chemistry traits than is expected on growth traits. This means that selection and breeding for increased santalols, altered santalol ratio and/or specific minor components may be possible. Genomic selection (i.e. using DNA markers to select genotypes with particular oil characters) may also be effective if the chemical pathways associated with oil synthesis are under the control of relatively few genes.

Overall objective of the strategy

Securing the future of *S. yasi* throughout its natural range is important both for the sake of biodiversity conservation and also because it is a plant of considerable cultural value and commercial potential. To underpin a strategy to conserve and develop the species, basic information on its genetic structure and diversity is required, as well as assessment of the impact of hybridisation with introduced species.

To achieve the vision of a sustainable, plantation-based industry, Fiji and Tonga must transition from dependence on wild harvesting to an efficient, plantation-based system, with integrated processing and value adding. Significant volumes of *S. album* oil from northern Australian plantations will progressively enter the market, so it may be necessary to differentiate *S. yasi* products. To do this, the remaining *S. yasi* diversity needs to be secured and the quality of germplasm and plants improved. Recent research under the ACIAR project 'Assessing genetic diversity of natural and hybrid populations of *Santalum yasi* in Fiji and Tonga' (FST/2015/020) identified inbreeding in many of the existing stands, which may diminish plantation performance.

The short-term goal for *S. yasi* is to secure the remaining genetic diversity in Fiji and Tonga. This should be done by establishing ex-situ and circa-situm conservation stands that collectively have an adequate sample of the remaining diversity of the species. This could be achieved through collecting seeds and by vegetatively propagating selections.

A medium-term goal is to establish provenance–progeny trials across a range of sites in Fiji and Tonga. These trials need to comprise selections from across the native range of the species. The purpose of the trials will be to carry out growth-based selections for further breeding. In the long term (20+ years) the trials can be used to assess mature heartwood and oil characteristics.

A medium to long-term goal is to produce genetically improved trees that will maximise the profitability of plantations and downstream industry through enhanced heartwood and heartwood oil yields and quality.

Breeding strategy overview

The strategy proposed for *S. yasi* encompasses elements of both a conservation strategy and traditional domestication involving recurrent selection and breeding. This is because the **base population** (i.e. the population of wild and planted trees from which selections can be made) is critically fragmented and in danger of further depletion.

The process of recurrent selection and breeding is shown in Figure 16.4. Initially, a broad range of trees will be selected from throughout the base population in Fiji and Tonga and planted in trials at a range of sites. The trials, comprising the **breeding population**, are designed so that the identity of progeny grown from the seed harvested from individual mothers is kept intact. The performance of the progeny in terms of the traits of interest (survival, heartwood yield and oil characters, disease and cyclone resistance) is assessed. Though it is possible to perform controlled pollinations among trees in the breeding population, the simpler strategy that will be employed for *S. yasi* is to allow trees to freely interbreed (i.e. open-pollinated mating). Seed from the best-performing individuals is then harvested to form the basis of the next generation. The **propagation population** can be established either using seed or highly selected individuals grafted out of the breeding population into seed orchards in a separate planting. This population is used to produce seed for distribution to nurseries for planting. As a matter of practicality, it may be beneficial to supply the trees required for production populations to community groups, who can supply good quality seed to local growers. As the process of recurrent selection and breeding tends to narrow the genetic base in each generation, the members of the breeding population will become more closely related and

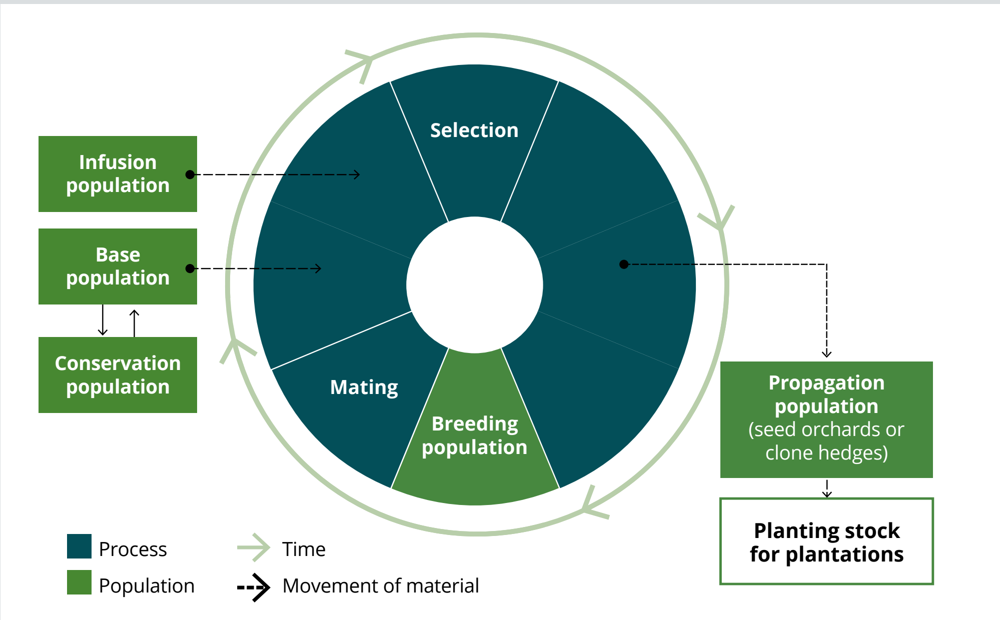

Figure 16.4 Diagram representing recurrent selection and breeding for general combining ability

inbreeding problems will eventually occur. To manage this, a set of new, unrelated individuals from the base population (the **infusion population**) is included after each cycle to maintain genetic diversity in the breeding population.

In the case of *S. yasi* it will also be important to maintain a **conservation subpopulation** to preserve the remaining diversity. Conservation plantings comprising unselected samples of the base population sufficient to adequately represent its genetic diversity should be established in dedicated plantings and gene banks. This subpopulation comprises a component of the base population. An important component of the conservation subpopulation is to include circa-situm plantings. These are genetically diverse and situated close enough to existing wild planting that geneflow (via pollen) is possible. These plantings may be genetically improved or include selections for specific traits: their primary purpose is commercial wood production, but in a sustainable, cyclical harvest system they present a standing conservation resource.

Genotype-by-environment and genotype-by-genotype interactions

An initial priority is the establishment of trials across a range of environments that involve a wide range of *S. yasi* genotypes. As a first stage, trials of unselected individuals from across the natural range need be established at as many sites in Fiji and Tonga as practical.

Genotype-by-genotype (sandalwood-by-host) interactions should be studied using a restricted range of host genotypes that are not themselves highly genetically diverse to minimise analytical complexity. The assessment of optimal hosts for planting sandalwood in different situations should be addressed separately but is also an important research question.

Personnel and funding

Having a properly resourced workforce with the appropriate technical skills is essential for a successful tree breeding program. Tree breeding, especially of species with a long rotation length such as *S. yasi*, is a long-term pursuit, and institutions must make a correspondingly long-term commitment to maintain staff capacity over decades. Capacity building of suitable technical and research staff is a major priority in both Fiji and Tonga: this may be the most important prerequisite to achieving the long-term vision for sandalwood development. At present, there are only a small number of staff in the two nations with the required background and technical competencies to carry out some of the more technically challenging aspects of the program. Specific areas for skill development include:

Applied skills required to carry out the operational aspects of a conservation and breeding program:

- nursery and propagation including grafting and seedling production
- long-term databasing and record-keeping related to spatial and pedigree data
- spatial and mapping skills related to inventory
- seed orchard management and planning
- data analysis and processing.

More advanced skills, requiring specialised postgraduate training, required for self-management of an entire breeding and conservation program:

- wood and oil chemistry and associated sciences
- population genetics
- quantitative genetics.

Capacity-building activities to support tree improvement and associated research and development should be high priorities for the short, medium and long-term horizons.

Challenges to be addressed

Making selections in the first generation will be challenging, as there is a lack of information on heartwood formation and development with tree age. A further challenge is that genotype-by-environment interactions with respect to wood and oil traits are unknown: the effects of climate, soils and cultivation practices on heartwood properties and oil yield are unknown. As previously discussed, a further challenge with all sandalwood species is the interaction between the tree and its host. This phenomenon has not been previously studied in a systematic way in other tree species to our knowledge.

A general list of challenges that need to be addressed includes:

- ongoing harvest of wild material and loss of genetic diversity
- sporadic flowering and seed set combined with limited storage capacity of *S. yasi* seed. It may be challenging to collect seed from a satisfactory number of genotypes in a single year
- cutting and grafting, while possible, is not widely practised and success rates may be comparatively low
- locating secure sites with suitable tenure and ownership arrangements can be challenging in some parts of Fiji and Tonga
- finding staff, as local staff with sufficient training to carry out specific technical tasks related to some aspects of the breeding strategy may not be available. Training and/or bringing in expertise from outside may be required
- exchanging seed/seedlings among islands and nations may be challenging.

While none of these challenges is insurmountable, it is possible that delays in implementing the strategy may be experienced due to a lack of suitably trained staff.

Actions for next decade

The main emphasis during the decade to 2030 should be on ensuring that wild genetic resources are captured and secured in gene banks, seed orchards and other plantings. Apart from formal conservation and breeding program plantings (gene banks, seed orchards), the production of genetically diverse seed crops for deployment to growers will form an important part of the strategy. Genetically diverse, outcrossed seed should overcome the potential problems of inbreeding and will help conserve the *S. yasi* gene pool.

Laying the foundations for more sophisticated domestication and breeding activities will also be a priority. Because of the long lead times associated with sandalwood heartwood development, many of the activities associated with genetic parameter estimation of growth, heartwood and oil traits will occur in the decade after next. Some of the key activities for the next 10 years will include:

Establishment of trials and conservation plantings:

- assembly of gene banks on secure sites using grafted planting stock
- establishment of genetically diverse seed orchards comprising seedlings from multiple seed sources in Fiji and Tonga
- establishment of across-site trials of provenance and family accessions using a restricted set of genetically uniform, best-bet hosts
- exchange of germplasm between Fiji and Tonga.

Wood and oil properties:

- analysis of wood and oil properties through sampling of trees felled for commercial purposes
- gain a better understanding of heartwood development and variation within trees over time
- assessment of the relative merits in terms of both oil yield per mass of heartwood and qualitative oil components (santalols and minor components) of *S. yasi*, *S. album* and their hybrids
- calculation of heritability of oil characters is dependent on trial establishment and will probably not be possible until the following decade (2040).

Host–sandalwood interaction:

- studies on the role of host–sandalwood interactions in respect to growth performance, heartwood and oil properties
- assessment of breeding system from controlled pollination studies and using molecular tools
- host performance trials to establish the relative performance of best-bet host species and interactions between *S. yasi* and host genotypes.

Human resources and cooperation:

- capacity building in applied tree breeding areas including plant propagation, trial and seed orchard establishment, database and pedigree record-keeping
- coordination and harmonising of breeding strategy approaches with other Pacific sandalwood species in the Pacific. *S. album* is being commercially developed and genetically improved in Australia and *S. austrocaledonicum* is being developed in Vanuatu (Page et al. 2020)
- value chain development.

Strategy review:

- The breeding strategy should be reviewed towards 2030. By this time, it is hoped that the *S. yasi* value chain will have developed (Thomson et al. 2020) and economic breeding objectives can be better defined.

Concluding remarks

The establishment of a domestication and conservation strategy for *S. yasi* is a high priority. The species has great commercial potential, and growers are enthusiastically planting. Yet the species is under threat because of the overharvesting that has already occurred and that may still be ongoing. Hybridisation with exotic sandalwood species may be an additional threat. Fragmentation of the genetic resource necessitates action on gene-banking and conservation. This can be carried out in tandem with a traditional domestication and breeding program that relies on recurrent selection and breeding. The provision of genetically diverse planting stock to growers has the potential to conserve the genetic resources of the species and ensure the ongoing future of *S. yasi*.

Domestication and tree improvement have the potential to significantly increase the profitability of *S. yasi* as a commercial tree crop. There are several challenges associated with the domestication of *S. yasi*. These include the usual challenges of breeding trees that have long rotation lengths, such as the long period before wood properties can be assessed, but also the additional challenge of host–sandalwood interactions unique to parasitic plants. Technical capacity building of the people that will carry out these activities is identified as an essential priority and prerequisite for success.

Acknowledgements

This chapter was published in modified form in Bush D, Thomson LAJ, Dutt S, Hamani S, Bolatolu W, Tauraga J, Mateboto J and Young E (2020) 'Domestication provides the key to conservation of *Santalum yasi* – a threatened Pacific sandalwood', *Australian Forestry*, 83(4):186–194.

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17 Are smallholder forestry and financial services for smallholder forestry compatible? A case study with a high-value tropical forestry species

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Abstract

The cultivation of forest products can improve the standards of living of the community by providing alternative livelihoods while reducing the pressure on scarce natural resources. Using Vanuatu sandalwood as a case study, the paper evaluates the financial performance and risk of high-value tropical forestry products and the suitability of existing lending opportunities to such an activity. Results show that smallholder forestry can be a profitable investment. Discount rates must be low enough to maintain the financial profitability, magnitude of loans must match initial investment, loan term must consider the long-term feature of forestry and the requirements for loans must be consistent with what smallholders can meet.

Introduction

The cultivation of forest products can improve the standards of living of the community by providing alternative livelihoods while reducing the pressure on scarce natural resources. Due to overexploitation, some forest products that have historically been harvested from natural forests are now under protection or with limited availability for harvesting. Cultivation is a good option for high-value forest products with sufficiently attractive markets where land and tree tenure is secure (Belcher et al. 2005).

In the Asia-Pacific region, a forest product with high potential for cultivation is sandalwood (*Santalum* spp.). The species *Santalum album* has been utilised since antiquity and other related species in the Pacific have been exploited over the past 200 years. All sandalwood species provide high-value, low-volume, non-perishable products (Page et al. 2012a). Their fragrant heartwood oil has been traditionally used for religious and customary purposes and is now used for cosmetics, aromatherapy, soaps, perfumery and medicines (Page et al. 2010). Despite the development of large-scale sandalwood plantations in Asia-Pacific countries (Thomson and Doran 2010), there is still more demand than supply and positive prospects for expansion of smallholder organically grown sandalwood (Tate 2012).

Despite the opportunity for smallholders to plant sandalwood to meet market demands there are underlying constraints limiting their involvement in tree planting. High initial investment, long maturity periods and high risks make forestry less appealing to smallholders with immediate needs (Pagiola et al. 2007; Hoch et al. 2009; Rahman et al. 2015). Credit is often unavailable for smallholders, who are often unable to meet institutional requirements, including the provision of collateral (Zhou et al. 2016; Arano et al. 2004; Larson and Ribot 2007; Boscolo and Whiteman 2008). Further, small loans are usually provided for short terms and require a minimum level of literacy and trust between the stakeholders involved (Larson and Ribot 2007; Boscolo and Whiteman 2008). Using Vanuatu sandalwood as a case study, the aim of this study is to evaluate the financial performance of small-scale tree growing of a high-value tropical forestry product under current levels of access to credit and the suitability of these financial services to the activity.

Brief description of the species studied

Santalum austrocaledonicum Vieill. is one of 16 species of sandalwood and is native to New Caledonia and Vanuatu. *S. austrocaledonicum* produces a highly valuable aromatic oil within its heartwood that is in high demand in international agarbatti and fragrance markets. The most valuable product is a clear grain log used for carving, followed by heartwood for oil extracted through distillation and then powdered heartwood used for incense products. Primary processing of the logs consists of removing the sapwood from around the heartwood, typically undertaken manually by harvesters using a large machete. The sapwood chips have a limited and low-value market. A second stage cutting of remaining sapwood is typically undertaken by traders following purchase from resource owners. The resulting chips from this second cutting (2CC) retain some heartwood and can also be sold for the manufacture of incense and other products (Page et al. 2012b).

Smallholder lending opportunities in Vanuatu

There have been efforts to increase access to rural credits at reasonable interest rates in Vanuatu for decades, through the Comprehensive Reform Program, followed by the country's Priorities and Action Agenda and several national institutions created to provide inclusive financial services (McCaffrey 2011). However, as of 2007, only 13% of people had access to bank accounts (ADB 2007), and in 2011, McCaffrey (2011) estimated that 19% of the population used financial services.

Lending is often unavailable for smallholders who have no capacity to provide collateral. The Vanuatu Agriculture Development Bank had, by June 2011, about 800 loans with an average of VUV450,000 (USD3,947) each (McCaffrey 2011). It makes both secured and unsecured loans, lending to smallholders who cannot access loans from commercial banks. Even when access to credit is possible, they often are unsuitable for tree growing, a long-term venture. In Vanuatu, loan terms vary between 1 week for small amounts and 7 years for larger amounts at commercial banks (McCaffrey 2011). For instance, Credit Corporation Vanuatu Ltd provides loans to small and medium-sized business with a 30% deposit, using vehicles as collateral and a declining interest rate of 16%, but for 2 or 3 years only, and VANWODS Microfinance Inc. (Vanuatu Women Development Scheme) offer four different loans, all of which are for up to 20 weeks (McCaffrey 2011). Loans that may suit sandalwood tree growing for smallholders considering timeframe, deposit and collateral requirements are presented in Table 17.1.

When carrying out financial analysis of sandalwood investments in Vanuatu, Page et al. (2010) assumed a 10% discount rate (*r*) while Thomson et al. (2011) and Harrison and Harrison (2016a) used 8%. These discount rates are at the bottom end of what can be accessed in real terms (Table 17.1). In this study, the discount rates of 10, 17 and 28% will be tested based on the loan opportunities for smallholders in the country.

Table 17.1 Credit opportunities for smallholders in Vanuatu

Loan and financial institution	Interest rate on loan	Amount	Term of the loan	Deposit, collateral and conditions
Business loan, Ni-Vanuatu Business Development Fund Cooperative Development Fund	10% flat interest rate	VUV50,000–5 million (USD438–43,860)	Variable	Applicants must submit a clear business plan and a 50% deposit of the loan, and attend a 2-week small business training course
Personal Finance ANZ	Variable discount rate. For a small loan up to 12 months the discount rate is of decreasing 17%	Minimum of VUV50,000 (USD438)	Up to 7 years	Can be either secured (cash or vehicle) or unsecured
Micro and Small loans National Bank of Vanuatu (NBV)	28% declining annual interest rate	Micro loans: VUV25,000–250,000 (USD219–2,193) Small loans: VUV250,000–3 million (USD2,193–26,316)	Undetermined	Applicants must first save for at least 6 months to access loans up to four times their savings

Source: McCaffrey (2011)

Research methods

Data for the development of the financial model were sourced from a comprehensive review of the literature. These data were complemented and validated with information obtained from experts in Vanuatu and Australia. Among the experts consulted were national and international researchers, business owners, sandalwood growers, government officials and farm managers.

The financial model was developed in Excel and had as a starting point the one developed by Harrison and Harrison (2016a). We assumed the system proposed by Page et al. (2012b), which counts with 444 sandalwood trees, 556 intermediate host plants and 111 long-term host plants per hectare. A mortality rate of 20% was assumed (Thomson 2006). Silvicultural practices in the model include: (1) fertilisation at planting and annually until year four of 50 g/tree; (2) weeding up to year seven (Harrison and Harrison 2016b); and (3) pruning up to year four (Tony Page, pers. comm.). Labour needs were based on Harrison and Harrison (2016b) and are available in the supplementary materials (Table SM1). Harvesting of 50% of the trees takes place at age 15 and final harvest at age 20 (Page et al. 2012c; Page et al. 2010). Heartwood production was calculated with a simple regression model using age seven as the beginning of production of heartwood and a yield of 17.5 kg at age 18. For each 18 kg of heartwood, the same amount of sapwood and 2.5 kg of 2CC can be obtained (Page et al. 2012b). This ratio was used to calculate the amount of each product in our model. It was estimated that only 5% of the heartwood would serve as carving timber, and the remaining would be sold as heartwood. Harrison and Harrison (2016b) considered a seed production of 1 kg/tree. However, smallholders are unlikely to be able to collect this full amount (Tony Page, pers. comm.). We considered that 0.25 kg of seeds would be harvested per tree to be sold from year nine on. Costs for seed collection, processing and selling are presented in the supplementary materials (Table SM2) along with other financial parameters of the model.

Because of the potential fluctuation and the range of possible prices smallholders can achieve, the prices for sandalwood products were included in the financial analysis with a triangular distribution to perform Monte Carlo simulations with 1,000 iterations using the @Risk 7.6 add-in for Excel. The minimum, most likely and maximum values for each product can be found in the supplementary materials (Table SM3). The internal rate of return (IRR) and net present value (NPV) were calculated for the models using r = 10, 17 and 28%. Calculations were done in USD using a conversion rate of USD1 = VUV114.

Results

The annual cashflows for the sandalwood growing scenarios remain negative for at least 11 years. There are no inflows in the project until year nine, when seeds are harvested for sale. The sale of seeds is an important component of the portfolio of products from the plantation for bringing a regular income early in the project. Revenue from all products (i.e. craftwood, heartwood, sapwood, 2CC and seeds) at age 15 is of USD73,405. At age 20, this value is of USD104,067.

Outflows include an initial investment of USD3,265, of which about 21% are labour costs. Adding the initial investment to the costs of maintenance and protection activities up to year eight, about USD5,000 is needed. Payback happens at year 11 and 14 for 10 and 17% discount rates, respectively (Figure 17.1). For the scenario with *r* = 28%, the inflows by year 20 are just enough to make up for the establishment and maintenance costs, as the mean IRR was of 28% (SD (standard deviation) = 1.19).

At its lowest point, the project balance for *r* = 10% was of –USD4,625. At the end of the project, the balance was of USD37,553. The NPV for this scenario ranged between USD26,572 and USD48,805, averaging USD37,553 (Figure 17.2). For *r* = 17%, the lowest project balance was of –USD4,434, while mean NPV was of USD11,578 ranging between USD6,961 and USD16,074. At year eight, with *r* = 28%, the project balance was of –USD4,220 and at year 20, USD23. For *r* = 28%, NPVs were between –USD1,429 and USD1,413.

Over 20 years of project, 628 person-days of work are needed. Labour demand is mostly concentrated around harvesting time (Figure 17.3). Income at the end of the project is about USD60 per day of work in the best-case scenario, USD18 for *r* = 17% and virtually zero for *r* = 28%. When removing the cost of labour from the annual cashflows, the IRR of the project increases to 32% and NPV increases by USD2,897, USD1,890 and USD1,349 for the scenarios with *r* = 10, 17 and 28%.

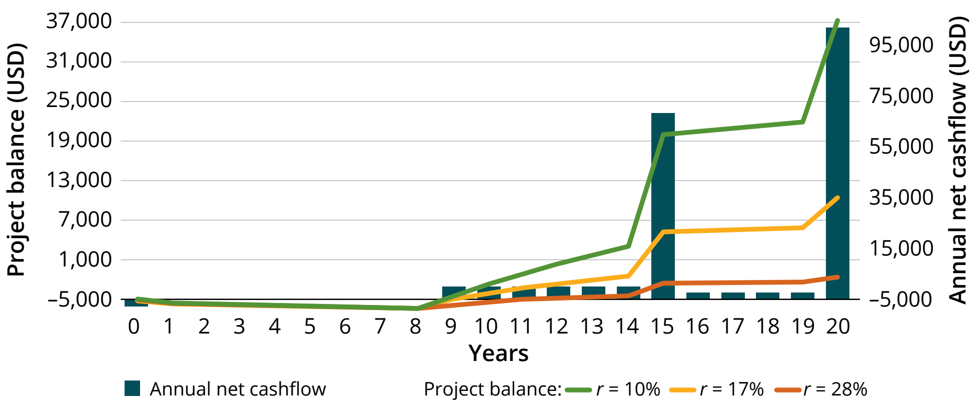

Figure 17.1 Project balance and annual net cashflow for smallholder sandalwood plantations with discount rates of 10, 17 and 28%

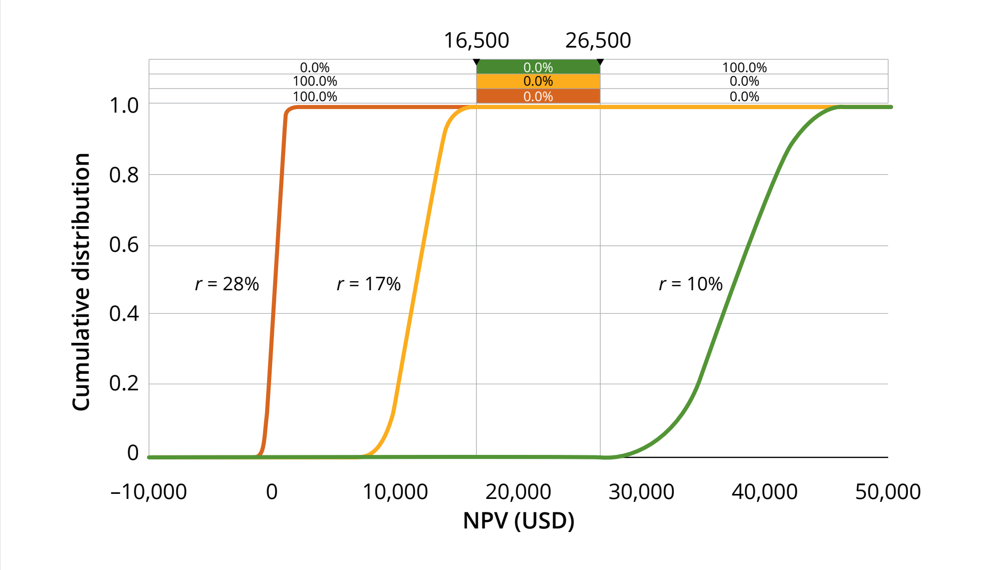

Figure 17.2 Cumulative distribution of net present values (NPVs) of smallholder sandalwood plantations under 10, 17 and 28% discount rates

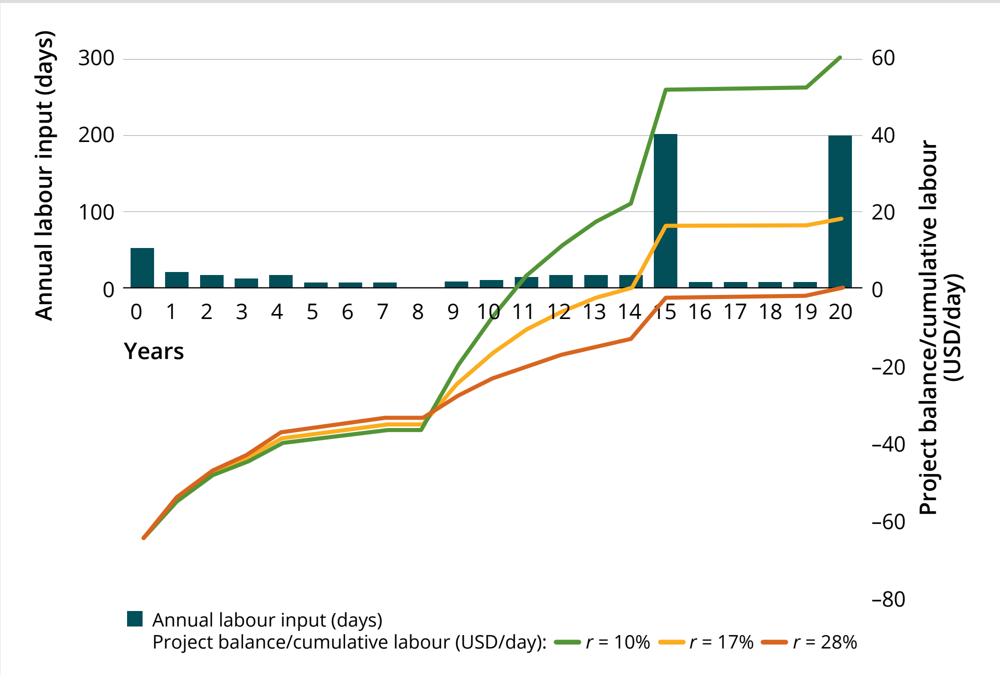

Figure 17.3 Labour input profile throughout project life and average returns per day of work

Discussion

Sandalwood tree growing can be a profitable livelihood activity depending on the financial services smallholders can access. The scenario with r = 10% had by far the highest NPV, and lower relative financial risk. Risk can be represented by the standard deviation of return, based on the mean-variance approach (Markowitz 1952). Despite the wide range of potential outcomes, this scenario had a standard deviation of only 10%. With r = 17%, risk was higher, with a standard deviation of 15%.

The NPV of USD37,553 for r = 10% is comparable to what has been found previously. Page et al. (2010) had a NPV of USD21,786 for an agroforestry with sandalwood system planted at 3 m × 4 m, interplanted with garden species, with harvesting at ages 15 and 20, and r = 0%. Harrison and Harrison (2016a) estimated a NPV of USD23,631 for a sandalwood agroforestry system also containing food and commercial crops. Crops were added to the system for weed control and income for the early years of the project. However, in this case a discount rate of only 8% was used.

Considering the financial risk, NPV of only USD11,578 and returns of only USD18 per day of work after 20 years, smallholders are unlikely to invest in sandalwood plantations with r = 17%. The IRR calculated in this study of 31% is above the range of the previous studies on sandalwood plantations of 16–28% (Page et al. 2010; Thomson et al. 2011). However, the only source of credit to smallholders is often through informal money lenders. In such circumstances, interest rates tend to be high. In Ethiopia for example, informal money lending had interest rates of 50% and over (Duguma 2013) and in Pakistan between 31 and 36% (Hussain and Thapa 2012). This emphasises the need to enhance smallholder access to formal credit. Despite being unprofitable, the NBV Small Loan (Table 17.1) has appropriate magnitude for sandalwood investment and its discount rate is the closest to reality for most smallholders in developing countries.

The amount needed to invest is compatible with all three borrowing opportunities. However, only the business loan with r = 10%, providing loans from USD438 to USD43,860 with a variable loan term, proved suitable for a profitable investment in sandalwood tree growing. Despite the profitability of the investment under such circumstances, the requirement for a 50% deposit of the loan can constrain smallholder access to the financial service. Some smallholders have lower levels of asset liquidity (Daniels 2001) and the provision of deposits or collaterals for loans is a barrier for them. Alternatives have been created to enable smallholders to access credit, for instance, in the USA, Latin America, Asia and Africa, the warehouse receipt system (Chapoto and Aboagye 2017; Coulter 2009). In this system farmers can deposit farm production (grains) at a warehouse and use it as collateral for a loan. If a smallholder has the title for the land, this can also be used as collateral for loans (Besley and Ghatak 2010; Deininger and Feder 2001).

Besides the need for collateral or deposit, the term of the loans is often insufficient for forestry. The 7-year term of the ANZ Personal Finance Loan is too short considering the project balance for r = 17% is negative until year 14. Smallholders are often unable to cope with long periods of negative project balance. For an earlier payback, other products could be incorporated into the system. Inclusion of fruit and vegetable species in agroforestry systems focused on a long-term product can help to service short-term loans (Harrison et al. 2016; Appiah 2001).

Conclusions and policy implications

There is market demand for tropical forestry products (Tate 2012; Saha and Sundriyal 2012; Kollert and Lagan 2007) and sandalwood is highly sought in the international market (Coakley 2013). The Government of Vanuatu has recognised the importance of planted forests by enabling agreements and registration of forestry rights over tree plantations and woodlots through the *Planted Forest Act No. 7 of 2015* (Vanuatu 2015). This is further supported across broader national development goals to reduce deforestation and ensure rehabilitation and reforestation is commonplace (Vanuatu 2016). There is the opportunity to tackle several regional and global goals with smallholder forestry. Small-scale tree growing can help address several of the United Nations Sustainable Development Goals, including numbers 1, 2, 6, 7, 8, 13, 15 and 16 (Katila et al. 2017; Mbow et al. 2014; De Jong et al. 2018; Waldron et al. 2017).

Smallholder forestry can be a profitable investment if access to credit is enabled and financial services are suitable for the nature of smallholder forestry. Discount rates must be low enough to maintain financial profitability, magnitude of loans must match initial investment, loan term must consider the long-term features of forestry, and the requirements for the loan must be consistent with what smallholders can meet. On a more technical side, other components can be incorporated to the system for earlier financial returns and faster payback.

Acknowledgements

Local and international stakeholders that contributed to this study including Joseph Tungon, Michael Tabi, Hanington Tate, Godfrey Bome, Mesek Sethy, John Doran, Lee Peterson, Jonathan Naupa, Craig Mowatt, Edmond Julun, Steve Nilwo, Abel Joel, Jackson Novoi, Jonsen Boe, Andrew Iawak and David Kalanga. We acknowledge funding support from the Australian Centre for International Agricultural Research (ACIAR) under FST/2016/154, and Sandalwood Regional Forum (FST/2016/024) projects.

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Supplementary materials

Table SM1 Labour requirement for smallholder sandalwood tree growing

Activity	Labour requirement and unit
Fencing labour	0.36 hours per metre of fence
Site preparation	1 day/ha
Hole digging	12 min/tree
Planting and watering	10 min/seedling
Infilling	6 min/tree
Weed control, year 1	15 min/tree
Weed control, year 2	10 min/tree
Weed control, year 3–7	5 min/tree
Pruning, year 1	2 min/tree
Pruning, year 2	4 min/tree
Pruning, year 3	5 min/tree
Pruning, year 4	10 min/tree
Root lifting and cleaning	3 hours
Tree felling, bucking & debarking	2 hours/tree
Sapwood chipping time	1 hour/tree
Total harvest labour	6 hours/tree
Tree protection (year 1 for protection of seedlings and annually from year 12 on[1])	5 min/tree

Source: Harrison and Harrison (2016a)
[1] (Page, personal communication)

Table SM2 Financial parameters for analysis of smallholder investment in sandalwood tree growing

Parameter (unit)	VUV	USD	Source
Labour cost per person per day of 8 hours of work	1,412	12.39	Harrison and Harrison (2016a)
Drying area materials and construction	83,000	728.07	
Foregone annual revenue from planting site per hectare	4,150	36.40	
Outlay on hand tools	8,300	72.81	
Cost of transport to house per tree	415	3.64	
Chemical fertiliser and mulch at planting per tree	66.4	0.58	
Cost of transport to house per tree	415	3.64	
Fencing materials cost per metre	200	1.75	Field data
Sandalwood seedling	202	2.39	Page, Potrawiak, et al. (2010); Thomson LAJ et al. (2011)
Intermediate-host seedling cost	Usually seeds and seedlings of hosts are not purchased and growers use available germplasm from their farms		Field data
Long-term host seedling cost			
Seeds collection, processing and selling cost per kilogram	1,000	8.80	Estimation

Table SM3 Parameters using a triangular distribution for Monte Carlo Simulations for smallholder sandalwood tree growing

Parameter	Minimum	Most likely	Maximum	Source
Craftwood price (VUV/kg)	3,000	3,500	4,000	Republic of Vanuatu (2014)
USD/kg	26.32	30.70	35.09	
Heartwood for oil price (VUV/kg)	2,000	2,500	3,000	
USD/kg	17.54	21.93	26.32	
Seed price (VUV/kg)	2,580	5,700	8,550	Page (personal communication)
USD/kg	22.63	50	75	
2CC price (VUV/kg)	75	100	125	Estimation
USD/kg	0.66	0.88	1.10	
Sapwood price (VUV/kg)	37.5	50	62.5	Page et al. (2010)
USD/kg	0.33	0.44	0.55	

18 Participatory domestication strategy for *Santalum austrocaledonicum* in Vanuatu

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Abstract

Sandalwood is a valuable crop in Vanuatu, especially for providing income to smallholder growers on remote islands. Sandalwood contains heartwood that is a highly valuable export product. Improvement of sandalwood through domestication has the potential to increase tree productivity, heartwood volumes and heartwood oil quality. This will improve the income and livelihood benefits associated with producing sandalwood in Vanuatu.

Sandalwood occurs naturally on at least nine islands from Santo in the north to Aneityum in the south. The amount of the oil-bearing heartwood determines the value of individual trees in the marketplace. This is linked to growth rate, oil concentration and chemical composition (santalol-rich oils most desirable). There is substantial variation in all these characteristics, especially between individual trees within populations but also between populations within and between islands. Much of this variation, particularly of oil characteristics, can be attributed to genetics. Many growers are planting seedlings from non-selected seed sources. This results in less than optimal productivity and market potential for their sandalwood crop. A compelling economic analysis of the benefits of using improved seed is given in the 'Germplasm delivery pathways' section of this report.

This project aims to address this problem by initiating a carefully planned and strategically placed breeding program with a 'participatory domestication' mechanism to ensure the improved seed produced is widely available to sandalwood growers. This program will build on the work of earlier Australian Centre for International Agricultural Research (ACIAR) projects: (1) the first sampled the natural stands throughout the country, made selections based on oil characteristics, and vegetatively propagated these selections into a clonal archive at Tagabe, Efate; and

(2) the second used the clonal archive as a base population and set-up small clonal seed orchards on several islands to provide somewhat improved seed where it was most needed.

From this departure point this domestication strategy aims to:

1. Establish new grafted seed orchards on at least four islands that are actively planting sandalwood. The aim is to utilise as many of the Tagabe clones (39 in total) as possible in these orchard plantings and thus conserve the existing genetic base that is slowly being lost through natural attrition. The genetic worth of individual clones will be assessed first in progeny trials in Efate and later in participating islands and communities. The poorest performing families in these trials will be the basis for the culling of some clones from the breeding population.
2. Add to the genetic base of established orchards by introducing new selections from plantations and the wild in a 'rolling front' breeding strategy (as described in this report) for each orchard. When these set seed, their progeny will be tested in progeny trials on participating islands to assess their genetic performance and the poorest clones culled from the orchards.
3. Undertake relevant research to address knowledge gaps and produce a series of technical notes to improve knowledge development and transfer among stakeholders. Research proposed includes establishing provenance trials and perfecting means of controlled pollination and striking cuttings to advance the breeding program, while technical notes on grafting techniques, seed collection and wood grading are under development.
4. Place seed orchards where improved seed is most needed and develop a participatory domestication mechanism whereby improved seed is equitably distributed among smallholder growers.

The domestication strategy has been developed with consideration of the resources and capacities of the stakeholders within Vanuatu. It is, therefore, based on conventional approaches to plant improvement to ensure the risks are manageable. Grafting is central to the capture of selected individuals and based on established and reliable techniques for sandalwood. Furthermore, existing orchards have proven robust against cyclonic winds. The orchards will be placed with reliable growers who are associated with grower groups, and other organisations responsible for the equitable distribution of the improved seed produced.

Introduction

The need for a participatory domestication strategy for Vanuatu sandalwood

Santalum austrocaledonicum is considered a commercially attractive agroforestry species on sites suitable for its cultivation in Vanuatu, in particular to generate cash revenue for rural communities in remote areas. Sandalwood species are hemiparasites, whereby they are capable of photosynthesis but depend on root grafting to other plants for nutrient uptake. They are, therefore, ideal for home gardens where they can be grown with a mixture of ornamental and productive plants that serve as hosts.

The valuable fragrant oils of *S. austrocaledonicum*, as in other sandalwood species, are concentrated in its heartwood. The market value of a given volume of heartwood will depend primarily on the concentration and quality of its oil, which varies between species and can be influenced by genetic, environmental and agronomic factors.

Sandalwood oil consists of a range of different compounds, but its quality in the marketplace is typically determined by the relative proportions of α-santalol and β-santalol. The high heartwood oil concentration (av. 6–7%) and the high levels of santalol in East Indian sandalwood (*Santalum album*) (ISO 3518:2002(E) minimum levels: 41% for α-santalol and 16% for β-santalol) result in a strong demand for, and a high value of, this species. The comparative heartwood oil concentration (av. 3–5%) and lower average santalol levels of *S. austrocaledonicum* from Vanuatu lie somewhere between the elevated levels of East Indian and lower levels of Australian sandalwood (*Santalum spicatum*).

The market price of *S. austrocaledonicum* is reflective of its intermediate heartwood quality but its trade is still considered to be lucrative.

S. austrocaledonicum grows at moderate rates and can produce substantial quantities of the valuable heartwood on a rotation of 25–40 years. It has been estimated conservatively that more than 300,000 seedlings were planted by smallholders and commercial entities between 2000 and 2006 (Page et al. 2012a), which extrapolates to a planted estate of some 860,000 trees by year 2020. Not even the most rudimentary selection of mother trees for desirable traits has been applied to most of the seed used in plantings to date.

There is increasing interest among smallholder sandalwood growers, other small-scale entrepreneurs and government agencies to expand the scale of planting. This expansion provides the opportunity for developing an appropriate and coherent 'participatory domestication' strategy to optimise the commercial potential of this species. This strategy will aim to ensure wider availability of improved sandalwood germplasm which, in turn, is expected to result in greater investment in sandalwood planting and improvement in the quality of sandalwood traded. The establishment of new breeding resources can lead to a greater participation of the private sector in sandalwood germplasm improvement.

The process of domestication

Developing an appropriate domestication strategy for Vanuatu sandalwood (*S. austrocaledonicum*) involves a continuum of several, often interrelated activities (Figure 18.1). These include exploration and collection of natural or planted populations, evaluation and selection of suitable provenances, genetic improvement in traits of commercial interest (tree breeding), multiplication and dissemination of improved germplasm, development of propagation techniques, optimisation of agronomy or silviculture, utilisation and tree-product marketing, and the development and dissemination of relevant technical information (Roshetko and Verbist 2000).

Earlier projects, such as the South Pacific Regional Initiative on Forest Genetic Resources (SPRIG) (1996–2006) and two previous Australian Centre for International Agricultural Research (ACIAR) (FST/2002/097 and FST/2008/010) projects, have contributed much to our understanding of this species in Vanuatu, with reports available on many aspects relevant to domestication (see references to this report).

Aim of this report

The main purpose of this report is to outline an appropriate participatory domestication strategy for Vanuatu sandalwood. It commences by introducing factors influencing the choice of breeding strategy for *S. austrocaledonicum* in Vanuatu, the basic concepts of breeding strategy, the recommended strategy and work plan for its implementation and research needs, and concludes with identification of appropriate diffusion pathways for the improved seed from the breeding program.

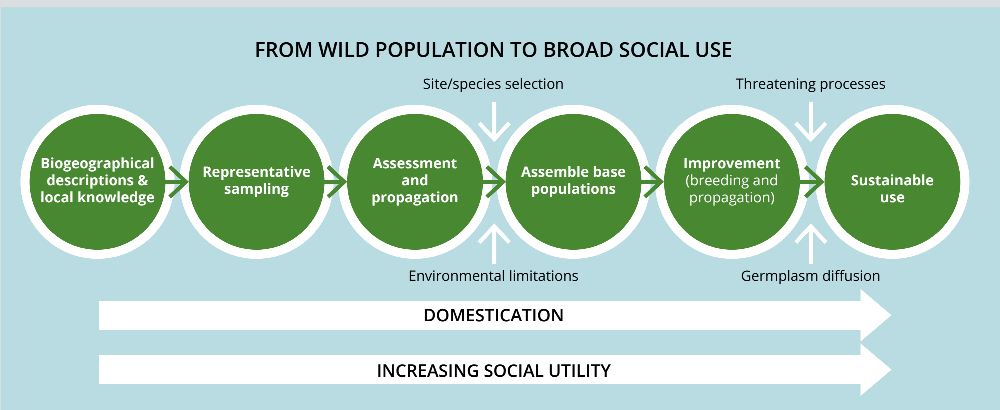


Figure 18.1 The process of tree domestication

Source: Pinyopusarerk and Kalinganire (2003)

Developing a breeding strategy for *S. austrocaledonicum* in Vanuatu

Factors to consider

Distribution of the species

S. austrocaledonicum occurs naturally in the island archipelagos of New Caledonia and Vanuatu in the south-west Pacific. In Vanuatu, it occurs naturally on the islands of Espiritu Santo (west coast), Malekula, Efate, Moso, Erromango (north-west, west and south-west areas), Aniwa, Tanna, Futuna and Aneityum (see Figure 18.2). However, the climatic and edaphic conditions of eight other islands (Malo, Aore, Ambae, Pentecost, Ambrym, Epi, Paama and Shepherd) are also suitable for its production (Gillieson et al. 2008). Their suitability represents an opportunity for the industry to increase production over a wider geographical area, which will increase the volumes of heartwood available, broaden the economic benefits and mitigate the impact of natural disasters such as cyclones.

This species prefers warm to hot, lowland, subhumid or wet/dry tropical climates with a mean annual, mainly summer rainfall of 800–2,500 mm and a short to lengthy (0–5 months) dry season in the cooler months. Altitudinal range is 5–800 mASL. Tropical cyclones are a feature of the entire distribution range, occurring mainly during the hot, wet season from December to April. The species prefers well-drained acidic to alkaline soils and does not grow well on waterlogged soils and strongly acidic, clayey soils.

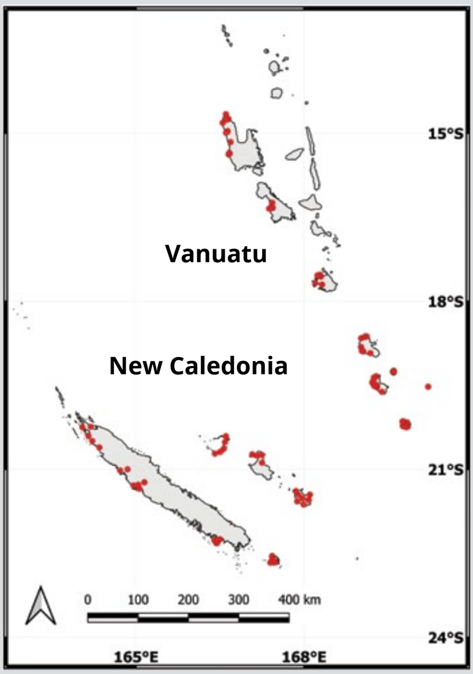


Figure 18.2 Natural distribution of *S. austrocaledonicum* in Vanuatu and New Caledonia

World sandalwood market

Larger pieces of heartwood of *S. austrocaledonicum* are mostly used for carvings, which are in strong demand and sell for high prices. The heartwood not suitable for carving is prized as a source of sandalwood oil, produced by steam distillation of the wood after it has been chipped and ground to powder, and used in expensive perfumes and attars. The oil also has traditional as well as modern medicinal uses and is employed in aromatherapy and in personal hygiene products. Average commercial yields from *S. austrocaledonicum* heartwood are between 3 and 5% w/w, FW (weight/weight, fresh weight). Lower grade heartwood, sapwood and spent charge from distillation are used in the production of agarbatti (sweet-smelling incense such as joss sticks).

There are many challenges in determining accurate sandalwood production and trade data – including commercial secrecy, illegal harvesting, substitutes and adulterants. Statistics for the sandalwood industry summarised from various sources and based mainly on *S. album* (traded as East Indian sandalwood) from natural stands have been reported by Thomson and Doran (2012) and have been updated for South Pacific sandalwoods by Thomson (2013).

The annual global demand for sandalwood heartwood for handicrafts has been estimated to be approximately 5,000–6,000 t; 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 for heartwood, together with India, which has its own production capability. Current world demand (USA and Europe the main importers) for sandalwood oil was estimated to be about 250 to 300 t/year, which equates to over 15,000 t of wood. India (85% of world production) produces about 120–150 t of sandalwood oil per year with about 80 t/year used domestically and the remainder exported (ca. 40 t/year). Indonesia (10% of world production) exports about 15 t/year, while other sources, including substitutes, accounted for 5% (7.5 t/year) of world production.

Sandalwood heartwood and oil have increased in price throughout almost its entire traded history due to increasing demand and diminishing supply. *S. album* (East Indian sandalwood) heartwood prices at auction in India were about USD150/kg in July 2014 and East Indian sandalwood oil is presently trading in the range of USD1,500/kg to USD2,500/kg on the international market. In the case of *S. austrocaledonicum* oil, its use in the perfumery industry currently outweighs its use in medicine and natural therapies. Oil quality in this species varies according to geographic origins. Currently the 30 to 35% α-santalol type, typically from trees of Malekula and Santo origins, trades for about USD900/kg to USD1,200/kg.

The present shortfall in world production of sandalwood heartwood offers a great opportunity for Pacific islands to develop sandalwood into a commercially viable, sustainable industry. This is not without its challenges of course. Thomson (2013) lists some of these including extreme climate hazards, notably tropical cyclones, ineffective regulatory environments, lack of propagation materials, theft and cost of security, the long-term nature of the crop and risks that markets will shrink and/or prices will fall while trees are being grown.

Biology of the species

To develop an effective breeding strategy, it is vital to have information about the biology of the species involved. Aspects including reproductive biology, potential for vegetative propagation, relationships between characteristics of economic importance and extent of variation and the heritability of such characteristics are all required. A summary of available information on the biology of *S. austrocaledonicum* that will influence the choice of breeding strategy is given below, but presently there are large gaps in our knowledge base, particularly concerning genetic parameters for key commercial traits.

Molecular diversity in Vanuatu

The genetic diversity of *S. austrocaledonicum* from across the islands of Vanuatu was generally higher than that observed between the island populations of New Caledonia, according to a study using molecular markers (Page et al. 2018). In Vanuatu, population differentiation due to genetic structure was lowest among the three southern islands of Erromango, Tanna and Aniwa. The small island of Aniwa exhibited the lowest genetic diversity, not unexpected given the small population size and its possible anthropogenic introduction. Small clusters of genetically related trees were observed on Espiritu Santo and Malekula, which may be the result of localised inbreeding or due to the planting of seed from a single source tree. Some level of inbreeding in *S. austrocaledonicum* is likely given that, in controlled crossing experiments, 12.5% of self-pollinated flowers developed into seed and 6.3% of these into healthy seedlings (Page et al. 2012b).

Within and between-provenance variation

Information on within and between-provenance variation in commercial heartwood traits comes from the work undertaken in the first ACIAR sandalwood project (FST/2002/097) in Vanuatu. Wood core samples were collected in 2004 from multiple populations on seven islands (Santo, Malekula, Moso, Erromango, Aniwa, Tanna and Aneityum). In all, more than 250 individual trees were cored.

Based on this sampling, Page et al. (2007) reported significant tree-to-tree variation in heartwood proportion varying from 1 to 73% with a mean of 27%. Similarly, for the level of heartwood santalols in Vanuatu, these varied from 1 to 47% with a mean of 20%. Populations on the northern islands of Espiritu Santo and Malekula had a higher frequency of trees with elevated levels of santalols (Figure 18.4 and Table 18.2). Heartwood oil concentration also varied between trees with a range of 0.1 to 8%. No geographic pattern was identified for trees with high oil concentrations. It is unknown what level of genetic control these traits are under, as suitable trials (common garden plantings) do not exist.

Selection of the optimum provenance of a species for planting on a particular site can make a huge difference to growth and, therefore, commercial outcomes. In the tea tree (*Melaleuca alternifolia*) oil breeding program in Australia, switching the industry to the optimum provenances for biomass and foliar-oil characteristics, identified from simple provenance trials at the start of the program, improved yields by 30% (Doran et al. 2006). Provenance trials to assess variation in growth and oil characteristics with location of planting have not yet been undertaken with sandalwood in Vanuatu. Therefore, we are not sure how well provenances from the north of the country will do in the south and vice versa. We recommend actions within this strategy to address this gap in our knowledge by collecting seed from ex-situ plantings of island provenances in the Santo Gene Bank, augmented by seed collections in planted stands of known provenance as on Malekula, such that the main areas of the species distribution are represented. Provenance trials that include this range of genetic material should then be established in the north, central and south of the country.

Genetic parameters

At present almost nothing is known (at least in the public domain) for *S. austrocaledonicum* (or indeed for any other sandalwood) of the heritability and genetic correlations of growth parameters, such as height and diameter, and wood characteristics such as amount of heartwood, its oil concentration and chemical composition of its essential oils.

Certainly, in the case of source species for foliar essential oils, such as various *Eucalyptus* and *Melaleuca* species, oil concentration in leaves and proportions of major oil components have been found to be highly variable between and within provenances, moderately to highly heritable, with no substantive genetic correlations among them (Baker 1999; Doran 2002). There are, therefore, good prospects for genetic improvement of foliar oils in these genera through recurrent selection and breeding. Similarly, in a study of genetic variation of wood durability traits in *Eucalyptus cladocalyx*, including extractives content, Bush et al. (2011) found substantial genetic variation in all traits studied, with wide scope for genetic improvement. It is reasonable to assume that similar findings will be forthcoming for sandalwood heartwood oil characteristics once appropriate studies are concluded.

Page et al. (2010) report of a positive phenotypic correlation between a tree's stem basal diameter and heartwood diameter in an uneven aged population of *S. austrocaledonicum* in Vanuatu, which bodes well for selection of fast-growing, larger trees. A similar result was reported in a study of 20-year-old *S. album* in southern India (Arunkumar et al. 2011). Here, oil concentration was found to be independent of tree diameter and heartwood percentage.

Estimation of genetic parameters through progeny trials will be of paramount importance in further development of the breeding strategy for this species.

Reproductive biology

Morphology of reproductive structures – **Inflorescences** comprise terminal and axillary panicles of bisexual (monoecious) flowers. **Flowers** are small (~5 mm across) with four or, rarely, five tepals, which remain greenish white to cream through to maturity. Yellow disc lobes alternate with the tepals and anthers. Long unicellular hairs occur at the base of each anther filament and extend to the anther. Pollen is shed from longitudinal slits in each anther. The stigma is typically 3-lobed (rarely 2- or 4-lobed) and fused into a single style. **Fruits** are subglobular or ellipsoid, single-seeded drupes, 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. Fruit size can vary between populations. **Seed** kernel is woody enclosing a light-coloured endocarp and single seed. Vanuatu seedlots typically comprise 3,300 to 4,500 seeds/kg of 80 to 90% germination rate. Seed storage behaviour is described as short-lived orthodox.

Pollinators – *S. austrocaledonicum* is insect pollinated. The most common pollinators are bees, flies, beetles, ants, butterflies, wasps and thrips (Tate 2015).

Flowering phenology – Under good conditions plants begin fruiting from an early age, typically about 3–4 years, but heavy fruiting may take 7–10 years. In Vanuatu, flowering occurs in January to April, July and October. Mature fruits have been reported almost throughout the year, but the main fruiting season is November to January. Fruits mature about 3–4 months after flowering (Thomson 2006; Thomson et al. 2011).

Page and Tate (2013) studied the onset and duration of flower opening, pollen shed and stigma receptivity in three sandalwood species including *S. austrocaledonicum*. This knowledge is important for understanding plant breeding systems, as well as developing methods of controlled pollination as it allows the correct timing of emasculation, pollen collection and pollination. As a result, effective controlled pollination techniques and procedures are now available for *S. austrocaledonicum*. This work determined that these species are either slightly protandrous (pollen shed before stigma receptivity) or pollen shed and receptivity occur simultaneously, thus increasing the opportunity for self-fertilisation.

During observations of floral morphology and undertaking controlled crosses with three *Santalum* species (*S. austrocaledonicum*, *S. album* and *Santalum lanceolatum*), Page and Tate (2018) found that genotypes varied substantially in production of pollen. Those with higher pollen production were typically more successful in siring seeds when used as a male parent. Interestingly, these were also relatively more successful seed-bearing parents. This apparent variation in fecundity could explain the existence of the folklore 'man' and 'woman' varieties reported for *S. austrocaledonicum* in Vanuatu (Thomson 2006), although the authors advise that further investigation is required to confirm this breeding behaviour.

Tamla et al. (2011) showed that there are no reproductive barriers between *S. austrocaledonicum* and at least three other commercial tropical species: *S. album*, *S. lanceolatum* and *Santalum yasi*. This can be viewed as an opportunity allowing better performing, site-specific hybrids to be developed or as a threat with conservation implications. Introduction of compatible exotic sandalwood species within the natural range of *S. austrocaledonicum* will likely result in uncontrolled geneflow between them and modify the genetic structure and diversity of natural stands. Negative impacts may include a reduction in heartwood development and decreased cyclone tolerance.

Mating system – Knowledge of the mating system is an important factor in the design of a breeding strategy as it determines what approach can or must be taken to maximise efficiency in the improvement of the breeding population.

Da Silva et al. (2016) described the general breeding system of *Santalum* species as facultatively allogamous (incompletely outbreeding), with variation between families and individuals at the level of self-incompatibility and with no capacity for apomixis or parthenocarpy. *Santalum* species were described by these authors as mass flowering with typically less than 10% developing into viable seed. In a controlled pollination experiment with *S. austrocaledonicum*, Page et al. (2012b) found that 12.5% of self-pollinated flowers developed into seed and 6.3% of these became seedlings. The preferential outcrossing nature of the breeding system and the capacity for self-fertilisation is advantageous, providing the genus a capacity to colonise new islands.

Mazanec (2009) described the implications of the ability to self-fertilise for a breeding program in that inclusion of selfs in trials may inflate estimates of heritability, in a manner similar to that of eucalypts. Estimation of heritability in *S. austrocaledonicum* may require some adjustment of the coefficient of relationship (r) to compensate for selfing effects as is commonly done with eucalypts, where $r = 0.4$ is commonly applied.

Inbreeding depression – The effect of inbreeding depression as a result of selfing or related mating is not known for *S. austrocaledonicum*. There is some anecdotal evidence from seedlots from isolated parent trees that selfing may lead to spindly, unhealthy plants but this is also disputed by some growers. Controlled crossing experiments or applying molecular markers on progeny resulting from mixed mating are required to examine the effect of inbreeding depression as a result of selfing and related mating in this species.

Cytogenetics

Da Silva et al. (2016) report that previous studies showed that the somatic cells of *Santalum* were diploid, with $2n = 20$. Mahesh et al. (2018) published the genome for *S. album* and confirmed a somatic chromosome number $2n = 20$ and reported it to have a small genome compared with most other tree species.

Cloning

Clonal propagation can permit the routine multiplication of plants with desirable traits to support tree domestication. Successful grafting of *S. austrocaledonicum* has been demonstrated using a top-cleft graft with actively growing semi-hardwood stems (Tate et al. 2006; Spencer et al. 2018). These authors suggested that the success of grafting was dependent upon the skill of the propagator, with the percentage of successfully grafted unions varying between 60 and 90%.

S. austrocaledonicum was also found to be amenable to propagation by leafy stem cuttings in low-cost, non-mist propagators. Collins et al. (2000) found substantial variation in the percentage of stem cuttings with adventitious roots between experiments (64 and 20%) and genotypes (25 to 89%) for *S. austrocaledonicum*. Tate and Page (2018) showed provenance-based variation in the capacity for cutting propagation where cuttings taken from genotypes derived from the island of Erromango outperformed (rooting percentage) those from Tanna. Variation in cutting performance was also demonstrated between genotypes derived from Erromango, suggesting a benefit for optimising cutting propagation protocols for individual genotypes. The level of success in cutting propagation is negatively associated with ontogenetic age. Successful cutting propagation from tissues of young seedlings is reasonably successful, but success reduces rapidly in seedlings from 1 to 2 years. This can be managed by routine hedging of seedling stock, but successful routine cutting propagation from tissues of mature selected trees will be challenging.

Basic concepts of breeding strategy

A breeding strategy is a particular method of selection, combined with a particular way of mating the selected trees, which may be repeated over several generations. Effective breeding programs maintain four general types of population as described in Eldridge et al. (1993) and given diagrammatically in Figure 18.3.

According to Raymond (1991) a breeding strategy should ideally aim to:

1. assess the scope of variation within a species
2. acquire a wide range of potentially useful genotypes
3. generate genetic information about the species
4. develop the optimum breeding population from which the best possible propagules for commercial use can be produced at any time
5. maintain pedigree information
6. maintain genetic variation to ensure continuous and long-term improvement of the species.

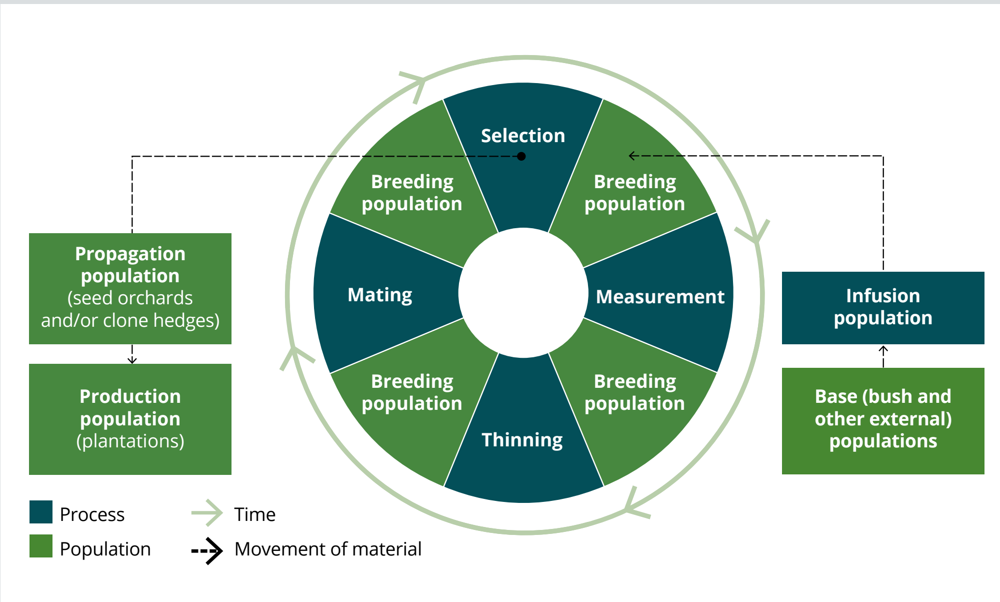


Figure 18.3 Typical breeding cycle where four general types of population – base, breeding, propagation and production – are maintained

Source: After Mazanec (2009)

Breeding programs and breeding base populations also play a critical genetic conservation role for many Oceanic tree species (Bush and Thomson 2018) and *S. austrocaledonicum* is no exception. Despite a conservation strategy for Vanuatu sandalwood involving the Vanuatu Department of Forests (VDoF) and prepared during SPRIG 1 (Corrigan et al. 2005), few of the recommendations of this report have been enacted apart from the advances in ex-situ conservation through gene banks and grafted seed orchards established as part of breeding activities since 2004.

To determine a feasible strategy for the proposed sandalwood improvement program within Vanuatu and with due consideration of the species' biological determinants, a practical assessment must be made of the available genetic resources, objectives of the program, and the limited resources available in terms of facilities, staff and budget within Vanuatu (VDoF and the private sector) to implement it.

Genetic resources available at the start of the breeding program in 2018

The genetic base for breeding *S. austrocaledonicum* available in 2018 is provided by selections made from more than 250 trees (families) from across the range of the species in Vanuatu sampled and selected during ACIAR project FST/2002/097. Selection of individual trees was based on the highest possible percentage of santalols in total oils. Those trees meeting, or approximating, the *S. album* standard (ISO 3518:2002(E) minimum levels: 41% for α-santalol and 16% for β-santalol) were given highest priority for grafting into a clonal archive and seed orchard at Tagabe, Efate, planted in May 2007 (see summary in Figure 18.4 and details in Appendix 1 and Appendix 2). The number of clones now available in the VDoF Tagabe clonal archive has been reduced from 42 that were captured in 2007 to 39 grafted families (see Appendix 2). Some of these families are in poor health currently (e.g. S46) or have proved difficult to propagate by grafting in the recent past. In the last ACIAR project (FST/2008/010) from December 2013 to August 2014, efforts were made to replicate the archive on seven islands (Ambae, Ambrym, Efate (Onesua), Epi, Malekula, Pentecost and Santo) and provide clonal seed orchards for local use. A grand total of 39 clones were established but only an average of 18 clones were planted on any one island. The plantings on four islands have been reasonably successful and seed has been obtained from some clones in as little as 4 to 14 months. Regrettably, survival has been low within the orchards on Ambae (0% in 2015), Epi (47% in 2015) and Santo (55% in 2015) due mainly to poor maintenance.

Estimates of the number of individuals required to maintain a diverse breeding population vary widely but 300 effective breeding individuals is generally regarded as the minimum to sustain an entire breeding program for several generations (e.g. Cotterill 1986). In this project we are starting off with 39 selections (clones) represented in grafted seed orchards (GSOs) on Efate (Figure 18.4 and Appendix 2), but one (S46) is in poor health and might not be able to be propagated, and three clones (Err04, Err57 and Mo04) are of dubious oil quality (i.e. low in percentage santalols). Three clones (S06, Err04 and Ayn19) are only represented in GSOs outside of Efate (i.e. on Ambrym, Epi and Malekula), with one of these (Err04) of dubious oil quality. These clones might be able to be propagated into the breeding population over time as VDoF staff visit these islands and bring back scions for grafting.

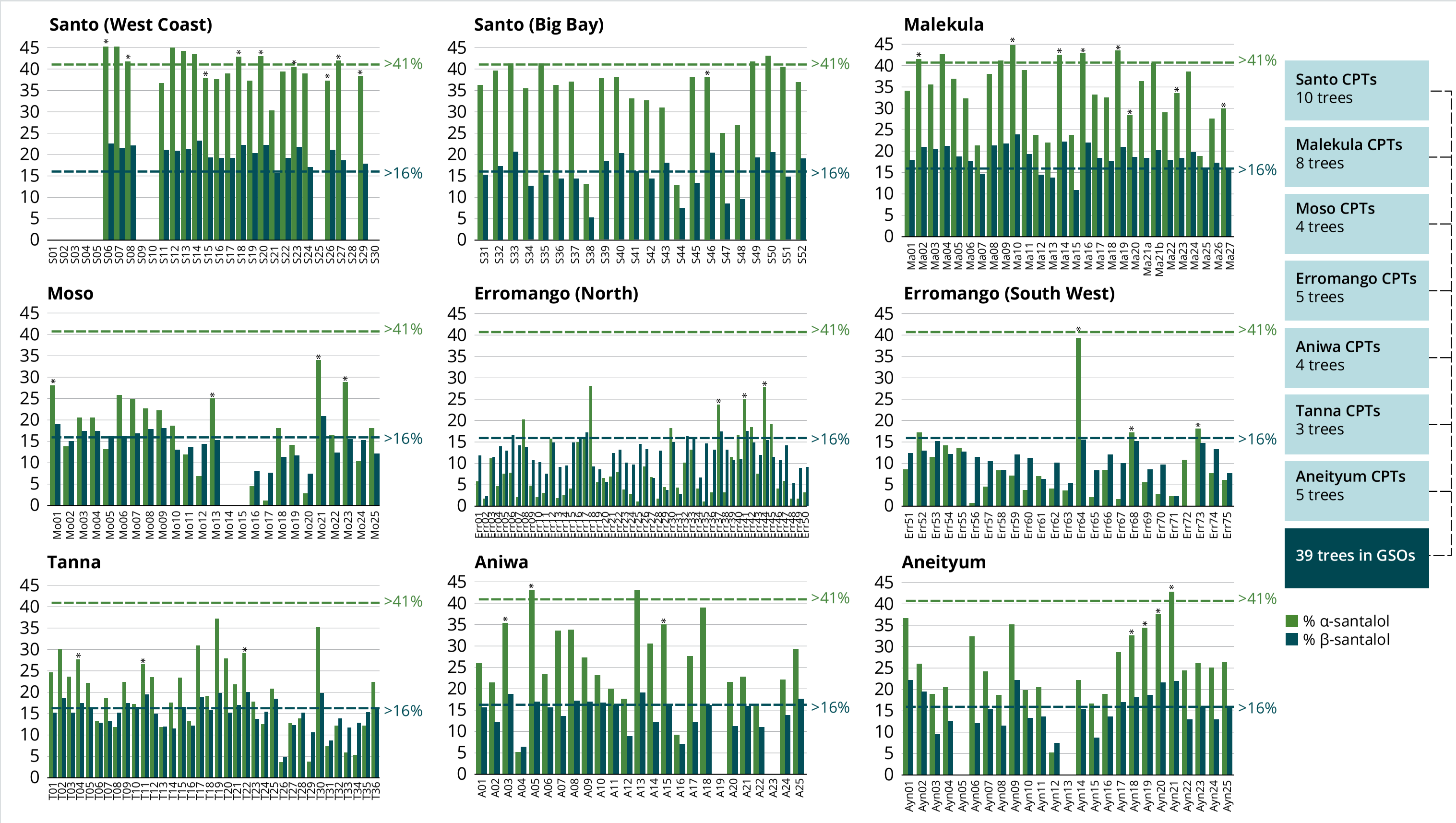


Figure 18.4 Graphs give percentage α-santalol and β-santalol in the heartwood of individual trees of *S. austrocaledonicum* by island populations (ordered from north to south) against the standard for *S. album* oil (ISO 3518:2002(E) minimum levels: 41% for α-santalol and 16% for β-santalol)

Note: Trees marked by * were trees originally selected for grafting into the clonal archive and seed orchard (GSO) at Tagabe, Efate. The clones available at Tagabe in 2018 total 39 clones (dark blue) and by island in the blue boxes. CTP = candidate plus trees.

The need for infusions

The presently available genetic base for breeding needs to be expanded as a matter of urgency.

A first step will be to assess the origins of the Summit Estate seed trees of Santo (six trees) and Erromango (seven trees) planted by Des Parkes in about 1998 and selected by Summit staff in 2015 after heartwood percentage was deemed favourable from cores taken at 15, 50 and 100 cm from ground level. Oil chemistry was not assessed, and this should be undertaken before the best of these trees can be considered as candidate plus trees (CPTs) and added to the breeding population.

Many young sandalwood plantations in Vanuatu, including the gene bank on Santo established during earlier projects, could also be surveyed for CPTs, which could very quickly expand the number of selected trees available for inclusion in a breeding program. Ideally, the origins of the plantations being surveyed for new CPTs should be known so as to avoid, or at least be able to cater for, relatedness among the selected trees. A method of ranking CPTs using a 'Candidate Plus Tree Assessment Record Sheet' (see Appendix 3 and Appendix 4) has been documented. This form, the methods described, and criteria set should be used for any new CPT selections.

Determining heartwood oil quality of candidate plus trees (CPTs) – Quantifying oil concentration and determining its chemical composition can only be undertaken in an appropriately equipped laboratory with the technology currently available. Solvent extraction followed by gas chromatography/mass spectrometry (GC/MS) is usually employed or, ideally, because it better replicates commercial extraction, extraction by steam distillation should be employed if the heartwood is available in larger quantities. These are time consuming and costly processes. Any core or biscuit samples taken for estimating the quantity of heartwood present in a tree should be stored for later study of oil concentration and composition when the opportunity arises.

In terms of ranking CPTs on oil quality, the industry seems to be equally divided on whether or not it is important either to aim to match or better the East Indian standard (*S. album*) for the santalols (ISO 3518:2002(E) minimum levels: 41% for α-santalol and 16% for β-santalol) or to ignore oil composition as a selection trait altogether (i.e. accepting the oil as it comes naturally from harvest). According to one industry source, there is a ready market internationally for *S. austrocaledonicum* 30–35% α-santalol oil, which falls in its own niche between *S. album* and *S. spicatum* (D Hettiarachchi, pers. comm., 2019).

Until more is known of market preferences, improving the average santalol content of total oil to the 30–35% range is considered to be a sound objective. This might be achieved by selection among the trees in the Tagabe clonal archive (Appendix 1) without significant erosion of the already narrow genetic base.

Baldovini et al. (2011) stress the importance of the santalols to the fragrance of *S. album* oil, which presumably extends to santalol-rich forms of *S. austrocaledonicum* oil. The odour of α-santalol is described as 'slightly woody reminiscent of cedarwood and α-cedrene' while β-santalol is given as 'more potent and responsible for the highly prized typical warm-woody, milky, musky, urinous animal aspects' of sandalwood. There are other compounds (e.g. nuciferol, α-bisabolol, bergamatol, lanceol, β-curcumin-12-ol and γ-curcumin-12-ol) that occur in modest proportions in the oil that most likely contribute to the unique odour of Vanuatu *S. austrocaledonicum* oil (D Hettiarachchi, pers. comm., 2019). However, little is known of their olfactory effect on the total oil so no recommendations can be made at this stage on their inclusion or exclusion in the selection process. Farnesol content, although typically at very low levels (<2%) in *S. austrocaledonicum* oils, is also worth monitoring in oil samples. Firstly, farnesol is a recognised allergen in cosmetics (Baldovini et al. 2011). Cosmetic regulations are based on the total farnesol level in final formulation; EC Regulation 1223/2009 and IFRA standards specify 0.001% as the limit for leave-on cosmetic products such as perfumes and creams. Here the sandalwood oil component of the cosmetic formula might only be 1%, so the oil of *S. austrocaledonicum* and other tropical sandalwoods should easily comply. It is, nevertheless, worth ensuring that farnesol levels are low. Secondly, higher than typical farnesol levels could indicate adulteration with other oils such as those from *S. spicatum* (D Hettiarachchi, pers. comm., 2019). This latter source has also noted an issue with *S. austrocaledonicum* oils turning dark with oxidation, which is a negative if an oil to be used as a fixative is to be stored for any length of time. The lower quality (santalol-poor, curcumin-12-ol-rich) oils are faster to turn dark than higher quality oils.

Breeding objective

To increase the yield of high-quality heartwood per unit area of sandalwood plantation by improving:

- growth rate
- tree form
- early onset of heartwood formation
- oil concentration
- chemical composition.

Selection traits and selection index

Selection traits are the traits that we measure on individuals in progeny trials, gene banks and in natural or planted stands. This information is used to rank individuals when selecting CPTs. The quantity of heartwood, concentration of oil in the heartwood and the levels of α-santalol and β-santalol in the distilled oil determine the market value of a tree. These characteristics are, therefore, key selection traits recommended for the sandalwood breeding program. Table 18.1 gives a summary of recommended selection traits.

The final selection of a CPT for breeding purposes may have to wait some 20 years until most trees have a good proportion (>60%) of heartwood. Preliminary selections can, however, be made among younger trees. We consider that heartwood initiation can start from a minimum of 5 to 10 years in *S. austrocaledonicum*, so screening for initial heartwood quality can be possible at about 10 years or when trees growing under good conditions have a basal diameter (measured at 20 cm above ground level) of more than 10 cm. This is, of course, speculation and research (i.e. longitudinal studies of trees of known provenance, age and growth rate and ideally across a range of sites) is much needed to determine the earliest one can reliably select CPTs for heartwood quality (amount and oil characteristics) in *S. austrocaledonicum*. In the meantime, tree diameter can be considered an indicator of heartwood content, as it is the most important direct measure in the field. Also of importance is tree form, as heartwood development concentrated in a single-stemmed trunk should enhance individual tree market value.

Table 18.1 Proposed selection traits for the *S. austrocaledonicum* improvement program

Selection criteria	Details
1. Tree size and health	Estimated from diameter (cm) at 20 cm and breast height (1.3 m). Record individual diameters when multistemmed. Crown and bole(s) healthy with no evidence of substantial insect attack or disease.
2. Stem form with focus on single stems	Scored 1 (multistemmed from near ground of poor form); 2 (multistemmed after short, crooked trunk); 3 (multistemmed after relatively long, crooked trunk); 4 (single, relatively long crooked stem with single leader); 5 (single, relatively long, straight stem with single leader).
3. Heartwood percentage	In the absence of a volumetric equation, we recommend taking a bark-to-bark core sample at 20 cm above ground. Select fast-growing trees with the maximum heartwood percentage (ideally ≥50%).
4. Oil concentration	Determined on core heartwood with oil extracted by solvent and concentration determined by GC/MS.
5. Oil quality	Determined on core heartwood with oil extracted by solvent and oil composition determined by GC/MS. The most critical components to be identified are the santalols (α- and β-santalol) ranked by their proximity to the East Indian standard (minimum 41% α- and 16% β-santalol).

In general, the greater the number of traits in the selection process, the smaller will be the improvement in any one of these traits. Five selection traits are a substantial number of traits for simultaneous selection, but each is presently deemed to be essential in increasing the volume of sandalwood heartwood per hectare and improving its value. Later, these selection criteria might be modified based on new information coming from the project trials recommended below.

A simple multi-trait selection index should be developed and applied to improve efficiency of individual tree selection in breeding project trials (see Cotterill and Dean 1990).

Resources to implement the plan

Tree breeding is a long-term activity. Selection of even a simple breeding strategy that is warranted here will require a substantial continuing commitment of VDoF and the private sector to provide ongoing physical, human and financial resources to the program.

The following resources are common to most tree breeding programs:

Physical

- Land – for progeny tests, seed orchards, breeding arboreta. A minimum of two replications (sites) of key plantings is to be recommended for security reasons.
- Nursery – for the secure raising of source identified and often valuable (irreplaceable) seedlots and grafts.
- Office – for the long-term storage of complex and accurate records, analysis of data, reports, etc. Computer facilities with basic tree breeding software is essential.
- Store/lab – an area for the secure storage of equipment, chemicals, seed and for processing of samples (e.g. heartwood core samples for oil determination, pollen drying and storage).

In this project it is envisaged that land for trials and orchards will be provided largely by private sector partners in the project, nurseries will be a shared responsibility between VDoF and the private sector and record-keeping and research activities will largely be the responsibility of VDoF.

Personnel

For a project of this type it is essential that a core of permanent, experienced people be developed and maintained in order to give the project continuity. Ideally, the breeding team will require the following members:

- Tree breeder – to manage the program. A person with existing skills in biometrics, or capacity to be trained in these skills.
- Tech support – to assist the tree breeder in activities such as raising plants, laying out of experiments, measuring and analysing trials.
- Labour – to maintain trials and seed orchards.

In this project, breeding advice will be provided as part of the ACIAR project with technical support provided by VDoF. Maintenance of trials and orchards will be the domain of the private sector.

Ideally, VDoF should be considering the long-term appointment of a qualified tree breeder to assist in the improvement of sandalwood and other indigenous and exotic tree species of importance to Vanuatu.

Funding

- Budget – an adequate budget is essential. It must be guaranteed and continuous because of the long-term nature of the work.

Importance of genetic gain trials

The justification for the sandalwood breeding project herein described is the genetic gain actually realised in improved plantations and the financial return on the investment in breeding. Yield trials with larger plots than progeny trials and a good statistical design, where the commercial-scale products of the breeding program are compared with well-defined controls (e.g. seedlots in commercial use before the breeding program commenced), are usually employed to give realistic estimates of genetic gain.

Breeding programs can seem like limitless and expensive activities. To counter this it is often very important to start early in demonstrating industry-wide the financial benefits of a breeding program. We have recommended an early start to this here with the establishment of trials comparing bulked seedlots from Tagabe and Onesua GSOs with seedlots used routinely by growers. Later, trials of this type should be established to quantify gains from the new GSOs established by this project.

Proposed breeding strategy for *S. austrocaledonicum* in Vanuatu

The strategy proposed can be described as 'recurrent selection with open pollination and maintenance of family identity'.

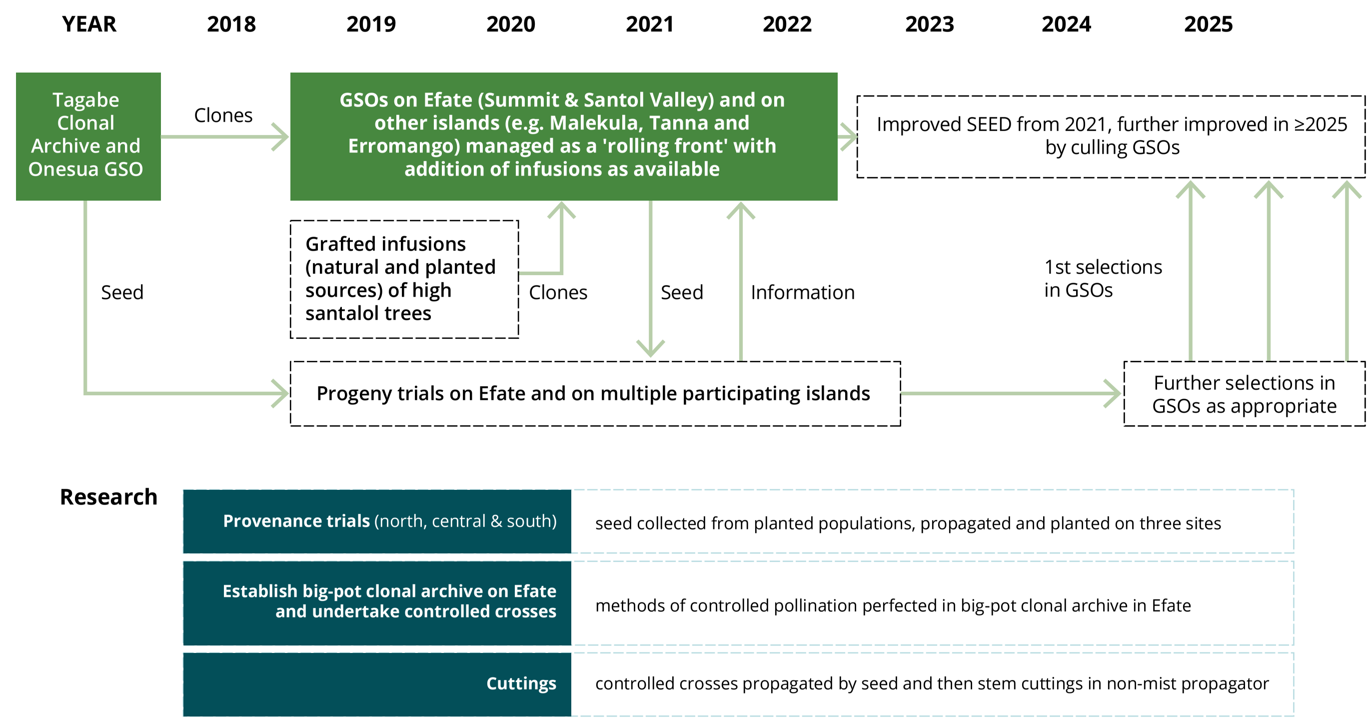
Outline of strategy with proposed timelines

The process is presented diagrammatically in Figure 18.5 and an indicative timetable by key activity is given in Table 18.2.

The first priority is conserving the selections already made and conserved in the Tagabe clonal archive and existing grafted seed orchards by their propagation as grafts and distribution to participating islands. Their genetic value will be assessed first in progeny trials in Efate and later on in participating islands and communities. The poorest performing families in these trials will be the basis for the culling of some clones from the breeding population.

The second priority is to add to the genetic base of established orchards by introducing new selections from plantations and the wild in a 'rolling front' strategy (as explained below) for each orchard. When these seed, their progeny will be tested in progeny trials on participating islands to assess their genetic worth.

A third priority is to undertake relevant research to address gaps in our knowledge base and produce a series of technical notes to improve knowledge development and transfer among stakeholders. Research proposed includes establishing provenance trials and perfecting means of controlled pollination and striking cuttings to advance the breeding program, while technical notes on grafting techniques, seed collection and wood grading are under development.



GSO = grafted seed orchard

Figure 18.5 Diagrammatic representation of the main activities for the first generation of breeding *S. austrocaledonicum* in Vanuatu and recommended research

Table 18.2 Proposed sandalwood breeding activities under this project by year

Year	Activities	Comments
2018–19	**GSOs** – plant one new GSO at Summit	Transfer by grafting as many of the Tagabe clones (39 clones) as possible. 21 clones available in Feb. 2019 from grafting in Sept. 2018
	GSOs – 'restore' GSOs at Onesua and Santo with full complement of currently available clones	Fill gaps with santalol-rich clones
	PTs – plant PT at Summit with seedlots from Onesua GSO	This trial of eight families was established in 2018 using a row/column design
	Infusions – selects from Summit plus trees	Cores from Summit plus trees tested for oil quality, graft at Tagabe and plant at Summit and Onesua
	Research • establish excess clones in big-pot archive at Tagabe nursery • start collection of seed for Prov trials as opportunities arise	Clones in big pots to be resource for developing practical controlled cross methods
	Market intelligence – study market preference for oil quality of wood put up for tender	Work with VISA, VDoF and wood buyers to ascertain the most desirable oil quality
2020–21	**GSOs** – plant two new GSOs with VISA-approved associations	Focused on clones of most desirable oil quality. These to be 'rolling front' GSOs to allow infusions (newly selected clones) to be included as they are selected on optimum oil quality
	Seed collections, PTs and Prov trials – continue to plant PTs of Tagabe clones. Collect seed for Prov trials and GGTs	Collect seed for PTs from Onesua and Tagabe and for Prov trials from Santo Gene Bank and Malekula. GG seedlots to include improved seed vs routine lots
	Infusions – graft CPTs from at least two VISA-approved associations marketing wood in 2020	Plant at Onesua, in big pots at Tagabe and in the two 2020 GSOs
2022+	**GSOs, PTs and infusions** – follow similar strategy to 2020–21	
	Prov trials – plant three Prov trials using the seed collected in 2018–21	Plant in the north, central and south of Vanuatu
	Genetic gain trials – plant three GGTs using seed collected in 2020–21	Plant in the north, central and south of Vanuatu
Future years	**GSOs and infusions** – continue the strategy as required to other islands and participants	
	PTs – as new GSOs seed, plant PTs. These PTs are essential to allow backwards selection in the GSOs and forwards selection into new GSOs	Note: Advance generation breeding populations will require approximately 100 offspring per parent (Cotterill 1986) to generate useful selection intensities, for example 35 offspring on each of three different sites

CAs = clonal archives; GGTs = genetic gain trials; GSOs = grafted seed orchards; Prov = provenance; PTs = progeny trials; VDoF = Vanuatu Department of Forests; VISA = Vanuatu Islands Sandalwood Association

Risks to the successful implementation of this strategy include failure of grafts, loss of seed orchards due to lack of maintenance and cyclonic winds, lack of information among growers on seed production and handling, and seed distribution.

The project's responses to these risks are:

- Techniques of grafting are generally well understood by VDoF staff, who regularly achieve a >80% success rate, so failure of grafts is unlikely.
- Only growers of proven track record in growing and maintaining sandalwood plantings and who are associated with grower groups, and other organisations responsible for the equitable distribution of the improved seed produced, will be chosen to host each orchard, thus mitigating the risk of poor maintenance of orchards and ensuring equitable distribution of improved seed.
- Most of the previously established orchards survived Severe Tropical Cyclone Pam so the orchards have proven robust against cyclonic winds.
- To fill the information gaps among growers, a series of technical notes covering seed handling, grafting and other silvicultural matters together with hands-on training will be provided.

A 'rolling front' strategy is when there is no distinction made between generations. This means that grafted clonal progeny selections and new infusions (grafted clones) will be added to the existing complement of grafted clones in the GSOs as they are selected to broaden an otherwise narrow genetic base. Progeny testing will be carried out as seedlots become available from a GSO rather than waiting for all seedlots to be available, as in discrete generations. Progeny trials will need to have sufficient linkage (say five common seedlots) to enable efficient comparisons and ranking across trials. The five common seedlots proposed come from five selected clones in the Onesua GSO. The problem here is the males involved each year could be variable and present variable outcomes of breeding values, which may influence overall rankings. A solution could be to use seed from the same five selected clones growing in the big-pot clonal archive, which were controlled crossed with a single male. These crosses would need to be done annually to ensure fresh seed is always available for the next progeny test of new selections.

All trees in a GSO will be compared using individual tree best linear unbiased prediction (BLUP) of the growth and heartwood development of their progeny in common garden trials. As each trial is measured, breeding values will be updated and GSOs can be culled based on backwards selection, and new selections in each progeny trial (forward selection) can be made to provide material for the next generation of GSOs.

Estimated seed production from existing and new GSOs

There were six (Efate [Tagabe and Onesua], Santo, Pentecost, Ambrym and Epi) functioning GSOs at the start of this project established under earlier ACIAR projects. Apart from Tagabe, which is much older, the others are 5 years old and we know some (e.g. Onesua, Santo and Pentecost) are seed cropping well. The establishment of a minimum of four new GSOs is planned under this project on islands where growers are actively cultivating sandalwood, such as on Malekula and Tanna.

In gaining an estimate of annual seed production from these improved seed sources, we can use Onesua GSO as an example. Thirty-six (18 clones in two replicates) grafts were established in March 2014 with 24 (67%) surviving in April 2018. Eighteen of the 24 had abundant bud crops in April 2018, and it is not unreasonable to predict a crop average of 1,000 mature seeds (ca. 280 g) per tree of 85% germination rate. This gives an estimated orchard production of 15,300 viable seeds each main cropping season with more available from the secondary flowering season. This readily meets the predicted countrywide requirement of 15,000 improved seeds annually over the next 20 years (see estimated seed requirements in the 'Germplasm delivery pathways' section of this report).

The key consideration of this project, of course, is not so much the amount of improved seed produced but its production where it is needed in sandalwood planting areas and with whom the orchards are placed to give maximum benefit to smallholder farmers.

Likely genetic gains from this strategy

If it can be demonstrated that heartwood essential oil characteristics (oil concentration, high proportions of the santalols, etc.) are under moderate to high additive genetic control, then 50–60% or more of the variation seen for a trait in a population can be captured in individuals following selection. It follows that by employing a modest intensity of selection (say 1 in 10) for heartwood oil concentration, progeny can be expected to out-yield the group of parents from which they were derived by approximately 25–35%. There will be gains also in a more consistent oil composition of higher quality. Further yield gains can be expected in other traits, such as growth rate and form, that are under low to moderate additive genetic control, of approximately 10%, assuming genetic correlations between traits are neutral. Gains of this magnitude might be achieved for at least a few generations of breeding before the roadblock of declining variation presents itself.

Genetic gain trials will be required to quantify the actual gains achieved by the program.

Research needs

Despite all the work that has gone before over two ACIAR projects, designing this breeding strategy faced many constraints because of gaps in knowledge. Much of the work outlined above will address these knowledge gaps and could mean future adjustments to the strategy based on new information.

The knowledge gaps that will eventually be closed by this strategy are:

- Knowledge of the optimum provenance(s) for planting in each region for fast growth and the most desirable oil quality, provided by a series of provenance trials.
- Information on genetic parameters (heritabilities and genetic correlations) of key commercial traits to inform design of the optimum breeding strategy for this species, provided by multiple progeny trials in key production areas.
- A substantial broadening of the genetic base available through a program of intensive screening to identify infusion candidates and their propagation and planting in GSOs. These GSOs to be managed as a 'rolling front' (new selections added as older selections are culled on PT performance).
- Market intelligence to inform the breeding program of the most desirable oil quality to aim for in selecting candidates for inclusion in GSOs.
- Quantifying genetic gain through establishment of GGTs to inform the breeding program on the economic advances achieved by the program.
- Recent work under ACIAR project FST/2016/054 on early inducement of heartwood formation in *S. austrocaledonicum* is an associated research activity that could have a major influence on selection criteria for CPTs and commercial rotation lengths.

Regular review of the breeding strategy is recommended to allow for changes in direction or emphasis as a consequence of the research outlined above.

Other research to be considered

- Controlled crossing of best × best CPTs – Best × best CPTs crosses should be tried as a means of increasing genetic gain. CPTs planted in the big-pot clonal archive on Efate will provide a resource suitable for this activity. Protocols for carrying out controlled crossing in *S. austrocaledonicum* are available and could be the subject of a technical note prepared by the project.
- Development of practical techniques for induction/promotion of heartwood following on from the FST/2016/054 study briefly described above – The amount and composition of heartwood oil produced within each sandalwood tree determines its economic value. Promotion or acceleration of heartwood oil production may be possible through silvicultural management and/or treatments. Such techniques can reduce time to harvest and increase the economic value of sandalwood from Vanuatu.
- Clonal propagation using a non-mist propagator – Reintroduce the non-mist propagator for clonal propagation of progeny from controlled cross seedlots. Rooted cuttings can then be established in experiments across a range of sites for various studies that would benefit from the use of clones, for example, the extent of genotype × environment interaction in *S. austrocaledonicum*. A technical note covering the use of the non-mist propagator is warranted prior to its deployment.
- Development of molecular genetic tools for improving sandalwood oil quality – This is a field of research that seeks to provide DNA markers to allow the early screening of trees for high santalol oil production rather than wait the decades necessary for heartwood to form naturally. Because of its potential advantage in allowing early selection of a key commercial trait (high santalol heartwood oils) and the flow-on effects to rate-of-gain from breeding, it deserves mention here, although it is very much speculative at this point in time. It should also be noted that research in this field is specialised, expensive and comes with a high level of risk.
- The *S. album* genome has been mapped recently (Mahesh et al. 2018) and, while there is still much work to be done in locating and characterising the genes involved in formation of the santalols in this species, this and other work (e.g. Celedon et al. 2016) has provided the backdrop to facilitate this work. Obviously, this research should focus first on *S. album* but, based on the likely scenario that the same genes are common to most species in the genus, the molecular markers developed for *S. album* should be able to be applied to *S. austrocaledonicum* and other sandalwoods.

Germplasm delivery pathways

The level of impact from sandalwood domestication will be influenced by the scale of deploying improved germplasm to growers. The successful diffusion of better adapted and genetically improved germplasm depends on several factors. These are the ready availability and grower access to improved germplasm, and its rate of adoption and use.

This project is predicated on a significant engagement with private sector (e.g. Summit Estate Ltd and others) and community partners. These partners will ultimately host new seed orchards and breeding trials and distribute the germplasm among their outgrower/ smallholder growers. Vanuatu Islands Sandalwood Association (VISA), the recently formed (March 2018) peak body for industry participants throughout the country, will be a key organisation in determining where (which islands) and with whom (which growers) the orchards and trials will be established and what arrangements will be in place to ensure an equitable distribution of the seed produced.

Distribution of improved sandalwood seed through industry networks is expected to contribute to the total planted resource of 1 million trees (of better genetic quality) over the next 20 years (S Bartrop, pers. comm., 2016). This assumes 1,000 households planting 50 trees (50,000 total) annually over a 20-year period. The modelling of economic impact (see below) is based on 30% of these trees being from improved sources. This would require germplasm resources from seed orchards to support the production of at least 15,000 improved seedlings annually.

The economic benefits from this project were estimated in the project proposal (Page et al. 2016) where it was assumed that the higher quality trees will attract a price premium at both farm gate and at export. In 2016 the farm gate ('on the beach') pricing structure in Vanuatu was VUV4,000 (USD36), VUV3,000 (USD27) and VUV2,000 (USD18) for first, second and third grade, respectively (VDoF 2016). Grading is often subjective and based on heartwood size, oil concentration and quality and form (i.e. whether they meet carving log specifications). First grade heartwood is often found in older (>25 years) wild trees. Suboptimally managed (the norm in Vanuatu) planted trees with a rotation of 15–20 years would generally be of lower quality compared with old growth wild trees. Through generalised modelling of the benefits associated with improved sandalwood, it can be expected that at least 10% will be first, 70% will be second and 20% will be third grade. For unimproved stock it is expected to be closer to 5% first, 30% second and 65% third grade for planted trees. This is combined with an expected minimum 10% increase in heartwood yield for improved stock (18 kg/tree for unimproved and 20 kg/tree for improved stock).

The modelled smallholder sandalwood system (Table 18.3) assumes a planting density of 400 stems/ha (final stocking rate) across 1,000 households equating to an overall annual production of 900–1,000 t. Based on these assumptions the net present value (NPV) of the investment in participatory deployment of improved germplasm is approximately USD4.3 million. There are compelling economic reasons, therefore, for use of improved seed, so grower adoption and enthusiastic use of the seed from project seed orchards is anticipated.

Table 18.3 Financial projections from the planting of improved sandalwood from deployment of germplasm resources through industry networks

Sandalwood genetics			**Improved**	**Unimproved**
Planting system			Sandalwood as a part of the garden fallow system on a 20-year rotation. Equal annual planting rate. Plant to final stocking with refilling as required.	Sandalwood as a part of the garden fallow system on a 20-year rotation. Equal annual planting rate. Plant to final stocking with refilling as required.
Participation	Potential number of adopting households[1]		1,000	1,000
	Annual household planting	ha/year	0.13	0.13
	Total household area after sequential planting	ha	2.50	2.50
	Combined smallholder estate area	ha	2,500	2,500
	Smallholder estate trees	trees	1,000,000	1,000,000
Production	Product sold		Heartwood	Heartwood
	Units of production		(kg)	(kg)
	Annual growth rate	Units ha/year	400	360
	Volume	Units/smallholder plot at harvest	1,000	900
	Mean product tree size at harvest[2]	Units/tree at harvest	20.0	18.0
	Annual wood flow from smallholder estate	Units/year	1,000,000	900,000
Gross smallholder returns	Unit price at farm gate[3]	USD/unit	USD26	USD22
	Household farm gate returns at harvest	USD/household	USD26,364	USD19,636

Table 18.3 Financial projections from the planting of improved sandalwood from deployment of germplasm resources through industry networks *(continued)*

Sandalwood genetics			Improved	Unimproved
National GDP contribution	Export price FOB[4]	USD/unit	USD60	USD50
	Household GDP contribution at harvest	USD/household	USD60,000	USD45,000
Present value of gross project returns over 20 years	Gross present value smallholder returns discounted at 10% real	USD/household	USD25,066	USD18,670
		USD/total estate	USD25,065,995	USD18,669,844
	Gross present value smallholder GDP contribution discounted at 10% real	USD/household	USD57,047	USD42,785
		USD/total estate	USD57,046,747	USD42,785,060
Economic impact of improved sandalwood		30% estate	USD4,278,506	

FOB = free on board; GDP = gross domestic product

1 Estimates of number of potential adopters based on projected joint venture arrangements with Summit Estate.
2 Conservative estimates of heartwood yield for *S. austrocaledonicum* in Vanuatu (Page et al. 2012a) at age 15–20 years.
3 Based on official prices for sandalwood paid to landowners as set by Vanuatu Department of Forests in 2016 (converted to USD at 2016 exchange rate). The average price was set based on expected proportion of trees meeting first, second and third grades.
4 Based on estimated current FOB market values for high-quality sandalwood heartwood (Wescorp Sandalwood).

Source: Page et al. (2016)

Acknowledgements

This chapter was published in modified form in Page T, Doran J, Tungon J and Tabi M (2020) 'Restoration of Vanuatu sandalwood (*Santalum austrocaledonicum*) through participatory domestication', *Australian Forestry*, 83(4):216–226.

The authors recognise the valuable support and contributions of VDoF management and technical staff including Rexon Viranamangga, Godfrey Bome, Michael Tabi, Mesek Sethy, Toufau Kalsakau, Sammy Kaku, James Samuel, Taura Titus, Dick Tomker, Ioan Viji, Anne Marie Sarisets, Judy Kalotap, James Samuel, Presley Dovo, Job Havo, Daniel Leyang, Samuel Bebe, Simon Naupa and Sam Iakar.

The authors wish to thank David Spencer and Dr David Bush of CSIRO and Dr Lex Thomson of University of the Sunshine Coast for their reviews of this document and the helpful comments provided. The assistance of Danny Hettiarachchi in drafting the section on oil quality, Antoine Kalinganire in sourcing Figure 18.1 and Paul Macdonell for providing Figure 18.2 is gratefully acknowledged.

Appendixes to Paper 18

Appendix 1

Table 18.A1 Oil characteristics (oil concentration and composition of major components) of selected trees from seven islands in Vanuatu. These trees are represented in GSOs

Tree no.	Oil conc. mg/g	%								
		Oil conc.	alpha sant.	beta sant.	nuc	cur	lanceol	e-b-s	e-a-b
Santo									
S06*	13.4	1.3	45	22.6	0.7	2.4			
S08	45.3	4.5	41.6	21.9	1	4			
S15	27.5	2.7	37.8	19.2	7	5.4			
S18	41.2	4.1	42.7	22.2	2.9	3.4			
S20	80	8	42.9	22.2	2.1	4.3			
S23	32.1	3.2	40.4	21.7	3	4.8			
S26	42.7	4.3	37.1	21.1	2.7	7.1			
S27	6.5	0.6	41.9	18.6	4	3			
S29	9.4	0.9	38.2	17.8	8	4.4			
S46**	16.5	1.6	38.4	20.5	5.8	5.9			
Malekula									
Ma02	21.2	2.1	41.8	21.1	1.4	3.4			
Ma10	71.9	7.2	47	24.1	0	1.4			
Ma14	43.1	4.3	42.8	22.3	1	2.5			
Ma16	72.8	7.3	43.2	22.2	0.8	3			
Ma19	42.1	4.2	43.8	21.2	0.8	1.4			
Ma20	50.2	5	28.6	18.8	3.3	17.8			
Ma23	36.9	3.7	33.9	18.6	6.1	9.4			
Ma27	25.2	2.5	30.3	15.9	9.9	12.9			
Moso									
Mo01	34.6	3.5	28.2	19.1	6.8	13.5			
Mo02***	11	1.1	13.9	15.1	12.7	25			
Mo13	6.5	0.6	25.1	15.5	11.6	15.1			
Mo21	52.7	5.3	34.2	21	3.8	9.6			
Mo23	17.7	1.8	29	15.5	8.2	12.2			

Table 18.A1 Oil characteristics (oil concentration and composition of major components) of selected trees from seven islands in Vanuatu. These trees are represented in GSOs *(continued)*

Tree no.	Oil conc. mg/g	%							
		Oil conc.	alpha sant.	beta sant.	nuc	cur	lanceol	e-b-s	e-a-b
Erromango									
ERR04***	41.1	4.1	4.6	14.1	15.7	33			
ERR37	13.9	1.4	23.8	17.3	9.7	16.6			
ERR41	34.4	3.4	24.9	17.5	8.9	15.1			
ERR44	18.2	1.8	27.9	15.4	19.6	7.3			
ERR57***	27.5	2.7	4.7	10.6	8.8	50.1			
ERR68	36.8	3.7	17.3	15.4	17	19.4			
ERR73	17.9	1.8	18.4	15	15.3	23			
Aniwa									
ANI01	21	2.1	26.1	15.7	8.4	19.9			
ANI03	17.9	1.8	35.6	18.8	8.3	4.4			
ANI05	0.6	0.1	43.3	17	0	0			
ANI15	9.9	1	35.1	16.1	10.1	6.9			
Tanna									
T04	11.7	1.2	27.7	17.2	8.4	14.2			
T11	28.1	2.8	26.5	19.4	8.2	11.4			
T22	17.8	1.8	29.1	19.9	6.9	12			
Aneityum									
AYN09	18.8	1.9	35.3	22.1	3.8	3.5	0.96	0	0.5
AYN18	12.8	1.3	32.6	18	7.6	12.6	1.13	0.39	0.91
AYN19*	6	0.6	34.5	18.6	9.4	5	2.3	0.62	0
AYN20	18.6	1.9	37.6	31.5	3.8	4.3	2.1	0.51	0.65
AYN21	7.97	0.8	42.8	21.8	6.8	2.5	0	0.52	0

alpha sant. = alpha-santalol; beta sant. = beta-santalol; nuc = *Z*-nuciferol; cur = (*Z*)-curcumen-12-ol; e-b-s = e-b-santalene; e-a-b = e-a-bisabolol

* = not available on Efate; ** = in poor health, excluded from grafting; *** = low in alpha-santalol

Appendix 2

Table 18.A2 Origins of the clones in the Tagabe clonal archive and of the 39 clones propagated in 2013–14 for the GSOs on seven islands established during project ACIAR FST/2008/010. The GSO on Ambae failed and is not recorded here

Clone	GSO location							Total
	Efate (Tagabe)	Efate (Onesua)	Ambrym	Epi	Malekula	Pentecost	Santo	
ANI03	1	2		2	2		1	**8**
ANI05	3		2	2	2	2	1	**12**
ANI15	3	2						**5**
ANI18	1		2			2	3	**8**
AYN09	1		2	2	2	2	2	**11**
AYN18		2		2	2			**6**
AYN19				1	2			**3**
AYN20	2	2	2	1		2	2	**11**
AYN21	4	2	2			2	2	**12**
ERR04			2	2		2	1	**7**
ERR37	2	2		2	2	2	1	**11**
ERR41	1		2				1	**4**
ERR44	1	2			2	1		**6**
ERR68	2		2	2				**6**
ERR73	1	2			2			**5**
MA02	2			2		2	2	**8**
MA10	3	2	1		2		1	**9**
MA14	2	2		2	2	3	1	**12**
MA16	2		2	2	2			**8**
MA19		2				2		**4**
MA20	1							**1**
MA23	3		2					**5**
MA27	1	2					1	**4**
MO01	3				2	2	2	**9**
MO02	1	2						**3**
MO13	2	2		2	2	2	1	**11**
MO21	2		2	2			1	**7**

Table 18.A2 Origins of the clones in the Tagabe clonal archive and of the 39 clones propagated in 2013–14 for the GSOs on seven islands established during project ACIAR FST/2008/010. The GSO on Ambae failed and is not recorded here *(continued)*

Clone	GSO location							Total
	Efate (Tagabe)	Efate (Onesua)	Ambrym	Epi	Malekula	Pentecost	Santo	
MO23	3		2					5
S06					2			2
S08	1	1	2	2		2	1	9
S15	2		2					4
S18	1	2				2	1	6
S20	2							2
S23	1	2						3
S26	4	2		2				8
S27	2		2	2	2	2		10
S29	1				2			3
S46	1 no scions							0
T04	2	2	2	2	2		1	11
T11	2		2	2	1	2	3	12
T22	1	2			1	2	1	7

Appendix 3

Table 18.A3 Candidate Plus Tree (CPT) Assessment Sheet

Appendix 3 Candidate Plus Tree (CPT) Assessment Sheet

In the field: focus on vigorous, healthy trees that have a high heartwood % for their age. Oil characteristics will be added to the selection process once lab tests have been carried out.
For plantations: the 4 check trees to be measured are the four closest to the CPT.
For natural stands: a comparison with check trees is unworkable since there will be age differences between trees and, likely with sandalwood, large distances between individual trees. CPTs in natural stands are to be assessed on their own merit and appearance. Selection will rely on the personal judgement of the assessor based on experience.

CPT number: **Location:**

Provenance (if known): **Date planted:** **Date assessed:**

Latitude (°S) **Longitude (°E)** **Altitude (m)**

TRAIT	CHECK TREES (CTs)					AVERAGE	CPT DATA	% > CTs
	1	2	3	4				
Diameter (cm) at 20 cm								
Diameter (cm) at breast height (1.3 m)								
Form (scored 1 to 5)								
Height (m)								
Canopy spread (m)								
Heartwood depth (mm)								
Sapwood depth (mm)								
Heartwood %								
Heartwood oil yield W/W%								
Heartwood oil quality								
% alpha santalol								
% beta santalol								

Comments: Include health of crown/suitability for scion collection; presence of flowering/seeding; record photo number

Appendix 4

Description of characters to be assessed in selecting CPTs

Diameter (cm) at 20 cm (basal diameter): Measured with a diameter tape or calipers. A CPT needs to have a basal diameter substantially greater than the check trees.

Diameter (cm) at breast height (1.3 m): Measured with a diameter tape or calipers. A CPT needs to have a diameter breast height over bark substantially greater than the check trees.

Form: Scored 1 to 5

- 5 – single, relatively long, straight stem with single leader
- 4 – single, relatively long, crooked stem with single leader
- 3 – multistemmed after relatively long, crooked trunk
- 2 – multistemmed after short, crooked trunk
- 1 – multistemmed from near ground, of poor form

Generally, trees with short boles (<30% of total tree height) are to be avoided.

Height (m): Measure the total height of the tree, preferably with height sticks.

Canopy spread (m): Average of the longest and shortest crown dimensions recorded using measuring tape.

The following to be determined on 5 mm bark-to-bark core taken at 20 cm height above ground:

Heartwood diameter (mm): measure to nearest millimetre with ruler or calipers = A.

Sapwood depth (mm): measure to nearest millimetre with ruler or calipers; average the two readings = B.

Heartwood %: A ÷ (A + B) × 100. Trees with ≥50% heartwood percentage the focus for selection.

The following to be determined in the laboratory from cores provided from the field:

Heartwood oil yield % w/w, FW (weight/weight, fresh weight): determined by solvent extraction and GC/MS analysis.

% α-santalol: percentage of total oils determined by solvent extraction and GC/MS analysis.

% β-santalol: percentage of total oils determined by solvent extraction and GC/MS analysis.

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Technical papers: Biochemistry and biology

19 Chemical composition of sandalwood (*S. album*) oil grown in Watusipat, Yogyakarta

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Abstract

The quality of sandalwood (*Santalum album* Linn.) oil depends primarily on the content of two major sesquiterpenes: α-santalol and β-santalol. The aim of this research was to identify the chemical composition of 13-year-old *S. album* planted at Watusipat, Yogyakarta, Indonesia. Five samples of *S. album* wood powder were obtained by drilling trees at 10 cm above the ground and were compared to a commercial sandalwood oil sample from a supplier in East Nusa Tenggara. The powder samples were extracted with *n*-hexane solvent. Identification of chemical compositions of these essential oils was conducted by gas chromatography/mass spectrometry analysis (GC/MS). The GC/MS investigation of *S. album* oils identified 26 compounds. Most of the chemical compositions belong to sesquiterpenes (15), monoterpenes (4), and others (7). The results showed the major compound of each sample, described as follows: sample 1 consisted of α-santalol (78.29%) and β-santalol (21.72%); sample 2 consisted of α-santalol (32.38%), β-santalol (22.08%) and α-sinensal (9.39%); sample 3 consisted of α-santalol (63.79%) and β-santalol (35.89%); sample 4 consisted of α-santalol (38.87%), β-santalol (37.83%) and α-sinensal (9.36%); sample 5 consisted of α-santalol (49.378%), β-santalol (18.37%) and p-menth-2-en-9-ol-trans (12.57%); and the sandalwood oil sample consisted of α-santalol (68.92%) and epi-β-santalol (8.16%).

Introduction

Santalum album Linn. or sandalwood, belonging to the Santalaceae family, is a precious commodity around the world (Fox 2000). The economic value is determined by its heartwood, which produces essential oil (i.e. sandalwood oil). Sandalwood oil is obtained by a steam distillation process of the heartwood and roots of sandalwood trees. Sandalwood oil is used for cosmetics, perfume ingredients, aromatherapy and medicine for several diseases (Kumar et al. 2012). It is also used as a tonic for the heart, stomach, liver, fevers and memory improvement, and as an antipoison and blood purifier (Rakesh et al. 2010). Sandalwood powder is used for incense and the wood for furniture and handicrafts.

S. album is distributed naturally throughout China, India, Indonesia (IUCN 1998) and Australia (Doran and Brophy 2005). Sandalwood trees are able to adapt to cooler climates with moderate rainfall, plenty of sunshine and long dry seasons (Das and Kuntal 2016). Sandalwood resources are reported to be decreasing, while global demand is increasing (Gillieson et al. 2008). In Indonesia, the species is primarily found in the islands of East Nusa Tenggara (ENT) Province (Rimbawanto and Masripatin 2005), where it occurs in small populations of several trees. These populations of sandalwood trees have declined because of overexploitation, grazing and limited replanting.

Some studies on the age of trees, their oil content, and the biosynthesis and chemical composition of sandalwood oil have been undertaken. Xiaojin et al. (2011) reported that 6-year-old sandalwood trees from Guangdong, South China, contain α-santalol, β-santalol, α-trans-bergamotenol, cis-lanceol and bicyclogermacrene. Bisht and Hemanthraj (2014) found that a 15-year-old sandalwood tree from India contained α-santalol, β-santalol, epi-β-santalalol, epi-β-santalene, α-santalene, β-santalene and α-bergamotol. In different locations, Subasinghe et al. (2013) reported that 15-year-old sandalwood trees from Sri Lanka contained trans-bergamotol, α-santalol, epi-α-bisabalol, epi-β-santalalol, β-santalol, (E,E)-farnesol, nuciferol, γ-curcumen-12-ol, β-curcumen-12-ol and lanceol.

The value of a sandalwood tree is determined by the mass of its heartwood and the concentration and quality of the oil contained within (Brand et al. 2012; Subasinghe et al. 2013). The quality of sandalwood oil is influenced by tree age and the location where it grew (Shankarnarayana and Kamala 1989; Rohadi et al. 2000; Lex 2006; Brand et al. 2007; Subasinghe et al. 2013). The objective of the present study was to identify the chemical compositions of sandalwood oil produced from trees planted in Watusipat, Yogyakarta, and a sandalwood oil sample from ENT.

Materials

Five samples of 13-year-old sandalwood trees were collected from the Sandalwood Ex-Situ Conservation Plot established by the Forest Research Centre for Forest Biotechnology and Tree Improvement Research at Watusipat, Gunungkidul, Yogyakarta, Indonesia (7°54‘07.0‘‘S 110°33‘28.4‘‘E). The description of the location is as follows: climate type C; rainfall 1,894 mm/year; wet season from October to March. The topography is flat-wavy with slopes of between 5 and 50%. Soil types are black grumosol, marl and volcanic tuff with low fertility rates, and the altitude ±150 m above sea level (Balai Besar Penelitian Bioteknologi dan Pemuliaan Tanaman Hutan 2013). The sandalwood powder collection and oil extraction followed the process explained by Bisht and Hemanthraj (2014), with some modifications. Wood of *S. album* was obtained by horizontally drilling the trees at 10 cm above the ground. Bark-to-bark cores were taken from each tree. The holes were filled with wax to prevent fungal and bacterial infection. To extract its oil, 3 g of the *S. album* wood was ground, dried, and 6 mL *n*-hexane solvent was added. The samples were centrifuged using a vortex (for 1 minute; every 3 hours × three times), then filtered. Nitrogen gas was added to evaporate the solvent so the oil remained. The sandalwood oil used as the comparison sample was obtained from a commercial supplier in ENT.

Chemical analysis

Chemical analysis was conducted by gas chromatography/mass spectrometry (GC/MS) (Howes et al. 2004). Gas chromatography (GC-2010) was coupled to a QP5050A mass spectrometer (Shimadzu Co. Ltd, Kyoto, Japan) using a fused-silica capillary column TC-1701 (0.25 mm i.d. × 15 m, 0.25 μm film thickness; GL Sciences). The GC-2010 was performed using the following conditions: column oven temp 70 °C; injection temperature 300 °C splitless mode; pressure 13.7 kPa; total flow 37.5 mL/mL; linear velocity 25.9 cm/s; purge flow 3.0 mL/minute and split ratio 68. The GC-MS-QP2010 was performed using the following conditions: ion source temperature 250 °C; interface temperature 300 °C; solvent cut time 3.5 minutes; detector gain 1.4 kV Absolute mode.
A mass spectrometry table was performed using the following conditions: start time 3.6 minutes; end time 60 minutes; mode AQC Scan; event time 0.50 s; scan speed 1,250; start m/z 28 and end m/z 600.
The chemical compounds were based on the National Institute of Standards and Technology (NIST) or WILEY database libraries. Quantitative data were determined by percentage peak area relative to the total peak areas from all compounds and was determined and reported as the relative amount of that compound.

Results and discussion

The results of the GC/MS analyses of six samples are summarised in Table 19.1. Twenty-six (26) compounds were identified in the sandalwood oil samples. Most of the chemical compositions belonged to sesquiterpenes (15), monoterpenes (4), and others (7). Sesquiterpene composition is the dominant composition in sandalwood oils (Srivastava et al. 2015). Sesquiterpenes are formed through cyclisation of farnesyl diphosphate and catalysed by metal-dependent terpene cyclases (Srivastava et al. 2015). Results showed the major compounds for each sample were: sample 1 consisted of α-santalol (78.29%) and β-santalol (21.72%); sample 2 consisted of α-santalol (32.38%), β-santalol (22.08%) and α-sinensal (9.39%); sample 3 consisted of α-santalol (63.79%) and β-santalol (35.89%); sample 4 consisted of α-santalol (38.87%), β-santalol (37.83%), α-sinensal (9.36%) and α-curcumene (9.92%); sample 5 consisted of α-santalol (49.378%), β-santalol (18.37%) and p-menth-2-en-9-ol-trans (12.57%); and sample 6 (the comparison oil) consisted of α-santalol (68.92%) and epi-β-santalol (8.16%).

Variations in the chemical compositions on each sample were found: sample 1 (2 compounds), sample 2 (10 compounds), sample 3 (3 compounds), sample 4 (9 compounds), sample 5 (9 compounds) and sample 6 (14 compounds). The variation in chemical compositions was considered to be due to tree nutritional status, variety, genetic background and a host of other internal and external cues and factors (Misra et al. 2013). Sample 6 had the most chemical compounds, probably because the oil was produced by the distillation of many individual sandalwood trees.

The five sandalwood samples from Watusipat had high α-santalol and β-santalol, not inferior to the sandalwood oil from ENT. This shows that high-quality sandalwood can be grown at Watusipat. This study also refutes the opinion of Boroh (2001) that sandalwood grown in Gunungkidul does not produce fragrant heartwood. The ex-situ genetic conservation site in Watusipat, Gunungkidul, is similar to the natural habitat of sandalwood in ENT. Watusipat has a type C climate (based on the classification by Schmidt and Ferguson (1951)), while in ENT the climate is types D and E. The annual rainfall is also slightly less at Watusipat than in ENT. In ENT, sandalwood grows well in a dry climate with an annual rainfall of between 625 and 1,625 mm, a temperature range of between 10 °C and 35 °C and at altitudes ranging from 50 to 1,200 m. Sandalwood prefers well-drained soil but it has also adapted to rocky sites with soil of low fertility (Sinaga and Surata 1997). Survival of sandalwood at the ex-situ genetic conservation site is about 76.25% (Hadiyan and Fiani 2015) and seedlings have been found around the stand (Yuliah et al. 2012). This indicates that sandalwood is adaptable and can grow well at the Watusipat site.

The quality of sandalwood oil depends primarily on the concentration of two major sesquiterpenes (i.e. α-santalol and β-santalol content). Sandalwood's pleasant characteristic aroma is produced by the organic compounds α-santalol and β-santalol, which are sesquiterpenes (Subasinghe et al. 2013). Both α-santalol and β-santalol are responsible for most of the oil's anticancer and tumour inhibitor properties (Zhang and Dwevedi 2011), antiviral properties (Koch et al. 2008), antimicrobial properties (Simanjutak 2003), neuroleptic properties and chemopreventive effects (Kaur et al. 2005; Ochi et al. 2005; Dwivedi et al. 2006; Kim et al. 2006; Bommareddy et al. 2007).

Table 19.1 Chemical compositions of the *S. album* oil samples

Chemical compositions	Sample					
	1	2	3	4	5	6
Sesquiterpene						
α-santalol	78.29[a]	32.38[a]	63.79[a]	38.87[a]	49.37[b]	68.92[b]
β-santalol	21.72[a]	22.08[a]	35.89[a]	37.83[a]	18.37[a]	1.76[a]
epi-β-santalol	-	5.97[a]	-	-	7.23[a]	8.16[a]
α-sinensal	-	9.39[a]	-	9.36[a]	3.92[a]	6.01[a]
α-santalene	-	-	-	0.45[b]	-	-
β-santalene	-	-	-	0.87[a]	-	-
epi-β-santalene	-	-	-	0.60[a]	0.98[a]	0.51[a]
α-curcumene	-	4.92[a]	-	9.92[a]	-	6.23[a]
Zingiberene	-	3.83[a]	-	-	3.03[a]	-
Bicyclo2.2.1 heptane,2-methyl-3-methylene-2-(4methyl-3-pentenyl)	-	-	-	-	1.94[b]	-
2-Penten-1-ol,2-methyl-5-(2-methylene bicyclo 2.2.1 hept-2-yl),1s-1alpha.,2alpha.,(*z*) 4 alpha.	-	-	-	1.85[b]	-	-
Bicyclogermacrene	-	-	-	-	2.59[a]	-
Isothujol	-	-	-	-	-	1.17[b]
Teresantalol	-	-	-	-	-	0.63[b]
Terpendiol II	-	-	-	-	-	0.89[a]
Monoterpene						
p-mentha-1(7),8(10)-dien-9-ol	-	5.40[b]	-	-	-	2.91[b]
p-menth-2-en-9-ol-trans	-	-	-	-	12.57[a]	-
Sabinol	-	7.83[b]	-	-	-	-
p-Menthane1,2:8,9-diepoxy	-	-	-	-	-	0.56[b]
Other						
Dibutyl phthalate	-	5.20[a]	-	-	-	-
Argon	-	-	0.32[b]	-	-	-
Kauran-18-al,17-(acetyloxy)-(4 beta)	-	-	-	0.36[b]	-	-
2-hexanone,3-methyl-4-methylene	-	2.99[b]	-	-	-	-
Delta-4-carene	-	-	-	-	-	1.11[a]
1,3,6-Heptatriene,2,5,5-trimethyl	-	-	-	-	-	1.06[b]
Cyclopropana,1-(2-methylene-3-3butenyl)-1-(1-methylenepropyl	-	-	-	-	-	0.81[b]

[a] Compounds were identified by comparison with the WILEY229 database library.
[b] Compounds were identified by comparison with the NIST62/12 database library.

Notes:
1. Samples 1–5 from 13-year-old trees and sample 6 from commercial sandalwood oil obtained from the industry in East Nusa Tenggara.
2. Quantitative data were determined by percentage peak area relative to the total peak areas from all compounds.

Variations in the α-santalol and β-santalol content between the samples are shown in Figure 19.1. Based on the ISO 3518:2002 standard for sandalwood oil, the required concentrations of α-santalol and β-santalol are 41–55% and 16–24%, respectively. From the results of the six samples, samples 1, 3 and 5 met these standards. In general, the 13-year-old sandalwood samples from Watusipat, Yogyakarta, had a higher α-santalol and β-santalol content than 15-year-old sandalwood from varied locations. For example, α-santalol and β-santalol content from trees of this age in Bangalore, India was 33.55–35.32% and 17.16–18.96% (Bisht and Hemanthraj 2014); in Sri Lanka 31.36–31.67% and 14.27–14.50% (Subasinghe et al. 2013); and in Australia 42.8–47.3% and 22.4–24.6% (Brand et al. 2007).

The α-santalol and β-santalol contents were not influenced by tree diameter (Table 19.2). At 0.1 m above the ground, sample 4 from a tree with a diameter of 6.68 cm produced α-santalol at a concentration of 38.87%, whereas sample 5 with a diameter of 6.36 cm produced α-santalol at a concentration of 49.37%. Sample 1, with a 7-cm diameter, produced β-santalol at a concentration of 21.72%, which was lower than sample 4 (6.68 cm in diameter), which produced β-santalol at a concentration of 37.83%. Bisht and Hemanthraj (2014) reported that there is no correlation between tree girth and α-santalol and β-santalol concentrations.

Based on the tree diameter (ranging from 4.55 to 7.00 cm), this group of trees was not yet ready for oil harvesting. Most estimates place the start of sandalwood heartwood formation at about 10 years. The predicted rotation length of plantation-grown *S. album* in north-western Australia is around 25–30 years (Radomiljac et al. 1998). Sandalwood trees with α-santalol and β-santalol contents that meet the ISO 3518:2002 standard should be used to support sandalwood genetic improvement programs. Genetic improvement is done by tissue culture (Sanjaya et al. 2006a) or micrografting techniques (Sanjaya et al. 2006b). Multiplication techniques (e.g. tissue culture and micrografting) are intended to retain sought after parent–tree characteristics through the use of scions for breeding programs.

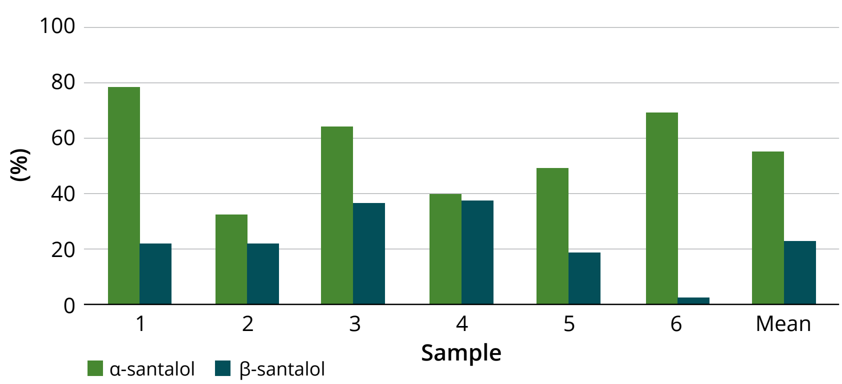

Figure 19.1 Percentage of α-santalol and β-santalol from the six *S. album* oil samples

Table 19.2 Tree diameter and concentration of the chemical compounds α-santalol and β-santalol

Individual	Tree diameter (cm)	Concentrations	
		α-santalol (%)	β-santalol (%)
1	7.00	78.29	21.72
2	4.55	32.38	22.08
3	6.78	63.79	35.89
4	6.68	38.87	37.83
5	6.36	49.37	18.37
Mean	**6.27**	**52.54**	**27.12**

Note: Measurement of diameter at 0.1 m above the ground.

Conclusion

This study showed that the sandalwood oil derived from 13-year-old *S. album* trees grown at Watusipat, Yogyakarta, contains two major sesquiterpenes: α-santalol and β-santalol. It also demonstrates that the Watusipat site is suitable for growing sandalwood in plantations. Three of the sandalwood oil samples analysed met the ISO 3518:2002 standard. The individual trees from which these samples were derived are therefore favorably recommended as candidates for tissue culture and micrografting purposes.

Acknowledgements

We thank the Director of the Centre for Forest Biotechnology and Tree Improvement Research, The Ministry of Environment and Forestry Indonesia for fully supporting this study and also the University of the Sunshine Coast (Australia) for supporting the presentation of this work at the 2019 Sandalwood Regional Forum in Vanuatu.

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20 Resource survey of wild sandalwood in Timor-Leste

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Abstract

Sandalwood (*Santalum album*) is a species that is indigenous to Timor-Leste where it is found growing naturally across the country. This sandalwood species is well-known as the most valuable among all sandalwood species growing throughout the world. Historically, *S. album* has had a strong connection with the economic, ecological, social and spiritual life of Timor-Leste. The important role of this species in Timor-Leste society therefore cannot be overestimated. This paper reports on a resources survey of wild sandalwood in Timor-Leste that was conducted with the aim of quantifying variation and identifying mother trees for future research and plantation development. Approximately 15 trees were evaluated within each of 10 locations across 10 administrative posts. The value of the tree is based on the volume of the oil-containing heartwood at the centre of the trunk. Significance variations for the heartwood development and growth rate were observed, between and within locations. External tree diameter was a poor indicator of heartwood content. Trees with a 20-cm diameter at 0.2 m above ground level had between 4 and 16% heartwood. The average growth rate of trees was estimated at 0.7 cm/year. The study's findings offer a pathway for the selection and cultivation of *S. album* for Timor-Leste's future economic development.

Introduction

Sandalwood (*Santalum album*) is species that is indigenous to Timor-Leste where it can be found growing naturally in the native forests of the country (Barreto 2017). This unique species occurs mainly in monsoon dry mixed tropical forest (Page et al. 2018). Among all existing sandalwood species, *S. album* is recognised as the most valuable due to its unique fragrance (Kumar et al. 2015; Lee et al. 2019). For this reason, the species has been of great interest for scientific research and development (Subasinghe 2013). Historically, *S. album* trees in Timor-Leste were highly sought after and overexploited for thousands of years by colonial traders (Nurochman et al. 2018). As a consequence, the island's wild-growing populations of *S. album* have been dramatically decreased (Ferreira et al. 2020).

Many resource owners recognise two types of the naturally occurring *S. album*, distinguishable primarily by their different timber colour and leaf size or shape.

Although the high value of *S. album* and its potential to grow in Timor-Leste have been well-known by many communities in the country, most are still reluctant to invest in plantations due to the long rotation period. It is suspected that this reluctance is also influenced by several other reasons, including the limited knowledge of heartwood development in the different types of *S. album*. The identification of select mother trees will therefore assist in better sandalwood resource development and contribute to building a much-needed source of information about the potential economic benefits of sandalwood production for Timor-Leste.

Methodology

The wild sandalwood survey was conducted in 10 different administrative posts across Timor-Leste in 2018. Data collected from each site included location characteristics (aspect, gradient and slope position); plant reproductive phenology (buds, flowers, developing and ripe fruit); plant samples (wood core, dried leaf, epi peels); tree age estimation (guided by local inputs); stem diameter and tree form (tree and bole height, canopy spread); new plant recruitment (seedlings and suckers); sun/fire scald (aspect and depth); pests and diseases (galling, caterpillars, root rot, scale, heartwood check); and associated vegetation (species occurring within 5–10 m of sampled sandalwood trees). All data recorded for each tree were collected using both a hard copy protocol and the electronic 'Open Data Kit (ODK)' software used on a smartphone. All data were transferred to Excel worksheets and analysed using Genstat software. Table 20.1 provides a summary of biophysical features of the survey locations and numbers of trees sampled at each.

The 10 locations were spread across the territory of Timor-Leste. Locations were chosen based on local respondents identifying areas where there was a significant stand of older *S. album* trees. Altitude was measured by global positioning system (GPS) on a smartphone for each of the sampled trees at each location. Annual rainfall was estimated by using the WorldClim weather data at a 25-arc minute resolution. The location data was plotted on the WorldClim climate data, and the climate was determined from the 1 km × 1 km cell that included that location. The locations covered a range of altitudes, from 7 to 738 m above sea level, and a range of annual rainfall, from 1,408 to 2,083 mm/year (Table 20.1).

Table 20.1 Altitude, annual rainfall and geology, and number of trees sampled for the 10 survey locations across Timor-Leste

Population	Altitude (m)	Annual rainfall (mm/year)	Geology	Trees sampled
Atabae	444	1,408	Sedimentary	15
Balibo	128	1,266	Sedimentary	25
Hatu-Udo	377	1,975	Limestone	15
Lautem (Lore and Com)	Lore – 198; Com – 417	1,513	Lore – Sedimentary; Com – Limestone	15
Same	7	1,577	Sedimentary	15
Soibada	738	2,083	Limestone	15
Tilomar	450	1,691	Limestone	15
Venilale	519	1,567	Limestone	15
Watulari	519	1,890	Sedimentary	15
Zumalai	371	1,691	Sedimentary	15

Results

There were significant differences in the population mean values for all tree and stem parameters measured except diameter at breast height (1.3 m) across the 10 survey locations (Table 20.2). Generally, the populations of Lautem and Balibo had smaller trees across these traits compared with those from Watulari. There were no significant differences generally in mean tree height, bole length and diameter among the remaining populations.

The reduced size of trees in Balibo may be attributed to their younger estimated age compared with Watulari. Lautem, however, had an equivalent mean estimated age to Watulari and thus the reduced size of the former may be due to reduced growth rates (Table 20.2). The population with the oldest estimated age was Zumalai, but was among the intermediate group for size trait, also possibly attributed to low growth rate. In contrast, trees from Hatu-Udo were among the youngest (20.9 years) but had the highest estimated rate of growth (1.02 cm/year).

Trees with a single stem (69% of trees sampled) were the most prevalent form followed by 2–3 primary stems (16%) and trunk forking (15%). No significant differences were found among these three tree forms for traits such as tree height, stem diameter, bole length or canopy spread. Tree height was positively correlated with stem diameter at 0.2 m (R^2 = 0.78) and 0.7 m (R^2 = 0.86) and 1.3 m (R^2 = 0.46) above ground level (Figure 20.1). No significant correlation was found between stem diameter and bole height.

The average tree height and stem diameter were moderately positively correlated with the annual rainfall of the sample site (Figure 20.2). The tallest trees were growing on elevated areas on the south coast with the longest wet seasons. The populations with the shortest trees with the smallest diameters were found in areas with the lowest rainfall, which is in coastal areas along the north and south coasts.

Table 20.2 Mean values for estimated tree age, tree height, stem diameter at 0.2, 0.7 and 1.3 m above ground level (AGL) and mean annual diameter growth rate (0.2 mAGL) across sample locations in Timor-Leste

Population	Est. age (years)	Tree height (m)	Bole length (m)	Dia. at 0.2 m (cm)	Dia. at 0.7 m (cm)	Dia. at 1.3 m (cm)	MAI at 0.2 (cm/year)
Atabae	24.1 abc	9.4 abc	2.3 ab	21.3 ab	17.8 ab	15.6 a	0.89 ab
Balibo	22.4 c	8.5 bc	2.5 ab	17.2 b	15.4 b	13.3 a	0.80 bc
Hatu-Udo	20.9 c	10.2 ab	2.7 ab	20.4 ab	18.9 ab	17.4 a	1.02 a
Lautem	25.5 abc	7.6 c	2.3 b	16.4 b	15.2 b	13.4 a	0.66 c
Same	24.6 abc	8.8 bc	2.6 ab	18.2 ab	15.4 ab	14.6 a	0.75 bc
Soibada	27.9 ab	8.8 bc	2.5 ab	18.3 ab	16.2 ab	14.9 a	0.68 bc
Tilomar	25.8 abc	8.2 bc	1.8 b	17.9 ab	16.2 ab	15.1 a	0.70 bc
Venilale	22.3 bc	9.2 abc	3.2 ab	18.8 ab	17.0 ab	15.8 a	0.88 ab
Watulari	26.4 ab	11.7 a	3.7 a	21.6 a	19.8 a	15.8 a	0.83 abc
Zumalai	30.1 a	9.8 abc	2.1 b	20.6 ab	18.2 ab	15.8 a	0.68 bc
P value	<0.001	<0.001	0.002	0.006	0.008	0.653	<0.001
LSD (*P* < 0.05)	4.6	1.8		1.94	2.9		0.142
CV (%)	22.8	26.1	48.8	23.7	23.9	25.4	29.9

CV = coefficient of variation; LSD = least significant difference; MAI = Mean annual increment
Note: Populations that share lower-case letters are not significantly different for the individual trait.

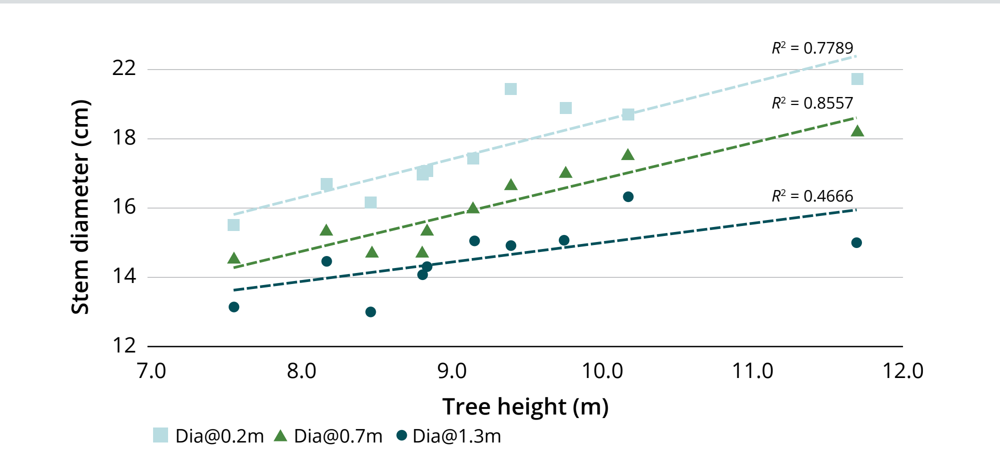

Figure 20.1 Correlation between mean tree height and trunk diameter at 0.2, 0.7 and 1.3 m above ground level across 10 locations in Timor-Leste

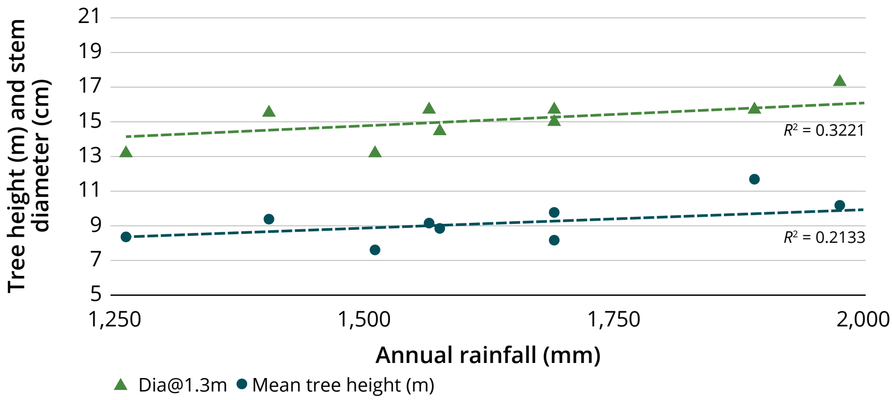

Figure 20.2 Correlation between annual rainfall, average tree height and stem diameter across locations in Timor-Leste

Heartwood characteristics

Mean percentage of heartwood core at 0.2, 0.7 and 1.3 m above ground level

There were significant differences between locations for the percentage of heartwood at 0.2 and 0.7 m above the ground level, but not at 1.3 m above ground level (Table 20.3). There was a very large variation between trees at each site, resulting in a very high (more than 100) coefficient of variation (CV %). A higher percentage of heartwood (i.e. more than 18%) was recorded at Watulari, Zumalai and Lautem, which are all located on the south coast. However, other sites on the south coast like Same and Hatu-Udo had lower percentages of heartwood. Of all the survey locations, Balibo and Hatu-Udo had the lowest rank in mean percentage heartwood (at 0.2 mAGL) of only 5.0 and 5.8%, respectively.

Heartwood cross-sectional area percentage at the three measurement heights (0.2, 0.7 and 1.3 m) were not correlated with tree height but significant correlation was found with the estimated age of the tree (R^2 = 0.18, 0.12 and 0.15 respectively) (Table 20.4). Heartwood area percentage at 0.2 m had a low positive correlation with stem diameter at 0.2 and 0.7 m but not at 1.3 m. No other correlations were found between heartwood area percentage or stem diameter among any remaining measurement point combinations.

Pests of sandalwood are widespread with galling and heartwood check damage found in every sampled population and scale and caterpillars found in 80% of sites (Table 20.5). The incidence of leaf gall was very high with 67% of sampled trees displaying symptoms. The incidence of scale, caterpillar and heartwood check occurred in 21–25% of sampled trees. Root rot was an exception, with observations found in only 40% of populations and an overall incidence of 4% of trees. The level or severity of damage from all pests was relatively low with mean scores of between 1 and 2 (Table 20.5).

Table 20.3 Percentage of trees containing heartwood and mean percentage cross-sectional area of heartwood in sampled trees at 10 locations in Timor-Leste

Location	Trees with heart (%)	Per cent heart at 0.2 m (%)	Per cent heart at 0.7 m (%)	Per cent heart at 1.3 m (%)	Mean heart content (%)
Atabae	93	9.2 [bc]	6.7 [bc]	6.2 [ab]	7.4
Balibo	40	5.0 [c]	2.4 [c]	0.8 [b]	2.7
Hatu-Udo	87	5.8 [c]	2.8 [bc]	1.7 [b]	3.5
Lautem	100	18.3 [ab]	10.1 [abc]	6.0 [ab]	11.5
Same	93	11.4 [abc]	8.9 [abc]	4.4 [ab]	8.2
Soibada	93	16.1 [abc]	9.5 [abc]	7.7 [ab]	11.1
Tilomar	67	11.3 [abc]	9.8 [abc]	6.1 [ab]	9.1
Venilale	100	16.2 [abc]	10.3 [ab]	9.1 [a]	11.9
Watulari	100	20.6 [a]	15.2 [a]	9.8 [a]	15.2
Zumalai	100	18.4 [ab]	13.7 [ab]	9.2 [a]	13.8
P value		<0.001	0.005	0.01	
LSD		9.3	8.9	na	
CV (%)		89	113	147	

CV = coefficient of variation; LSD = least significant difference; na = not applicable
Note: Populations that share lower-case letters are not significantly different for the individual trait.

Table 20.4 Correlation coefficients (R^2) of heartwood area percentage (0.2 m), estimated age and tree height each with stem diameter and percentage heartwood at three heights (0.2, 0.7 and 1.3 m)

R^2	Dia@0.2	Dia@0.7	Dia@1.3	%H0.2	%H0.7	%H1.3
%H0.2	0.14	0.10	0.01	1.00	0.38	0.28
Est. age	0.25	0.20	0.04	0.18	0.12	0.15
Tree height (m)	0.31	0.31	0.07	0.04	0.01	0.03

Table 20.5 Incidence (proportion of trees) and severity score (within parentheses) for pest and disease across sampled site

Location	Galling	Scale	Root rot	Caterpillar	Heartwood check
Atabae	0.73 (1.1)	0 (-)	0.13 (1)	0.13 (1.5)	0.53 (1.1)
Balibo	0.72 (1.1)	0 (-)	0 (-)	0 (-)	0.12 (3.3)
Hatu-Udo	1.00 (1.3)	0.67 (1)	0.07 (1)	0.4 (1.2)	0.13 (1)
Same	0.87 (1.7)	0.67 (1.6)	0 (-)	0.07 (4)	0.33 (2.6)
Soibada	0.53 (1)	0.13 (1)	0 (-)	0.2 (1)	0.07 (1)
Tilomar	0.67 (1)	0.2 (1)	0 (-)	0.73 (2.5)	0.27 (1.5)
Zumalai	0.87 (1.6)	0.47 (1.3)	0 (-)	0.47 (1)	0.13 (2.5)
Venilale	0.33 (2.8)	0.13 (1.5)	0.13 (1)	0.2 (1)	0.27 (2.3)
Watulari	0.47 (1.1)	0.07 (1)	0 (-)	0 (-)	0.4 (1.2)
Lautem	0.47 (1.6)	0.33 (1.2)	0.13 (1)	0.07 (1)	0.33 (1.6)
Total	**0.67 (1.3)**	**0.25 (1.3)**	**0.04 (1)**	**0.21 (1.6)**	**0.25 (1.8)**

Note: Severity score was determined through subjective evaluation of abundance from 1 (low) to 5 (high).

Discussion

Tree size and estimated age were generally consistent across the sampled populations, which may be related to past harvesting pressures in Timor-Leste and consistent periods of recovery between sites. Over 85% of trees sampled had heartwood developed at 0.2 mAGL in all populations except Balibo (40% trees) and Tilomar (67% trees). Mean heartwood area percentage was generally between 10 and 20% for all but Balibo (5%) and Hatu-Udo (5.8%). This suggests that trees are still yet to have sufficient heartwood for commercial harvesting and populations are still in the progress of recovery. At this stage there is much greater value in retaining these few mother trees as seed-producing trees to assist with further natural regeneration and for propagation and establishment of smallholder woodlots. The market for sandalwood seed in Timor-Leste is becoming stronger, so the value of standing mother trees should also increase.

The high incidence of tree heartwood checking is cause for concern with close to one in every four trees with some evidence of this wounding. This evidence combined with observations of tree harvesting due to theft suggests that an illegal trade in sandalwood still operates in isolated areas of Timor-Leste. This has been confirmed by recent seizures of illegal consignments of sandalwood logs (Ferreira et al. 2020).

The leaf galling and scale pests were found to be particularly widespread on wild sandalwood trees in Timor-Leste. While the severity of these pests was generally not a cause for immediate concern, observations of particularly heavy infestations of planted trees were observed during the survey. It is likely that the severity of these pests can be of economic significance in planted trees, but at this stage they have not become a major issue for wild or isolated trees. The scale insect appeared to be a secondary infestation following leaf galling, possibly feeding on any exudate from the galls.

Caterpillar infestations of the bark were observed, but local landowners reported them to have no effect on tree health. Further study is required to identify species of gall, scale and caterpillar to determine their feeding behaviours and life cycles.

The finding that rainfall and mean tree height are correlated across sites is intriguing. These sandalwood populations are wild populations that have been subject to varying degrees of harvesting of the most valuable trees. There are several possibilities as to why there is a trend for trees to increase in height with annual rainfall. The first is that the correlation is not causal, and the sampling of trees from more locations would see the correlation break down. Second, the level of harvesting and pressure on the tree resource is higher at low rainfall locations. Increased pressure at low rainfall sites suggests that a harvestable tree may be considered to be smaller at these sites.

Further work is required to evaluate those trees that perform in terms of their growth rate and heartwood area percentage. Clonal propagation of individuals through grafting is an appropriate means for capturing this genetic variation and establishing the first generation of clonal seed orchards. Such orchards should be comprised of selections across most of the sites to attempt to maximise genetic variation within. They can provide a valuable resource for research and as a source of improved material for establishing new plantations in Timor-Leste.

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21 Heartwood oil induction in *Santalum austrocaledonicum*

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Abstract

The value of a sandalwood tree is determined by the mass of its heartwood and the concentration and quality of the oil contained within. The development of heartwood takes many years and methods for stimulating its induction can improve commercial viability of production. Two experiments were undertaken to test the hypotheses that wounding and chemical treatment in branches could induce oil production, and that non-wounding chemical treatment of trees could increase heartwood oils.

In the first experiment, tree branches were drilled and treated with one of eight compounds (ethrel, auxin, cytokinin, methyl jasmonate, salicylic acid, gibberellic, paclobutrazol and sterile water) and a non-wounded control. All treatments stimulated sandalwood oil production relative to non-wounding and oil concentration continued to increase 8 months after wounding, with no statistical difference between treatments. Essential oil composition was influenced by treatment with ethrel stimulating santalol production and all remaining treatments stimulating lanceol.

In the second experiment, exogenous application of: (1) ethrel (as a foliage spray and root drench); and (2) paclobutrazol (as a root drench only) was used to test non-wounding efficacy of these plant growth regulators. These treatments demonstrated an increase in sandalwood oil production within treated trees, with the paclobutrazol having the greatest effect. Heartwood area and heartwood to sapwood ratio in these treated trees were also greater than the control, although this was not significant.

This study demonstrated that heartwood oil production can be stimulated through controlled wounding of stem tissues. The application of plant growth regulators during the process of wounding can influence the chemical composition of the heartwood oils produced. Exogenous

application of ethrel (roots or canopy) and paclobutrazol (roots) can potentially increase heartwood oil concentration relative to untreated trees. This research has potential practical application for operational stimulation of heartwood in *Santalum austrocaledonicum*.

Introduction

Several tree species within the genus *Santalum*, commonly known as sandalwoods, produce a rich fragrant oil in mature heartwood. These fragrant oils are revered as a plant aromatic (Kumar et al. 2012) and have international market demand with a high commercial value (Coakley 2013). The value of a sandalwood tree is determined by the mass of its heartwood and the concentration and quality of the oil contained within (Brand et al. 2012; Hettiarachchi 2013). The formation of heartwood and the quality of the oils contained within is of both biological and practical importance. To date, there is limited understanding of how genetics and the environment contribute to heartwood and oil variation within different *Santalum* species.

Heartwood production can be stimulated in some tree species through specific mechanical, chemical and/or biological interventions (Ecker and Davis 1987; Hillis 1987; Seyfferth et al. 2018). Mechanical wounding of branches and stems of some trees can potentially stimulate a defence process to isolate the injured tissues and limit infection. Boundaries around the injury are formed by production of: (1) chemicals at the time of injury; and (2) chemicals and structural changes formed following injury (Shigo 1984). Many of these wound responses are characteristic of heartwood development, although the responses often decline with increasing distance from the wound (Lev-Yadun 2002; Delvaux et al. 2010; Arbellay et al. 2012).

The aim of this research was to determine: (1) the effect of stem wounding and treatment with plant growth regulators on heartwood oil production and quality over time; and (2) non-invasive application of ethrel and paclobutrazol on heartwood oil production and quality within the main stem.

Materials and methods

Two experiments were carried out on 11-year-old *Santalum austrocaledonicum* trees growing in a plantation at the Summit Estate in Vanuatu, approximately 5 km north-east of Port Vila (17°40‘55.69“S 168°13‘46.54“E).

Branch wounding and treatment (Experiment 1)

The first experiment was carried out on 14 trees to examine the effect of wounding and chemical treatment on localised oil production in branch wood. The primary branches (>4 cm diameter) of each tree were treated by drilling and inserting a wooden dowel that was soaked in one of seven solutions (2017-03-09). The treatments were positioned at least 25 cm apart with each being mechanically drilled (7.5 mm diameter and 40 mm deep), with resulting holes being filled with a wooden dowel (6 mm × 32 mm) soaked in one of either: (1) 6-benzylaminopurine (6-BAP) (10 mg/L); (2) ethrel (ethephon) (720 g/L); (3) indole-3-butyric acid (I3BA) (10 mg/L); (4) methyl jasmonate (MeJ) (10 mg/L); (5) methyl salicylate (MeS) (10 mg/L); (6) paclobutrazol (paclo) (4 mg/L); or (7) autoclaved distilled water (wounding only control). Treatments were randomly allocated along the branches and one position was left unwounded as a negative control. Shavings collected from each wound site were chemically extracted and analysed by gas chromatography/mass spectrometry (GC/MS) to determine the presence of sesquiterpenes prior to treatment.

Branches from four randomly selected trees (biological replicates) were harvested at 8, 16 or 32 weeks after inoculation. The branches were cross-sectioned through the wound site. Wood was sampled around each wound site and cut into 5-g sections, which were air dried and kept at ambient temperature until oil extraction and analysis by gas chromatography. The branches of the two remaining trees were harvested 22 (December 2018) and 33 (November 2019) months after treatment and sectioned transversely to determine the extent of heartwood development and spread.

Canopy and root treatments (Experiment 2)

The second experiment was conducted to test the non-invasive application of two plant growth regulators, ethrel and paclobutrazol, on heartwood oil production. A total of 73 trees from the plantation were available, and individuals were randomly selected for application of either ethrel as a canopy spray (n = 24) (1 L per tree at 0.1% concentration), paclobutrazol as a root drench (n = 24) (2 g a.i. in 2 L of water for each tree), control trees (n = 25), and an additional nine trees were treated with ethrel as a root drench. Two treatment applications were made: one at the commencement of the experiment (2017-12-15) and another 6 months later (2018-06-18). Bark-to-bark wood cores were collected at 0.20 cm above ground level at 12 months after the first treatment (2018-12-12). These wood cores were air dried and kept at ambient temperature until oil extraction and analysis by gas chromatography.

Oil extraction

The distinction between heartwood (HW) and sapwood (SW) was determined on the basis of colour (SW, pale/yellow; HW, dark/brown or red), and samples of each were coarsely ground to homogenise. Oil was extracted from wood shavings as previously described in Moniodis et al. (2017).

GC/FID and GC/MS

Gas chromatography conditions were as follows: stationary phase; DB-Wax column (30 m long, 0.25 mm ID, 0.25 μm film thickness, Agilent Technologies, Santa Clara, CA, USA). Carrier gas was helium at 1 mL/minute and pulsed pressure set at 172 kPa for 0.5 minutes. The injector was operated in pulsed split mode (1:10), with the injector temperature maintained at 250 °C. Oven was programmed at 40 °C for 1 minute, then raised at 10 °C/minute to 130 °C followed by 2 °C/minute to 200 °C, and 20 °C/minute to 240 °C for a further 10 minutes. Scan mode was used over the range of 40–250 m/z. Run conditions for GC/MS were similar to that of gas chromatography/flame ionisation detector (GC/FID), except the detector was opened 5 minutes after injection.

Statistical analysis

All statistical analyses were conducted using the R software package (R Core Team 2016). A Shapiro-Wilk test was used to check whether oil components followed a normal distribution. Differences were accepted as significant if $P < 0.05$. Parametric (ANOVA, Tukey's test) and non-parametric statistics (Friedman's, Kruskal-Wallis) were used for continuous variables normally or not normally distributed respectively.

Results

Branch wounding

Oil yield

Prior to branch wounding and treatment, no oil was detected in the branches except at three sites that contained minute amounts of *Z*-lanceol (~0.001% w/w). At 8 weeks, darkened wood containing oil was observed at all treatment sites with oil content measured at less than 0.1% (w/w). By 16 and 32 weeks the mean oil content in the treated positions was 0.5% ± 0.1% standard error (SE) (w/w) and 1.8 ± 0.2% SE respectively (Figure 21.1(a)). The oil yield at each sampling time was significantly greater than oil content from unwounded sites. The oil content at all treatment sites increased in time and was significantly higher than the previous harvest (Figure 21.1).

The mean oil content across the seven treatment sites was statistically similar at each harvest point (Figure 21.1(c)). The MeJ position had a higher oil content than MeS at 8 weeks, which was only slightly significant ($P = 0.05$). There was no statistical difference in yield when the six chemical treatments were combined (a to f) and compared with the wounding only site, indicating the primary response of oil production was due to wounding. Total oil content in untreated positions also increased with time to ~0.02 ± 0.2% at the 32-week harvest, although yields were still significantly less than treatment sites.

Oil accumulation was observed in the transverse sections of the treated stems at 22 and 33 months following treatment where dark-coloured fragrant wood surrounded the wound sites of all treatments (Table 21.1).

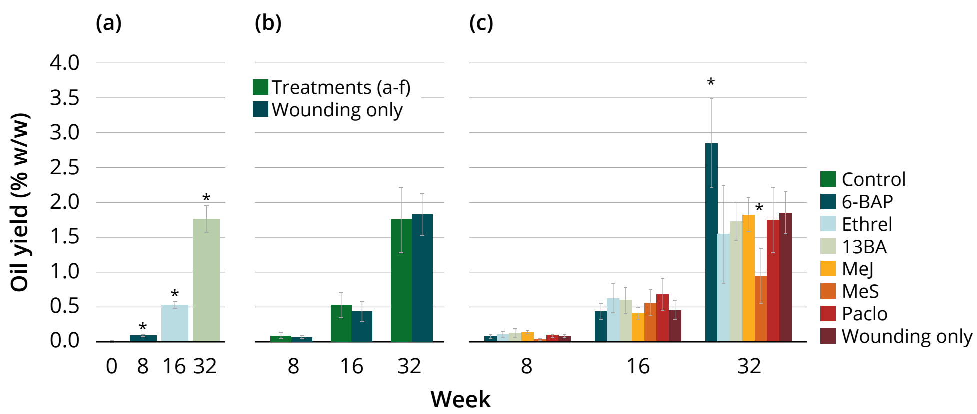


Figure 21.1 (a) Mean oil yield in percentage and (b) total oil yield at 8, 16 and 32 weeks ($n = 32$) with (c) six chemical treatments combined (a to f) and compared to the wounding only site

Note: Data corresponds to means ± SE (standard error). There was little, or no oil detected initially, and untreated sites were used as a negative control. Asterisks ($P < 0.01$) indicate values that are significantly different from the control and differences between time points (8–16 weeks, 16–32 weeks) (Pairwise Wilcoxon; $P < 0.001$).

Table 21.1 Stem longitudinal sections in trees 22 and 33 months following treatment with methyl jasmonate (MeJ), methyl salicylate (MeS), 6-benzylaminopurine (6-BAP), indole-3-butryric acid (I3BA), ethrel (Eth) and paclobutrazol (Paclo), and a wounding only control (W – sterile water soaked dowel)

Note: Some treatment sites were not recovered (N/A) due to wind damage of the treated branch.

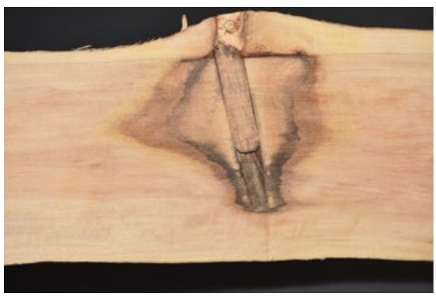
T	22 Months	33 Months
1 MeJ		N/A
2 MeS		
3 W		
4 BAP	N/A	

Table 21.1 Stem longitudinal sections in trees 22 and 33 months following treatment with methyl jasmonate (MeJ), methyl salicylate (MeS), 6-benzylaminopurine (6-BAP), indole-3-butryric acid (I3BA), ethrel (Eth) and paclobutrazol (Paclo), and a wounding only control (W – sterile water soaked dowel) *(continued)*

Note: Some treatment sites were not recovered (N/A) due to wind damage of the treated branch.

T	22 Months	33 Months
5 I3BA		
6 Eth		
7 Paclo	N/A	

The development of oil-infused wood continued to radiate beyond the immediate wound site both up and down the stem. In most instances this oil accumulation was observed to merge between treatment locations so that a continuous band of early formed heartwood was found in the treated branches. The observed heartwood response was stronger in the branches of the tree harvested at 22 months compared with 33 months. In the MeJ and ethrel-treated branches harvested at 22 months, wood tissue damage was observed (Table 21.1). This resulted in secondary colonisation by ants and substantial heartwood development in the surrounding tissues.

Oil composition

Differences in the composition of extracted oil were recorded between treatments at week 8, where α-santalol, β-santalol, epi-β-santalene and the corresponding santalols and bergamotol were only detected in the ethrel treatment. Total santalol content of 36.9% ± 2.1% SE in ethrel-treated branches was highest compared with other treatments, including the wounding only site at week 8, indicating a treatment effect additional to the wounding response. At week 8, lanceol content (% and g/L) was highest at MeJ sites, which contained 66.1% ± 6.5% SE, and significantly greater than ethrel positions ($P = 0.006$), which contained 14.8% ± 2.0% SE. Lanceol in ethrel extracts were also significantly lower ($P < 0.05$) than the wounding only site, 6-BAP, I3BA and paclobutrazol at week 8, indicating a treatment effect further to wounding.

At week 16, α-santalol, β-santalol and bergamotol were detected at all treatment sites except MeJ. Total santalol content was significantly higher in ethrel (17.9 ± 2.8%) than the MeJ (0.00%) sites ($P < 0.05$), which contained no detectable trace of the santalols. At 32 weeks, α-santalol and β-santalol content was still lowest at MeJ sites (7.2 ± 3.5%) and highest at two treatment sites – ethrel (25 ± 5.8%) and paclobutrazol (23 ± 4.0%). Average α-santalol and β-santalol content over the treatment course was highest for ethrel (26.7 ± 3.6%) and lowest for MeJ (2.48 ± 1.1%) sites when sampling point(s) were combined. The amount of α-santalol, β-santalol, epi-β-santalene and the corresponding alcohols and bergamotol all tended to increase between sampling points (Figure 21.2). Large standard deviations are indicative of the high natural variability of *S. austrocaledonicum* oils, which made detection of statistically significant differences difficult using four biological repeats.

Treatments with MeJ contained the highest average amounts of lanceol over all three sampling points. Overall, lanceol was the most dominant oil component at 8 weeks (50.1% ± 4.5% SE), 16 weeks (50.0% ± 3.6% SE) and 32 weeks (39.5% ± 3.6% SE). The proportional contribution of *Z*-lanceol to the oil profile tended to decrease between sampling points as other compounds were also being produced. By 32 weeks, a small volume of oil was detected in an untreated control (0.02 g/L) that contained *Z*-lanceol (18.9%), E-α-exo-bergamotol (4%) and α-santalol (1.74%). When oil composition was evaluated at various points from the wound site, lanceol levels were elevated at points close to the wound site, while santalols were elevated at sample points more distal to the wound (Figure 21.3).

A principal component analysis (PCA) showed clear differences in total oil composition between ethrel and MeJ after 2 months, which clustered separately (Figure 21.4). As the treatment course progressed, there was significant overlap in terpenoid profiles across individuals and treatments (Figure 21.4). There was a strong correlation between α-santalol and β-santalol (R^2 of 0.92, $P = 0.000$),

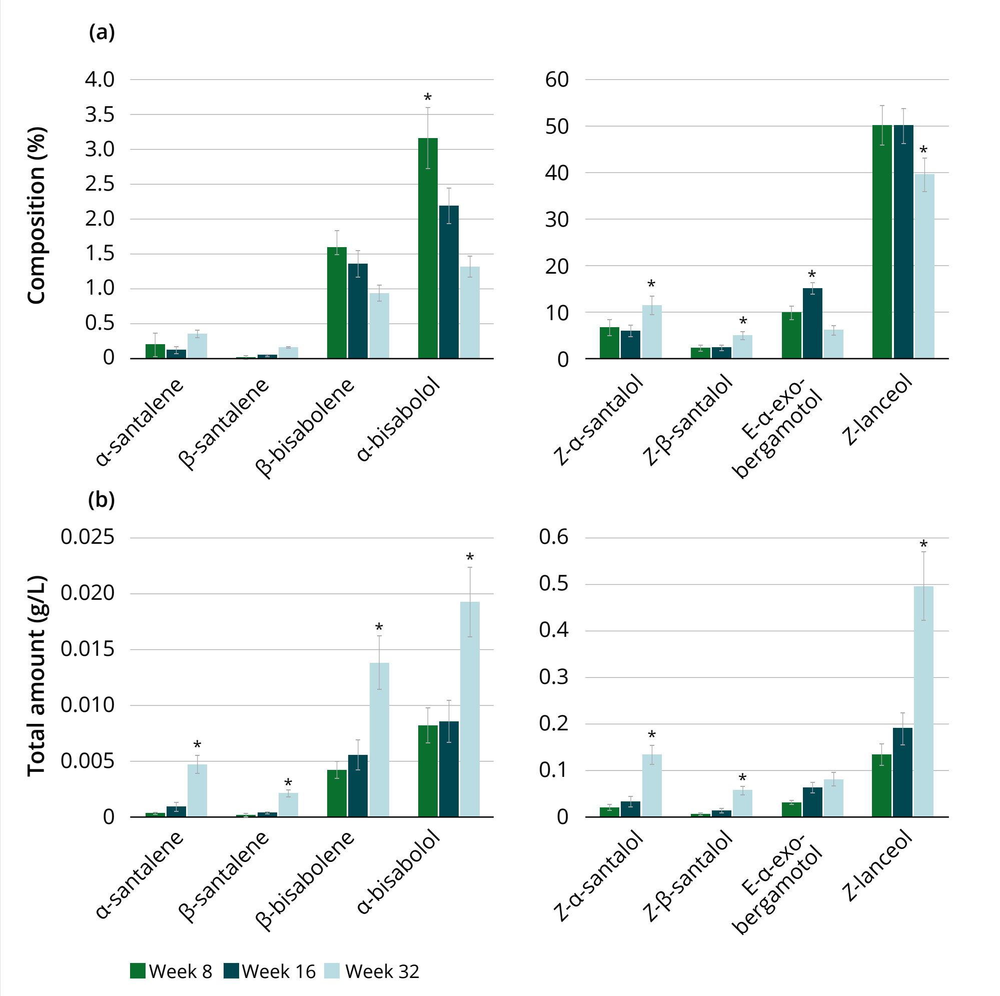


Figure 21.2 Branch oil extracts (a) percentage composition data showing how components change in their contribution to profile with wounding, and (b) total amount of each compound increasing with time

which was expected because they are co-produced, and between α-santalene and α-santalol (R^2 of 0.83, $P = 0.000$), which share a biosynthetic pathway. The enzyme producing lanceol has not yet been characterised, however α-bisabolol and *Z*-lanceol were strongly correlated (R^2 of 0.80, $P = 0.000$), which indicates they may share a biosynthetic pathway due to structural similarities. The PCA demonstrates that *Z*-α-santalol and *Z*-lanceol influence much of the variability and are the main contributors for the ordination of oil extracts in treated *S. austrocaledonicum* branches.

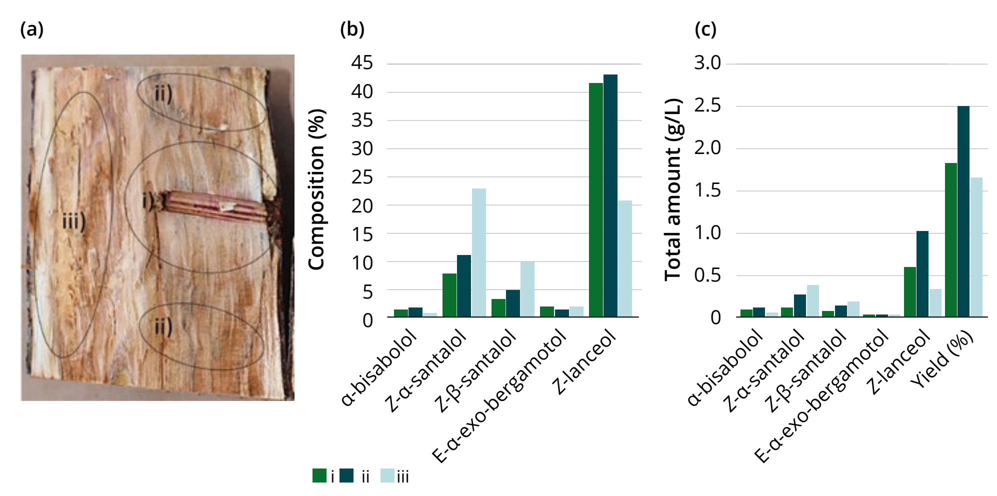


Figure 21.3 (a) Example branch at 32 weeks showing differences in oil profile around wound site (individual with MeS treatment). (b and c) The lanceol content is higher nearer the wound and santalols are higher further away from the wound

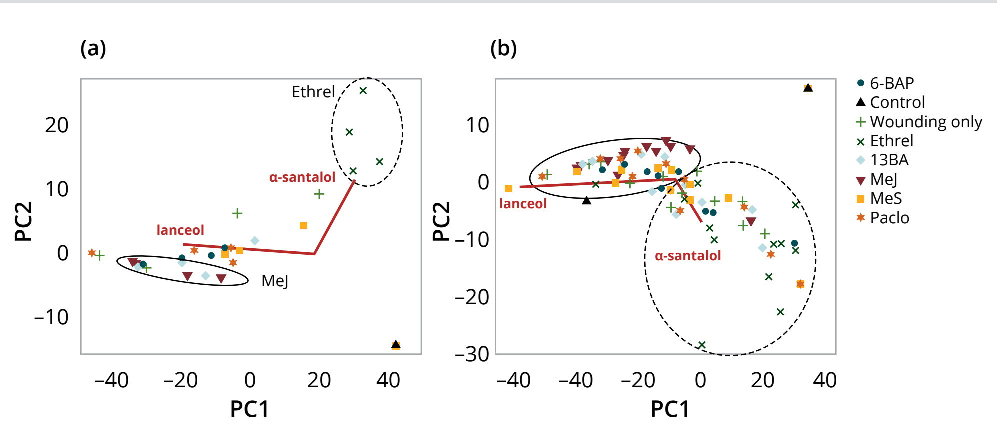


Figure 21.4 Two-dimensional principal component analysis (PCA) ordination scores of oil constituents explaining 0.895 of the total variance of *S. austrocaledonicum* harvested from chemically treated branches at (a) 8 weeks and (b) all weeks combined

Note: Each point represents an individual branch treatment, and points close together are similar in terms of composition. The ovals within each PC plot denote clusters of MeJ (solid line) and ethrel (dashed line) treated samples.

Non-invasive treatment

Oil yield

Total oil content in heartwood extracts was highest in the trees treated with the paclobutrazol root drench with a mean of 2.7% ± 0.4% SE followed by the ethrel drench 2.2% ± 0.9% SE, ethrel spray 2.0% ± 0.3% SE and the control group having the lowest mean of 1.6 ± 0.4% SE (Figure 21.5). Due to the large variation in oil yield, statistically significant results were only detected between the control and paclobutrazol ($P < 0.05$). Average heartwood oil content across all sampled trees was 2.11 ± 0.21% (w/w), which is indicative of young trees.

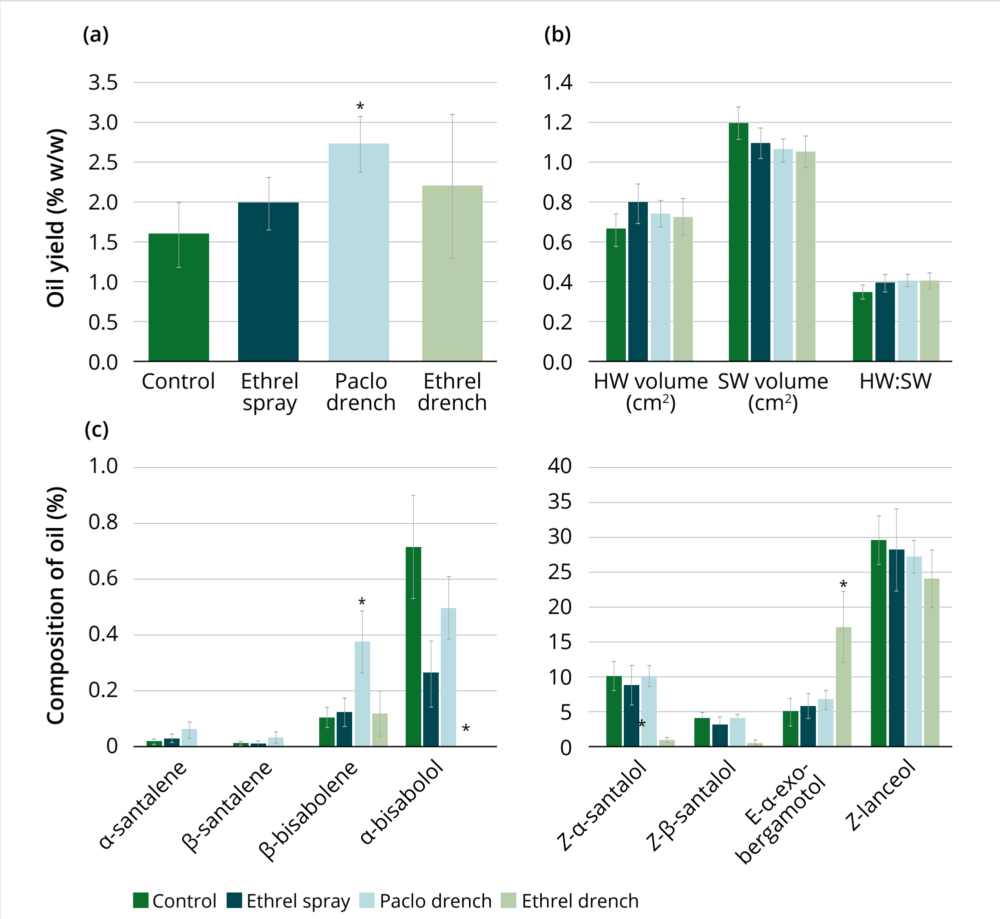


Figure 21.5 (a) Mean percentage of heartwood oil yield from *S. austrocaledonicum* trees treated with a foliar ethrel spray (n = 24), paclobutrazol (paclo) drench (n = 24) or an ethrel drench (n = 9); (b) heartwood (HW) volume, sapwood (SW) volume and HW:SW ratio across treatments; and (c) composition of major oil components in the heartwood oil extracts

Note: Data corresponds to mean ± SE (standard error). Asterisks ($P < 0.05$) indicate values that are significantly different from the control.

Since the greatest value to plantation managers is an increase in yield and heartwood volume, differences between stem diameter, heartwood area (cm^2), sapwood area (cm^2) and the HW:SW ratio were quantified. The HW:SW ratio was lowest in the control group; however, due to large variation, this was not statistically significant ($P > 0.05$).

Oil composition

Mean santalol content was highest in the control group, followed by paclobutrazol and significantly higher than the ethrel drench ($P = 0.004$) (Figure 21.5). The β-santalol content was significantly higher in control and paclobutrazol treatments compared with the ethrel drench ($P = 0.03$), which seemed to have a negative impact on santalol content and opposite to the branch induction experiment. Only a small number of components including β-bisabolene and E-α-exo-bergamotol were significantly different between treatments, with a larger number of terpenoid profiles showing significant overlap and no distinct clustering based on treatments (data not shown).

Discussion

Mechanical wounding

Mechanical wounding of wood tissues in *S. austrocaledonicum* stimulates the production of heartwood oils that accumulate over time around the wounding site. Heartwood oils were absent at the commencement of the experiment but increased to 1.8% at 32 weeks (8 months) after treatment. The application of plant growth regulators within the wounding site did not have an additive effect on heartwood oil accumulation beyond that of wounding only. This clearly demonstrates that initial stimulation of oil accumulation is related to a physiochemical response to wood tissue damage.

The accumulation of oils surrounding the wound site is an example of compartmentalisation that provides a defensive boundary around the injury to resist further spread and loss of function such as water conduction (Shigo 1984; Wiedenbeck and Smith 2018). Compartmentalisation following stem injury can include both anatomical responses such as increase in lignin content and thickened cell walls (Frankenstein et al. 2006), decrease in xylem vessel size (Delvaux et al. 2010; Arbellay et al. 2012) and vessel occlusion (Sun et al. 2008), and chemical responses such as secondary metabolite deposition (Byun-McKay et al. 2006; Deflorio et al. 2011; Nakaba et al. 2017; Klutsch et al. 2020) to isolate the site of injury and protect surrounding tissues. Ecologically, the sandalwood oils produced following wounding provide long-term protection against pathogens and microbial decay (Celedon and Bohlmann 2016).

The physiological changes associated with oil deposition often decline with increasing distance from the wounded tissues. The dominance of the sandalwood oil component lanceol was unexpected and is considered to be associated with the wounding response. This wounding is referred to in the literature as stress-induced as compared to time-induced developmental ageing (Schippers et al. 2015; Sade et al. 2018). Further research is necessary to determine if the essential oil profile of stress-induced heartwood is different from time-induced heartwood development and whether any difference continues beyond the initial period of stress.

Total oil content in untreated positions increased minutely (from 0 to 0.02%) after the 32-week harvest. It is possible that this marginal increase may have been influenced by the effect of adjacent branch treatments and oil production spreading laterally along the branch from the wound site. This lateral accumulation of heartwood oils was confirmed in the branches harvested at 22 and 33 months where transition wood merged between the treatment sites. The substantially darker and more fragrant wood observed in between the wounding zones for the tree harvested at 22 compared with 33 months is most likely due individual tree variation in the response to the treatments. Radomiljac (1998) demonstrated a localised heartwood oil response to small drill hole wounds in *Santalum album*. This localised wounding response and accumulation of heartwood oils in *S. album* is consistent with the results demonstrated for *S. austrocaledonicum* in this study. However, stem wounding treatments in 10 to 12-year-old *Santalum spicatum* trees were not found to consistently influence heartwood percentage, oil yield or oil composition 1 year after treatment (Smith 2019). They described that no visible 'pooling' of heartwood was observed at the location of the treated area for any wounding type.

Exogenous hormone application

This study clearly demonstrated the application of plant growth regulators within the stem had little effect on promoting heartwood oil accumulation beyond the initial wounding response. The oil composition did however vary between chemical treatments. This was most obvious in the ethrel treatment, which consistently produced oil with elevated levels of santalol relative to all remaining treatments. By 32 weeks (8 months), the oil profile of the ethrel treatment approached that of a mature sandalwood oil profile, demonstrating an ongoing process of oil accumulation.

Zhang et al. (2018) reviewed several published studies that demonstrated injection of biological or chemical elicitors into the stem of sandalwood trees could increase oil production. In 5-year-old *S. album*, Radomiljac (1998) demonstrated that stem injections (15 cmAGL) of paraquat (3 mL of 0.25% or 1% concentration) and its combination with ethrel (3 mL of 0.25% or 1%) induced heartwood oil production up to a height of 60 cm after 32 weeks (8 months). Injection with ethrel alone was no more effective at inducing heartwood compared with injecting pure water. The total volatile oil and santalol concentration within induced heartwood was equal or greater than naturally formed heartwood and greater than sapwood.

For *S. spicatum*, the application of dowel treated with methyl salicylate (98%) within the stem (8-mm hole drilled at 300 mmAGL) had no effect on heartwood percentage, oil yield or oil composition 1 year after treatment (Smith 2019). The variation in heartwood response to plant growth regulators between studies may reflect species and chemicals used, treatment site, methods of application and detection, genetic variation, developmental age, life history and environment.

Non-invasive treatment

The foliar application of ethrel and root application of ethrel and paclobutrazol on 11-year-old *S. austrocaledonicum* trees had a positive effect on heartwood oil concentration within the trunk relative to untreated trees. This result was statistically significant for paclobutrazol root drench. This finding suggests that this method may have a potential practical application for inducing heartwood in this species. When trees are approximately 10 years of age, towards the end of their fast-growing juvenile stage, a treatment could be applied that switches on heartwood formation in all trees. This can ensure that all trees have at least 10 years of heartwood formation before being harvested at approximately 20 years. The timing of treatment is important because in 9-month-old *S. album* seedlings, key genes for biosynthesis of sandalwood oil (i.e. HMGR and FPPS) were induced in both leaves and stems following foliar application of methyl jasmonate (Külheim et al. 2014). However, oil accumulation in the stems or roots within these seedlings was not demonstrated and full terpenoid biosynthesis of santalols is likely to be developmentally regulated. Therefore, while a treatment may activate the terpene synthase genes, only trees of a certain developmental age will subsequently produce heartwood oils. The results of the current study indicate that a non-invasive application of chemicals has the potential to influence yields and should be further explored to test different concentrations, range of chemicals, mode and number of applications.

The high variability in oil yield and quality found within the *S. austrocaledonicum* experimental trees in this study is likely to have been influenced by natural variation in oil traits for this species (Page et al. 2010) and life history of the trees. Two years prior to the experiment, category-5 Severe Tropical Cyclone Pam passed over the site causing extensive crown damage to the trees. This created a high level of background wounding, which was likely to influence oil production across the experimental trees. However, the results of this study indicate that the oil profile can be influenced via a non-wounding mechanism and therefore warrants further experimentation, particularly in trees across a range of age classes.

Potential practical applications

Two potential methods of heartwood stimulation and oil accumulation were demonstrated in this study: (1) physical wounding of the stem; and (2) non-invasive applications of ethrel and paclobutrazol. Given the significant tree-to-tree variation in responses to these methods, further evaluation and refinement is required to develop robust approaches for practical use. The use of wounding to stimulate heartwood formation has a localised effect with further development progressing over time to surrounding tissues. Radomiljac (1998) suggested operational application of wounding to be inappropriate, requiring numerous drill holes to produce small amounts of heartwood oil and that the holes would degrade the appearance of the wood and provide infection sites for fungi.

Despite the potential for field application of chemical induction methods, such methods will be influenced by consumer considerations of natural and/or organic production methods for sandalwood products. Therefore, the demand for sandalwood products derived from heartwood stimulated by plant growth regulators needs to be determined. It is possible that products derived from chemically stimulated heartwood may compete with low-end and/or synthetic sandalwood products. This would in turn influence the economics of sandalwood production with higher inputs (i.e. costs of stimulation), shorter rotation (trees harvested earlier) and lower unit returns (relative value of stimulated vs natural heartwood).

The research application for heartwood stimulation using these or similar methods include: (1) early determination of heartwood oil quality in young trees used for breeding purposes; and (2) determination of an association between the strength of tree response to heartwood stimulation and its precocity for natural heartwood development. Similar use of wounding was used in *Pinus sylvestris* where Harju et al. (2009) assessed the concentration of heartwood extractives in the wound response area for 3-year-old seedlings and heartwood of their mothers. The high heritability estimates across a range of extractives (Harju et al. 2009) indicate that wounding of young trees may be developed as a method for early selection of heartwood oil composition in sandalwood.

Conclusion

This study has found that heartwood oil production in sandalwood can be stimulated through: (1) controlled wounding of stem tissues; and (2) non-invasive applications of ethrel and paclobutrazol. The chemical composition of the heartwood oils produced following wounding can also be influenced by application of plant growth regulators. This study provides a foundation for further development of practical methods for stimulating early heartwood development in sandalwood. Given the large sample-to-sample variation, greater replication with fewer treatments and extended time is required for future studies. The development of operational methods of heartwood stimulation would also require consideration of the input costs of applying treatments, the reduction in harvest rotation, and market value of stimulated compared with natural heartwood.

Acknowledgements

Funding by the Australian Centre for International Agricultural Research (ACIAR) through the project ‘Enhancing the formation of heartwood in sandalwood in Vanuatu’ (FST/2016/054). The authors would like to thank Joerg Bohlmann and Jose Celedon from the University of British Columbia for providing *S. album* sequence information for the study on housekeeping genes in *S. austrocaledonicum*. We would like to also thank the Vanuatu Department of Forests and the Summit Estate in Vanuatu. This research is supported by the Australian Government’s ACIAR project FST/2016/054 – Enhancing the formation of heartwood in sandalwood in Vanuatu.

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22 Propagation of *Santalum lanceolatum* from Cape York Peninsula

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Abstract

On Cape York Peninsula in northern Queensland, Australia, *Santalum lanceolatum* occurs naturally either as individual trees or in small groves of up to 20 trees. These trees grow across a broad range of environments. Some grow within metres of the salt water, others in the open savannah forests, at the margins of rainforests and on basalt intrusions. This research focuses on sandalwood trees from north of the Jardine River. The paper gives general and technical information about propagating *S. lanceolatum* with an emphasis on grafting, seed production and raising of seedlings. Grafting protocols were developed, as wild seed production is limited even though the trees flower profusely. Initial selection of trees to graft was based on previous work that identified individuals with high α-santalol and β-santalol levels. The second selection criterion used to select trees to graft was focused on ensuring we captured trees from a diverse genetic base, by limiting the number of trees captured from any one grove and capturing trees from across the region. Choice of appropriate scion material is critical to grafting success. So far, we have captured 30 individuals from the wild. These trees have been established in grafted seed orchards and seed production is abundant. Viability of this seed has been good (81.5%) and seedling growth vigorous.

Introduction

A previous study into the evaluation of oil characters of *Santalum lanceolatum* in northern Cape York Peninsula (Page et al. 2007) gave us the basis to start a propagation program focused on high oil content trees. After several visits to the Northern Peninsula Area (NPA) (Figure 22.1) at different times of the year, we concluded that a seed-based capture of the wild trees would not happen due to the low seed set. Therefore, grafting of these trees became the focus to capture trees into a testing and genetic improvement program (Lee et al. 2018).

Moving the propagation material from the NPA to Gympie in south-east Queensland, so far from its growing region, meant the establishment of an in-ground clonal seed orchard could have problems (e.g. issues with different soil types and climatic conditions). With these issues in mind, we decided to develop a potted clonal orchard. This method gave us control over the potting mix, watering schedules, fertiliser applications and hosts. The benefit so far has been the ease of managing and monitoring the developing orchard. We have a good mix of high oil and untested clones scattered throughout the orchard. Pollination has been exceptional, which has resulted in high seed production. The potted clonal seed orchard not only supplies us with high seed production but has also proved to be the best method for conservation of this locally endangered species in the NPA.

This study supports Indigenous Traditional Owners of the NPA in their endeavour to conserve and commercialise *S. lanceolatum* for future generations.

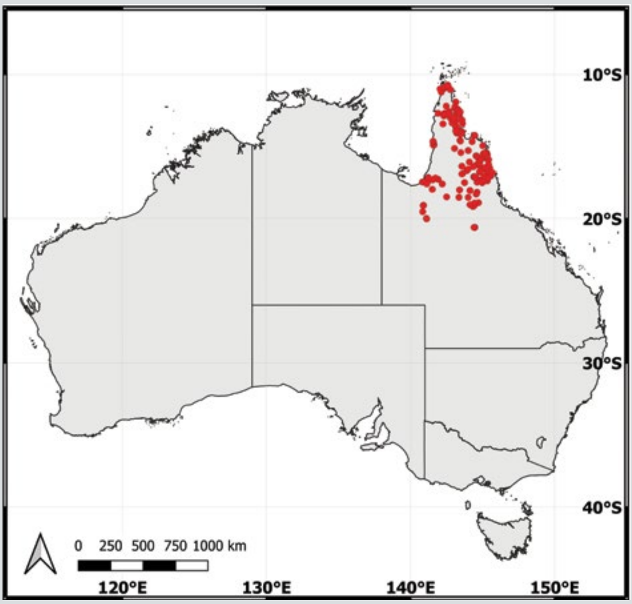

Figure 22.1 Distribution of sandalwood on Cape York Peninsula. The sandalwood focus area for this study included only the Northern Peninsula Area (NPA), north of the Jardine River

Grafting

As seed-based capture of wild *S. lanceolatum* trees was not practical due to the low seed set, capturing wild trees through grafting became the focus of the project for its conservation and domestication. Material transfer agreements were obtained earlier in the project with the Apudthama Land Trust but permits to move scion material through the Torres Strait had to be gained for each movement under the Torres Strait Regional Biosecurity Plan 2018–2023. Pests and diseases of plants and animals pose a major threat to the economic, environmental, social and cultural assets and values throughout the Torres Strait and Cape York Peninsula.

Scions were captured and placed between layers of moist newspaper in clip-sealed bags and stored in a cool esky. Material was then transported by sea, air and land to its final destination in Gympie, approximately 2,000 km away. The next day, the material was grafted onto actively growing seedlings.

Preliminary grafting was undertaken to evaluate the following: (1) best season to collect scion material: mid-wet, early-dry or mid-dry season; (2) type of scion material: semi-lignified versus lignified scions; and (3) impact of species of rootstock on grafting success: *Santalum album* or *S. lanceolatum*. Based on our studies, top-cleft grafting using semi-lignified scion material with active axillary buds, collected during the middle of the wet season and using *S. lanceolatum* rootstock (74% success relative to 44% success when grafted onto *S. album* rootstock), resulted in greater grafting success that any other method. Once a successful graft union was achieved, we found very little graft incompatibility, regardless of roostock species.

Newly grafted plants were placed in a temperature-controlled glasshouse with fogging mist applied every 10 minutes for 10 seconds to maintain high humidity. A fungicide treatment was applied weekly, and the plants would stay in the glasshouse until a graft union had been obtained (approximately 3 weeks). Each plant was supplied with the pot host *Alternanthera nana*. Grafted plants were then moved to a 50% shade cover for a month and then to full sun to grow on.

This method of sandalwood grafting has facilitated the capture of 30 wild *S. lanceolatum* trees from the NPA including nine trees with superior oil profiles, and 21 other trees that have not yet been characterised for their oil profiles. Selection of these latter trees was made to ensure a broad genetic base of the species from the region had been captured and conserved. Enough grafts from 12 clones have been used to establish a grafted clonal seed orchard back 'on Country' at the Northern Peninsula State College, Bamaga. Nineteen clones were used to develop two progeny trials at Bamaga: irrigated and non-irrigated. We also have a grafted seed/conservation orchard at Walkamin, on the Atherton Tableland in north Queensland.

Flowering of the grafted *S. lanceolatum* trees began in the nursery approximately 6 months after the scions had been successfully grafted. The grafted trees have continued to produce flowers regularly and abundantly since they have been planted out in the potted clonal seed orchard. The pollinators we have noticed so far are domestic European bees, flies, wasps, ants and butterflies. These pollinations have resulted in excellent seed production. We currently have enough seed to plant over 20 ha of sandalwood plantations.

The *S. lanceolatum* grafting sequence is shown in Figures 22.2–22.11.

Figure 22.2 Mature tree in the wild that is suitable for scion collection

Figure 22.3 Scion material without active axillary buds

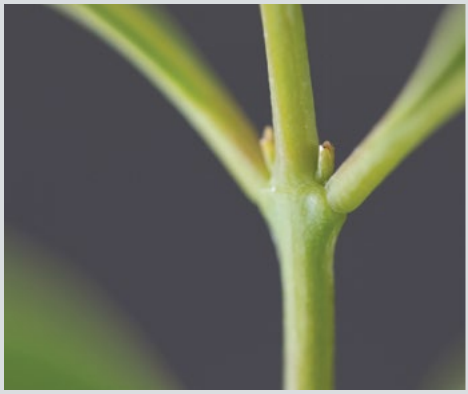

Figure 22.4 Scion material with active axillary buds

Figure 22.5 Scion prepared for grafting

Figure 22.6 Grafted sandalwood

Figure 22.7 Grafts in misted igloo

Figure 22.8 Graft union (after 3 months)

Figure 22.9 Six-month-old grafted sandalwood (flowering)

Figure 22.10 Four-year-old clone, potted in a 130-L pot, producing seed in the Gympie Sandalwood Clone Bank

Figure 22.11 Four-year-old graft union

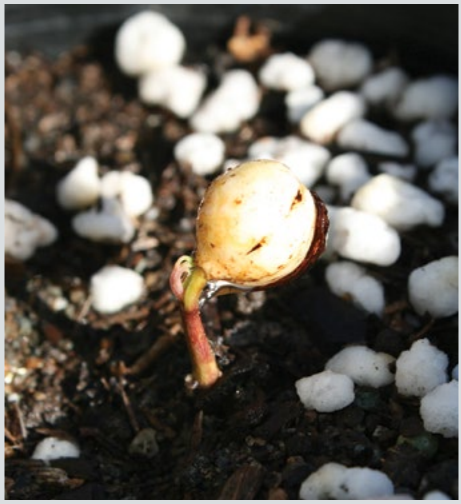

Figure 22.12 Germinating sandalwood seed

Germination and seed production

After collection of seed, the flesh needs to be removed immediately, otherwise there will be mould and fungal issues. We have found that seed with flesh removed and sown immediately had a germination rate of 55%. If seed is left to rest in a controlled environment at 20 °C for a minimum of 2 weeks, the germination rate rises to 81.5%. To initiate germination, seed is soaked in a solution of 0.02% gibberellic acid for a period of 16–24 hours. Once treated, the seed is sown in standard potting media and placed in a hothouse or igloo. This procedure produces a high germination rate.

First signs of germination occur after approximately 4 weeks, with a flush of germinations in the 5th week (Figure 22.12). Although seed can germinate 11 weeks after sowing, viability and vigour is extremely poor.

When both the seedling and host have established themselves in the hothouse (Figure 22.13), they are transferred to an outdoor shaded area for a period of 2 weeks. They are then transferred to direct sunlight to harden prior to planting.

Viability of seed of *S. lanceolatum* from our potted clonal seed orchards was good (81.5%), with an average of 35% of the seed-producing 'plantable' seedlings at age 6 months.

Figure 22.13 Potted sandalwood seedlings

Conclusion

The Queensland Department of Agriculture and Fisheries has supported the Australian Centre for International Agricultural Research (ACIAR) for the past 14 years in the development of *S. lanceolatum*. We now have a better understanding of this species. Looking towards the future, we will endeavour to capture new genetic material, and establish and protect it in our clone banks and seed orchards. In collaboration with ACIAR, the University of the Sunshine Coast and Traditional Owners, we will work towards the development of a commercial planting of sandalwood in the NPA.

Acknowledgements

Funding by ACIAR project FST/2014/069. Support and in-kind from the Queensland Department of Agriculture and Fisheries and the University of the Sunshine Coast.

We acknowledge the Traditional Owners of the sandalwood material who allowed us to collect and propagate the trees for our trials, especially members of the Ipima Ikaya Aboriginal Corporation, Gudang/Yadhaykenu group of Traditional Owners and the Apudthama Land Trust.

Our trials were established with the cooperation of staff and students from Northern Peninsula Area State College (Bamaga), MyPathways, Trility Water and Northern Peninsula Area Regional Council. Thanks also to Seisia Enterprises for the use of their agricultural equipment.

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23 Morphological and heartwood variation of *Santalum macgregorii* in Papua New Guinea

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Abstract

Santalum macgregorii is endemic to the southern part of Papua New Guinea (PNG). This species has been exploited commercially to the point where conservation through domestication is now required to help preserve natural populations. However, there is a lack of knowledge of the natural variation in *S. macgregorii* populations and therefore also the optimal sampling strategy to capture the remaining diversity. In this study, morphological variation (stem and tree form) and heartwood percentage were assessed in 126 *S. macgregorii* trees across five populations and three provinces in PNG.

Wood cores were extracted from each tree to determine the extent of heartwood development and oil quality. Mean tree diameter was found to be 16.4 cm at tree base (0.2 m) and not significantly different among the five populations sampled. A total of 79% of the trees surveyed had heartwood. Mean heartwood percentage was 15.8% of the basal area, with no significant difference among the populations. Significant tree-to-tree variation in heartwood percentage (0 to 61%) was found. A modest positive correlation was found between stem and heartwood diameter (R^2 = 0.15).

To date, informal domestication has been key to the conservation of *S. macgregorii*, with over half (56%) of the trees sampled established through planting or assisted natural regeneration. Physical damage through the action of bark slashing, heartwood check and anthropogenic fire was frequent. A higher incidence of bark slashing was found in trees that were proximal to a village, whereas heartwood check and trunk scald (associated with fire damage) was more frequently found in trees further from a village. Heartwood rot was recorded in almost one in five trees, and even more frequently in trees with trunk scald damage.

The isolated occurrence of sandalwood in the South Fly District (Western Province) had evidence of low harvesting pressures, however, tree size at this study site was equivalent to other heavily harvested sites. The South Fly site is also highly vulnerable to any harvesting activities, with evidence of reproductive depression/failure and no seedling recruitment recorded. Trees within the South Fly population had exclusively white-coloured flowers, which was distinct from the red-coloured flowers of the *S. macgregorii* populations in the Central and Gulf provinces. The results of this study can be used to guide the selection of particular individuals and groups to form the basis of new planted resources. The study also highlights the importance of conserving the few remaining wild stands for this threatened species.

Keywords: environmental variation, essential oil, heartwood, sandalwood, *Santalum lanceolatum*, *Santalum macgregorii*, terpenes, tree structure

Introduction

Trees within the *Santalum* genus (Santalaceae) are hemiparasitic and are distributed within South and South-East Asia, Oceania and Australia (Applegate et al. 1990; Harbaugh and Baldwin 2007). *Santalum macgregorii* F.v.Muell. is endemic to the southern coast of mainland Papua New Guinea (PNG) in dry savannah woodland up to 750 m above sea level, with a mean annual rainfall of around 1,000 mm (Gunn et al. 2002). *S. macgregorii*, also known as PNG sandalwood, is commercially important in the country and has valuable oil-rich fragrant heartwood that was exploited from the early 1890s to the late 1930s, and then again from the mid-1960s. In the early 2000s, harvesting increased to unsustainable levels, which contributed to a significant decline in mature stands (Rome et al. 2020) and the International Union for Conservation of Nature (IUCN) listing the species as Threatened (Eddowes 1998). A strategy for conserving and managing the wild resources of PNG sandalwood was developed by Gunn et al. (2002), although very few of the recommendations have been implemented (Bosimbi and Bewang 2007).

To improve the prospects for conservation and development of *S. macgregorii* in PNG, Bosimbi (2006) strongly recommended establishing in-situ and ex-situ conservation stands as well as building the capacity of local farmers to establish plantings. By 2012, it was evident that very little of this recommended work had been conducted and Kiapranis (2012) therefore called for immediate action to establish a breeding program to reinvigorate the significantly depleted resource. While a formal program was lacking, there has been considerable interest among landowners to plant *S. macgregorii* for future income (Rome et al. 2020). This interest has effectively led to 'community-based' ex-situ stands of *S. macgregorii* being established in some areas. These stands have been established through the planting of seedlings and assisted natural regeneration from remaining trees within regions.

The genetic diversity within natural and community-based ex-situ stands of *S. macgregorii* provides a good basis for the conservation and domestication of PNG sandalwood. This approach has been demonstrated to be effective in the initial domestication of *Santalum austrocaledonicum* in Vanuatu (Page et al. 2020). To date, the selection of cultivated plants in PNG has been somewhat biased towards heartwood percentage. This has been achieved by transplanting suckers and seedlings from mature harvested trees to village areas, but the approach remains largely random and not targeted towards any specific traits due to a lack of knowledge of what constitutes a desirable tree. Understanding the natural phenotypic and genetic variation of *S. macgregorii* is the first step to formally domesticating PNG sandalwood. A pilot study by Brophy et al. (2009) examined the variation in oil chemistry and yield of 14 heartwood samples from five areas in Central, Gulf and Western provinces of PNG and found significant variation in the oil composition. Apart from this study, no other studies have been published on the natural phenotypic and genetic variation of *S. macgregorii*. This paper will begin to close this gap by presenting the tree-to-tree morphological variation and heartwood percentage of 126 trees sampled from across the known natural distribution of *S. macgregorii* in PNG. This work is important for both commercial and conservation purposes.

Materials and methods

Study area

The natural range of *S. macgregorii* in PNG is shown in Figure 23.1. Sampling was undertaken in Rigo (9°46'S 147°34'E, 30–150 mASL) and Kairuku (8°44'S 146°35'E, 10–130 mASL) districts within Central Province, Iokea (8°24'S 146°17'E, 5–85 mASL) District in the Gulf Province, and a small area of the South Fly District to the east of the Mai Kussa River around the villages of Buzi, Berr and Sibidiri (9°07'S 142°15'E, 10–30 mASL) in Western Province. The sampling areas have a dry tropical monsoonal climate. The mean annual temperature ranges from 25.89 °C to 26.83 °C, and the mean monthly temperatures range from 20.17–21.05 °C to 31.02–32.27 °C. The annual rainfall ranges from 1,664 to 2,122 mm, with the wettest month typically receiving 243–273 mm and the driest month 35–102 mm (Fick and

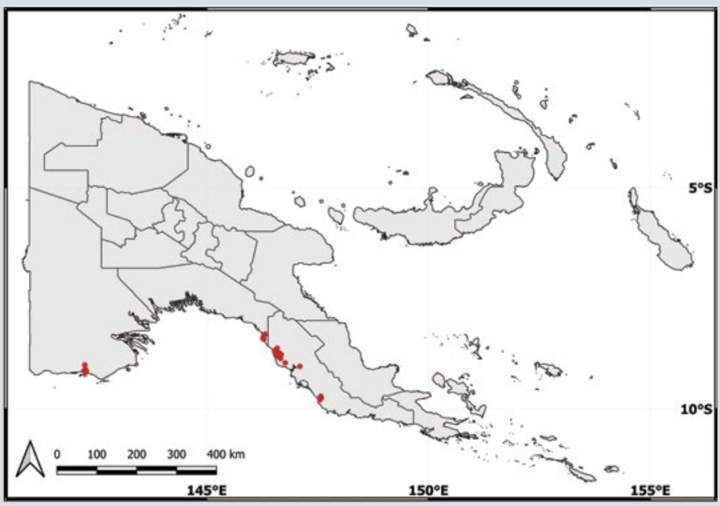

Figure 23.1 The natural range of *S. macgregorii* in Papua New Guinea and locations of trees sampled for this study

Hijmans 2017). The trees sampled were either located within cultivated areas close to or within village areas, in a protected situation within savannah woodlands, or within or adjacent to vine thickets along water courses/drainage lines that run through savannah woodlands. In Western Province, trees were found in savannah woodlands only.

Tree selection

Reconnaissance in the Central and Gulf provinces gave advance notice to landowners, identified where trees were located, and allowed villagers to scout for mature trees for sampling. This gave confidence that the trees sampled from these areas were representative of the remaining populations. In Western Province, sampling was limited to known trees around Buzi, Berr and Sibidiri, which had mostly been found by chance by hunters moving through the bush. There has been no systematic sampling or desire from villages in the South Fly District to locate trees, and therefore there is a high probability that many more trees occur throughout this area.

Selection of sampled trees was largely restricted to trees greater than 10 cm basal diameter. Smaller trees were included in areas where trees were present but there were no larger specimens. For planted specimens, some trees >10 cm were excluded when advised they came from the same mother tree. No other restrictions beyond diameter size were used to select trees as only small numbers remain.

Site description

Location, land form and land surface were described using the basic principles outlined in Terrain (2009). This included latitude and longitude (via global positioning system, GPS), aspect (compass), elevation (open source topographic digital map), gradient (clinometer), and slope position. Vegetation was described using general classifiers such as vine thicket, savannah woodland, savannah grassland, nearby major tree species (<10 m), and the dominant grass genus. The relative position of the sandalwood within the landscape was noted when relevant (e.g. on the edge of a drainage line at the change in vegetation from savannah woodland to riparian vine thicket). Soil field texture, colour and pH were also recorded.

Tree description

Sampled trees were described in detail. The descriptions included total height; bole length; habit; diameter over bark at 0.2, 0.7 and 1.3 m; age estimate; canopy spread from north to south and east to west; count and measurement of fire scars; and the reproductive status by estimating the density of buds, flowers, maturing fruits and mature fruits on a scale of 0 (nil) to 5 (high). Recruitment via suckers and seedlings within 10 m of sampled trees were counted and either basal or breast height diameter were measured when recruits were >100 cm in height. Any physical or biotic damage was recorded on a scale of 0 (nil) to 5 (high). Physical damage was further classified as deliberate or indiscriminate for bark slashing, and heartwood check was noted for severity, frequency and cardinal direction. Photographs were taken of the tree, bark, leaves, surrounding vegetation, and when present heartwood checks, slashing and fire scars. For the leaf photos, at least 10 leaves (5 of the topside and 5 of the underside) were placed on a white board with a 15-cm ruler and clear Perspex on top. These images were then converted to black and white to calculate leaf area.

Wood core

One bark-to-bark wood core was extracted from each tree sampled at a nominal height of 0.2 m. Any variance to this height was recorded and was caused by the presence of hollows, rot, fire scars and heartwood checks, which prevented coring at a consistent height. The cardinal direction also varied to accommodate tree shape and damage. Additional cores at 0.7 m, and sometimes also at 1.3 m, were extracted depending upon the amount of heartwood in the first core, the physical condition of the tree, and permission given by the owner to take additional cores.

Immediately after core extraction, each core was placed on an envelope and the sapwood, transition wood and heartwood were marked and measured using colour changes and smell to determine the transition boundaries. Not all wood types were present in all cores. A photograph was taken, and the core placed in an airtight container containing indicator silica gel for quick drying to preserve the oil constituents for later extraction.

Statistics

Differences between populations for measured traits were tested using general linear models and analysis of variance. Correlations between continuous numerical traits were evaluated using Pearson's correlation coefficient.

Results

Tree structure

Stem size and tree height

Trees from the Kairuku District had a statistically greater mean height than those from the Rigo, Iokea and South Fly districts (Figure 23.2). While trees from Kuriva had the greatest mean height, it was statistically intermediate between the two groups, primarily because of the low sample size (n = 4). Trees from Kairuku and

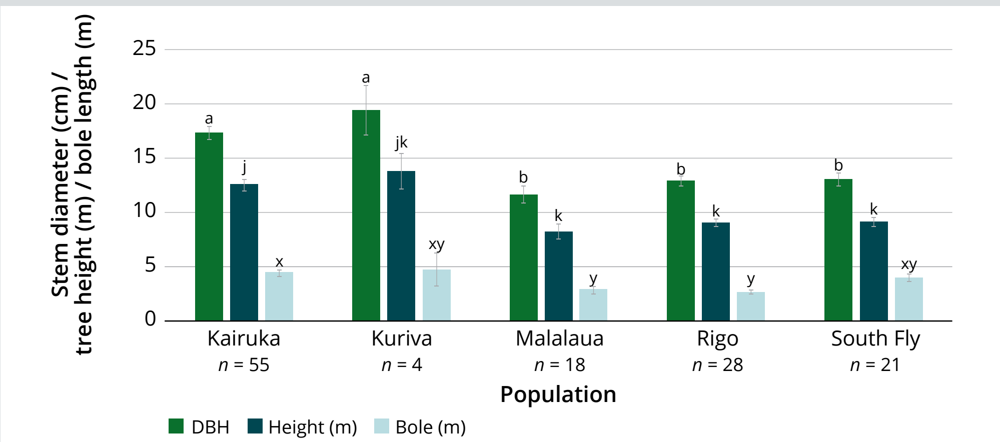

Figure 23.2 Mean stem diameter (diameter breast height over bark, DBHOB), tree height and bole length across five populations of *S. macgregorii* in southern Papua New Guinea

Note: Vertical bars represent standard errors of the mean, n = number of trees sampled from each population. Populations that share lower-case letters are not significantly different for the individual trait.

Kuriva districts had a statistically greater stem diameter at 0.2 m than those from the Rigo, Iokea and South Fly districts, with no significant difference in mean diameter (@0.2 m) within each of these two groups. The mean bole length of trees from the Kairuku District was statistically greater than that of trees from the Iokea and Rigo districts. Trees from the Kuriva and South Fly districts were statistically intermediate between the other two groups.

Tree form and stem taper

Trees with a forked trunk (65% of trees sampled) were the most prevalent form followed by single stemmed (28%), 2–3 primary stems (6%) and multistemmed shrub (1%). Trees with a single trunk were found to have a significantly ($P > 0.05$) greater bole length (4.8 m), but smaller canopy area (15.3 m^2) compared to trees with a forked trunk (3.4 and 22.3 m^2) and 2–3 primary stems (2.1 and 26.6 m^2). No difference in stem diameter (@0.2 m) was found among the three tree forms (single – 17.2 cm, forked – 18.2 cm, and 2–3 stemmed – 20.0 cm) (Figure 23.3).

Heartwood percentage

Overall, 78% of trees sampled contained between 14.6% (Kairuku) and 20.17% (Kuriva) (mean 15.86%) heartwood (Figure 23.4). Stem diameter (at 0.2 mAGL) was moderately positively correlated with sapwood diameter (R^2 = 0.38) and to a lesser extent with heartwood diameter (R^2 = 0.15), but not with heartwood percentage (R^2 = 0.075). Furthermore, no correlation was found for stem diameter and heartwood percentage among planted and natural trees. Excluding trees from the Kuriva District from the results as the sample size is too small, the diameter class was not a good indicator of heartwood percentage. Trees from the Kairuku District had the largest diameter and the lowest heartwood percentage, whereas trees from South Fly District had the second lowest average diameter but the highest heartwood percentage. Heartwood was found in all populations in trees with a stem diameter under 11 cm, with two containing <4% heartwood and two >20% heartwood.

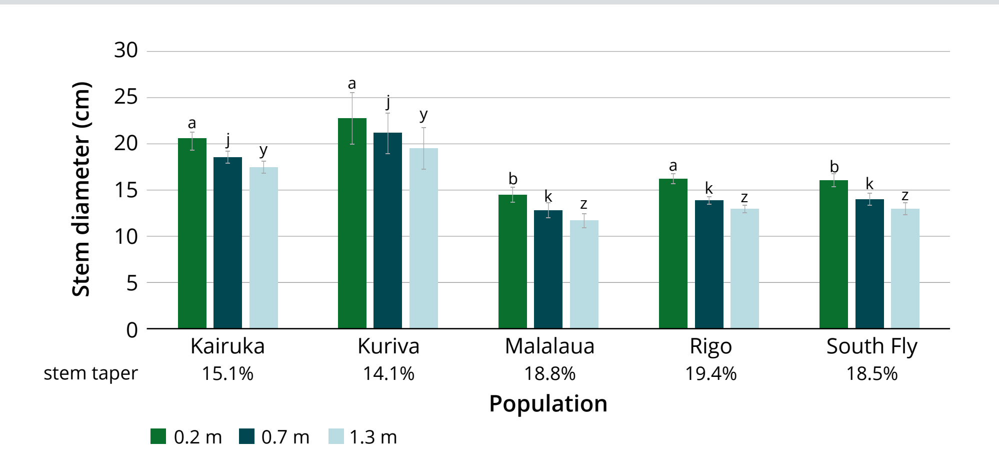

Figure 23.3 Mean stem diameter at three heights (0.2, 0.7 and 1.3 m) from the stem base for five populations of *S. macgregorii* in southern Papua New Guinea

Note: Vertical bars represent standard errors of the mean. Populations that share lower-case letters are not significantly different for the individual trait.

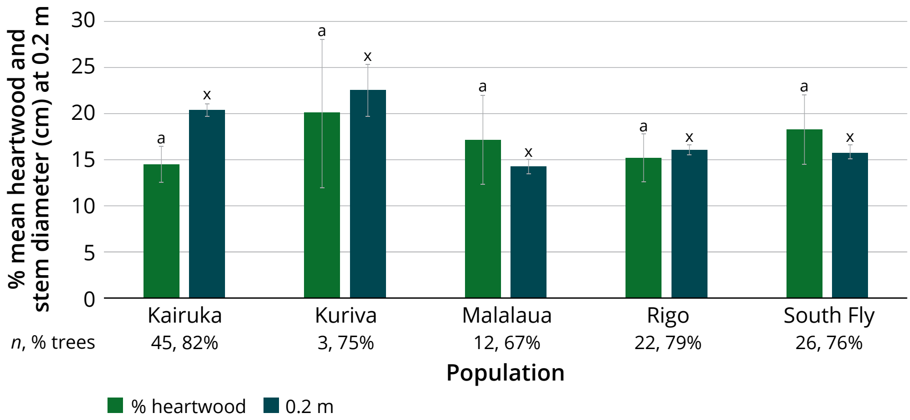

Figure 23.4 Heartwood percentage in cores at 0.2 m that had heartwood present

Note: Stem diameter is the average of the trees that had heartwood and not all trees in each population. Vertical bars represent standard errors of the mean. *n* = the number of sampled trees that had heartwood and % = percentage sampled trees with heartwood.

The lowest percentage of heartwood (<0.1%) was found in a tree with an 18.9 cm diameter, whereas the highest (61.4%) was in a 15.6 cm diameter tree.

Heartwood rot

Heartwood rot affected 19.4% of sampled trees and while there was some variation between populations (ranging from 12.5 to 33.3%), there was no statistical difference among them (Figure 23.5). Tree form influenced the prevalence of heartwood rot. A significantly ($P < 0.05$) greater proportion of trees with multiple stems (33%) had heartwood rot compared with forked (19%) or single-stemmed (16%) trees. No statistical differences in proportion of trees with heartwood rot were found among the latter two forms. The proportion of trees with trunk scald and heartwood check with heartwood rot was 33 and 26%, respectively, with the former being significantly greater than for all trees sampled (19%).

Pests and disease

Biological pests

No incidence of leaf galling, scale insects, root rot or leaf-eating caterpillars was found across all trees sampled in this study. There was an isolated pocket of trees in Ipaipana (Kairuku) that had leaf tiers but this was not observed in any other area.

Human-induced damage

Damage to tree stems due to human action was found to be prevalent, with 50 and 25% of trees with evidence of bark slash and/or heartwood check, respectively. Fire scald scarring was also common, being found in 25% of the surveyed trees.

In the Central Province and Gulf Province locations (Kairuku, Iokea and Rigo districts), between 27 and 39% of trees had evidence of bark slash. In contrast, only 5% of trees in the South Fly District presented with bark slash. For those trees with bark slash symptoms, the severity score was also lower for trees in the South Fly and Rigo districts (1.0–1.5) compared with trees in

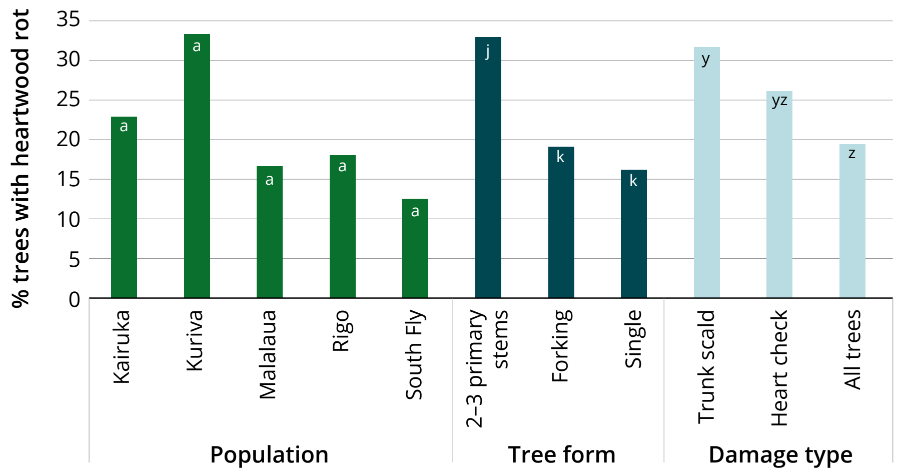

Figure 23.5 Percentage of sampled trees with heartwood rot from cores sampled at 0.2 m from the base for five populations of *S. macgregorii* in southern Papua New Guinea, three different tree form types and two tree damage types across all populations

Note: Populations, tree forms or damage types that share lower-case letters are not significantly different for percentage of trees with heartwood rot.

the Kairuku and Iokea districts (2.7–2.8), although these differences were not significantly different. This was mainly due to the low number of trees affected in the South Fly and Rigo districts.

Heartwood check was most prevalent in the Kairuku, Iokea and Rigo districts (27–39% trees affected), where a significantly ($P < 0.05$) greater proportion of trees in all three populations were affected compared with trees from the Kuriva (0%) and South Fly (5%) districts (Table 23.1). No difference in the severity of heartwood check symptoms was found between any of the populations where this damage was found.

A significantly ($P < 0.05$) greater proportion of trees with trunk scald was found in the sampled trees from the Rigo (54%) and South Fly (33%) districts compared with the Kairuku (15%), Kuriva (0%) and Iokea (11%) districts (Table 23.1). Fire scald damage was significantly ($P < 0.05$) lower in the Iokea District (116 cm^2) compared with the Kairuku (363 cm^2), Rigo (534 cm^2) and South Fly (467 cm^2) districts. There were no significant differences between the three latter sites.

Reproduction

Phenology

All observed flowering trees in the South Fly District had white-coloured flowers, which contrasts with all other populations which had exclusively red flowers. Bud and flower intensity in the South Fly District was statistically lower than the Iokea and Kairuku districts, and Rigo District was intermediate between these groups (Figure 23.6). No fruits were observed in the South Fly District and Kuriva District's sample size was too small for comparison. There was no statistical difference in immature fruit abundance between the Iokea, Kairuku and Rigo districts, however, the Iokea District had a greater abundance

Table 23.1 Incidence and severity score of bark slash, heartwood check and fire scald scars found across five populations of *S. macgregorii* in southern Papua New Guinea

Population	Bark slash		Heartwood check		Fire scald	
	% trees	Score	% trees	Score	% trees	Area (cm^2)
Kairuku	80 ^{b}	2.7 ^{a}	27 ^{a}	2.9 ^{a}	15 ^{b}	363 ^{a}
Kuriva	100 ^{a}	2.8 ^{a}	0 ^{b}	-	0	-
Iokea	67 ^{bc}	2.3 ^{a}	28 ^{a}	3.2 ^{a}	11 ^{b}	116 ^{b}
Rigo	7 ^{d}	1.5 ^{a}	39 ^{a}	3.7 ^{a}	54 ^{a}	534 ^{a}
South Fly	5 ^{d}	1.0 ^{a}	5 ^{b}	2.0 ^{a}	33 ^{a}	467 ^{a}
Total	**50**	**2.5**	**25**	**3.2**	**25**	**450**

Note: Severity score was determined through subjective evaluation on a five-point scale from 1 (low) to 5 (high). Lower-case letters denote a significant difference at the 0.05 *P*-value level between the populations within each column.

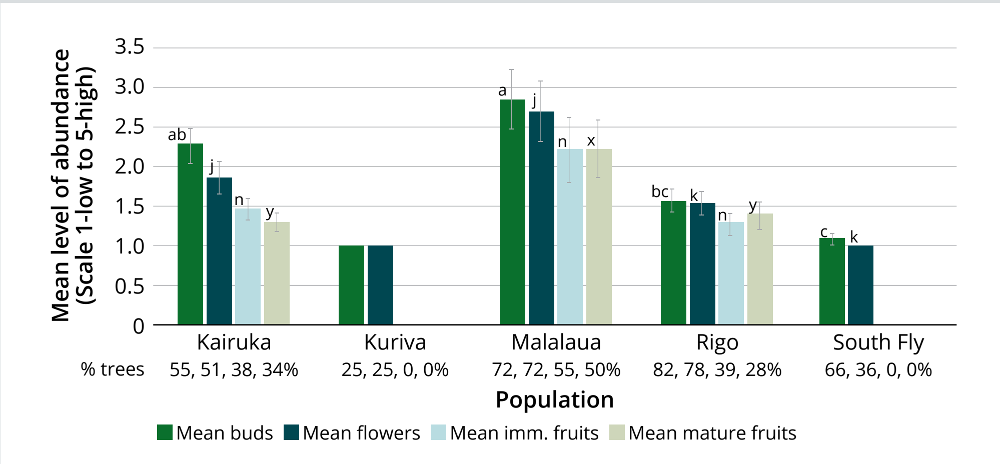

Figure 23.6 Mean level of abundance for and percentage of trees with buds, flowers, immature fruits and mature fruits for five populations of *S. macgregorii* in southern Papua New Guinea

Note: Abundance was a subjective measure on a five-point scale from 1 (low) to 5 (high) and means for each reproductive structure were calculated only for those trees where they were present. Vertical bars represent standard errors of the mean. Populations that share lower-case letters are not significantly different for the individual trait.

of mature fruits. Comparing cultivated against natural trees reveals that only one natural tree (n = 14) from the Kairuku and Iokea districts had reproductive structures, compared to 71% (n = 59) that were planted. In contrast, trees from Rigo District were reproducing regardless of their cultivation status (80% natural (n = 20), 87.5% planted (n = 8)) and may reflect differing environmental factors between the natural and planted areas.

Recruitment

Overall, recruitment was twice as likely to occur as vegetative suckers (42%) than seedlings (21%) (Table 23.2 and Table 23.3). There was no seedling recruitment in the South Fly and Kuriva districts and the there was no significant difference in both the percentage of trees (14–29%) or the mean number of seedlings (10.4–13.25) (Table 23.2) for the other three regions.

Table 23.2 Summary of seedling recruitment for five populations of *S. macgregorii* in southern Papua New Guinea

Population	Trees sampled (*N*)	Total no. of seedlings^	No. trees with seedlings	% trees with seedlings	Mean no. seedlings*+	
Kairuku	55	171	16	29 [a]	10.69	(3.91) [a]
Kuriva	4	0	0	0 [b]	-	
Iokea	18	52	5	28 [a]	10.4	(7.48) [a]
Rigo	28	53	4	14 [a]	13.25	(12.25) [a]
South Fly	21	0	0	0 [b]	-	
Total	**126**	**276**	**25**	**21**	**11.5**	**(3.23)**

^ Total number refers to the sum of all seedlings within a population.
* The mean number of seedlings are for only those trees where they were recorded.
+ Figures in parentheses are standard errors of the mean.
Note: Populations that share lower-case letters are not significantly different for the individual trait (column).

Table 23.3 Summary of root sucker recruitment for five populations of *S. macgregorii* in southern Papua New Guinea

Population	Trees sampled (*N*)	Total no. of suckers^	No. trees with suckers	% trees with suckers	Mean no. suckers*+	
Kairuku	55	20	11	20 [b]	1.82 [a]	(0.42)
Kuriva	4	0	0	0 [c]	-	
Iokea	18	11	5	28 [b]	2.20	(0.96) [a]
Rigo	28	82	21	75 [a]	3.9	(1.59) [a]
South Fly	21	184	16	76 [a]	11.5	(3.98) [b]
Total	**126**	**297**	**53**	**42**	**5.13**	**(1.22)**

^ Total number refers to the sum of all seedlings within a population.
* The mean number of suckers are for only those trees where they were recorded.
+ Figures in parentheses are standard errors of the mean.
Note: Populations that share lower-case letters are not significantly different for the individual trait (column).

Planted trees

A total of 56% of trees sampled were identified by landowners as having been planted as seedlings or established via assisted natural regeneration (Table 23.4). The latter included tending and transplanting naturally germinated seedlings (wildlings) or vegetative suckers. All four trees sampled at the Kuriva District recreation area were planted. In the Kairuku and Iokea (~80%) districts, the percentage of planted trees was significantly ($P < 0.05$) greater than in the Rigo (28%) and South Fly (0%) districts.

Discussion

Tree structure

Trees from the Kairuku District were found to have the largest height and diameter, followed by trees from the South Fly, Rigo and Iokea districts. The bole length followed the same order, except that trees from the Iokea District averaged 19 cm more than trees from the Rigo District. Forked trees were the most common form encountered (65% of sample), and while not an ideal form, they averaged an acceptable bole length of 3.4 m. However, this was 1.4 m less than the single-stem average.

The sampled sandalwood populations represent a snapshot in time of available trees that were managed in various ways, even within populations, and are therefore not a good indication of the relative growth performance, or form, of each population. The situation is somewhat different in the more isolated South Fly District where the population was the least modified. Landowner discussions revealed there has been no harvesting in this district over recent decades and heartwood check damage was almost non-existent. Despite this, mean tree diameter in South Fly District was either equal to or lower than other sites where intensive harvesting has been a feature. This is most likely a reflection of the difference in market potential between regions. For example, in the South Fly District, little to no time is spent protecting trees that have no perceived value and are 'harvested' by fire, whereas the eastern provinces have an established market and actively manage the resource, similar to the natural population in the South Fly District.

Table 23.4 The number and proportion of trees established via planting and assisted natural regeneration for five populations of *S. macgregorii* in southern Papua New Guinea

Population	*N*	Natural	Planted/ assisted natural regeneration	% planted/ assisted natural regeneration
Kairuku	55	11	44	80 [b]
Kuriva	4	-	4	100 [a]
Iokea	18	3	15	83 [b]
Rigo	28	20	8	28 [c]
South Fly	21	21	-	0 [d]
Total	**126**	**55**	**71**	**56**

Note: Populations that share lower-case letters are not significantly different for percentage of planted/assisted natural regeneration.

Heartwood percentage

The heartwood percentage varied considerably between trees and size class, giving no clear patterns to report. The overall heartwood average was 15.86% and individual districts all had a less than 5% difference to this overall average. In Rigo District, planted trees had twice the heartwood of wild trees (24.8% vs 11.6%), trees in Iokea District had three times the heartwood in natural trees (40.1% vs 12.6%), and trees in Kairuku District were more similar, with natural trees only 5% higher (18.9% vs 13.8%). It would seem logical that planted trees would be tended and grow quicker with fewer biotic stresses than natural trees. Therefore, natural and planted trees with an equivalent size class may have a different age class and so heartwood content may be greater in 'older' natural trees. However, there is no relationship between diameter and heartwood percentage for planted or natural trees, with examples of large natural individuals having little to no heartwood (e.g. 25.0 cm and 0.17%) and small planted individuals with high amounts of heartwood (e.g. 13.9 cm and 32.80%). The results of this study suggest that stem diameter positively influences the amount of heartwood within, but that the relationship only describes 15% of the variation. Other factors such as genetic and environmental variation and their interaction are likely to have a significant influence over heartwood development in this species.

Pests and diseases

Besides harvesting, fire is the biggest risk for mature trees to persist in the wild, but the genotypes themselves are probably quite robust and will likely survive as annual root suckers. It was not uncommon to find small suckers within the grasslands, and trees beyond waist height were mostly related to landscape position (e.g. gully, top of high ridges, within a riparian vine thicket) or that the landowner had cared for the trees by clearing grass to protect them from the annual fires.

A high incidence of bark slashing was found in populations that were located close to or within a village (Iokea and Kairuku districts) or public area (Kuriva District) with a high level of human activity. In contrast, a low incidence of bark slashing was found where trees occurred in areas that were more distant to the village that had a relatively low level of human activity (Rigo and South Fly districts). The prevalence of fire damage was opposite to this, whereby more trees were affected in isolated areas (Rigo and South Fly districts).

No substantial biological pests or diseases were observed in the trees in this study.

Reproduction and recruitment

The phenology data only provides a snapshot in time that may be indicative of seasonal conditions at the time of sampling. However, it is interesting that all types of reproductive structures were observed in the Kairuku, Iokea and Rigo districts, indicating that there is not one seasonal cue which induces reproductive structures. The higher propensity of reproduction found in cultivated specimens from the Kairuku and Iokea districts suggests that water, possibly nutrition, and diversity of host plants found around villages, could have a positive influence on seed production. The flower colour was red in all populations except the South Fly District, which was white, supporting the observations of Bosimbi (2006).

The landowners from the South Fly District reported to have never observed mature fruits, and none were observed in this survey. While flowering was observed on 14 trees (64%), it was very sparse on all but one tree with only one or two inflorescences per tree. This could reflect seasonal variation, but coupled with no observed seedlings, and landowners having never observed fruits, it is indicative of potential reproductive failure in this population, although this has yet to be properly investigated. Sexual reproductive failure has been recorded in other species of sandalwood such as *Santalum lanceolatum* resulting from population fragmentation and clonal reproduction, combined with self-incompatibility and pollen sterility (Warburton et al. 2000; Lee et al. 2019).

Through actions of harvesting and fire, people are the primary cause of the decline in PNG sandalwood. However, people are also key to this species' ongoing survival and expansion through tree farming. Resource owners suggested that most of the mature trees were removed during the early 2000s when there were high levels of trade (Rome et al. 2020). The remaining natural trees were either too small at the time of the recent harvest, had yet to form heartwood, or have regenerated through root suckers. With competition for resources and difficulties in protecting trees from fire, checking and poaching, resource owners are establishing trees within and nearby their villages to afford some level of protection. Over half (56%) of the trees sampled were cultivated, and this was as high as ~80% in the Kairuku and Iokea districts. Every effort was made to survey natural trees, but these figures reflect the very low numbers of trees growing beyond the village areas in more natural settings. In Rigo District, most sampled trees (72%) were located beyond the immediate village area, with many having regenerated as root suckers from previously harvested mother trees. However, there were still many trees within village areas, they were just too small to be included in this study. The South Fly District was completely opposite to all other areas where the resource remained largely untouched, with only two examples of villagers moving trees to village areas.

Clonal recruitment through root suckering was found to be a prominent form of reproduction in *S. macgregorii* across all the study sites. Seedling recruitment was found to occur in the populations of the Central and Gulf provinces (~20% of trees had approximately 10 seedlings each), but not in the isolated population within Western Province. Most seedlings were found within 5 m of the mature seed tree and were primarily less than 1 m in height. There was a distinct lack of saplings greater than 1 m or any saplings occurring beyond the seed trees. With frequent grass fires in natural sandalwood areas (i.e. beyond village areas), seedling recruitment in *S. macgregorii* was limited across its natural range.

Acknowledgements

This chapter was published in modified form in Page T, Jeffrey GK, Macdonell P, Hettiarachchi D, Boyce MC, Lata A, Oa L and Rome G (2020) 'Morphological and heartwood variation of *Santalum macgregorii* in Papua New Guinea', *Australian Forestry*, 83(4):195–207.

This study was conducted with the generous support of the Australian Centre for International Agricultural Research (ACIAR project FST/2014/069). The study acknowledges the support of landowners in Papua New Guinea who agreed to participate in the study and assisted the research team with locating sandalwood trees.

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24 Managing population structures and genetic processes to design a conservation strategy for Indonesian sandalwood (*Santalum album*)

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Abstract

This paper reviews previous studies on sandalwood in Indonesia with a focus on population structures, genetic parameters, mating systems, geneflow, selection and reproductive outputs. The ability to maintain outcross mating and higher genetic diversity within sandalwood populations, and to achieve high reproductive outputs, resulted from the combined effect of four factors: (1) the structure of a population, including landscape and habitat characteristics, which contributed to the degree of clonality, fragmentation and isolation; (2) the geneflow with regard to pollen flow and seed dispersal; (3) the reproductive biology, particularly the flowering, pollination and mating pattern; and (4) the composition of parents, with regard to the genetic base and clonality. Several recommendations for designing a sandalwood conservation strategy are proposed: (1) mapping of the genetic diversity and genetic differentiation according to the International Union for Conservation of Nature (IUCN) standard; (2) improving the parental genetic base; (3) preventing the parental clonality; (4) enlarging the population size; (5) facilitating natural generative seedling recruitments; (6) optimising outcrossing in populations by flowering, pollinators and pollination management, and outcross planting design; (7) creating landscape connectivity to facilitate geneflow and prevent habitat fragmentation; (8) managing the selection process in populations; (9) establishing sandalwood conservation areas; (10) establishing new plantations of sandalwood; and (11) conducting further genetic and taxonomic studies on the possible occurrence of new variants.

Introduction

The most valuable species of the Santalaceae genus, *Santalum album* Linn. (hereinafter referred to as sandalwood), has been cultivated extensively throughout India, Indonesia and Australia. There is still debate as to whether *S. album* is native to India or was introduced over 2,000 years ago from other islands, possibly Indonesia or Australia (Harbaugh and Baldwin 2007). Previous research has shown strong evidence that the Outer Banda Arc of the Banda Islands in the south-east of the Indonesian archipelago is the centre of origin of *S. album* worldwide (Angadi et al. 2003). The occurrence of *S. album* in India and Australia was even considered to be the result of gene introductions from Timor Island, Indonesia, many hundreds of years ago (Angadi et al. 2003; Rao et al. 2007), and the genetic differentiation that exists among sites was considered to be due to the effects of bottlenecks and genetic drifts (Angadi et al. 2003). Other authors believe that the genus *Santalum* originated from Indonesia, Australia or both. Different dispersal and speciation events throughout the Hawaiian Islands and the Indian subcontinent have caused differences in evolutionary and genetic processes, resulting in significant difference among sandalwood populations (Harbaugh and Baldwin 2007).

Australia, India and Indonesia were previously among the main producers and exporters in the international sandalwood trade (Angadi et al. 2003; Rao et al. 2007; da Silva et al. 2016). However, due to rapid habitat degradation, sandalwood production in Indonesia ceased in 2007, and since then, Indonesia has not participated in the global sandalwood trade (Kementerian Kehutanan RI 2012). In 1994, sandalwood was first listed as Vulnerable under the International Union for Conservation of Nature (IUCN) Red List of Threatened Species due to habitat degradation resulting in substantial population reductions (IUCN 1994). Since 2004, sandalwood has been considered Extinct in the Wild in most of its former native range in the south-eastern islands of Indonesia (Kementerian Kehutanan RI 2012; Bere 2012; Balai Penelitian Kehutanan Kupang, pers. comm.). In 2012, a re-inventory of wild sandalwood populations in Indonesia confirmed severe reduction within less than three generations (equal to 10 years) (Kementerian Kehutanan RI dan Pemprov NTT 2010). Since many observations have indicated an extreme reduction in Indonesia's wild sandalwood population size, the species' current IUCN Red List status of Vulnerable may soon need to be raised to Endangered, Critically Endangered or even Extinct in the Wild (IUCN 2009).

Considering the serious genetic depletion and habitat loss of sandalwood in Indonesia, numerous reintroduction and rehabilitation efforts have been conducted (Kementerian Kehutanan RI dan Pemprov NTT 2010; Kementerian Kehutanan RI 2012). However, in 2015 the Indonesian government announced the mass failure of sandalwood rehabilitation in the country.

Very low seed viability and seedling survival were the main factors in this failure (Anonymous 2015; Balai Penelitian Kehutanan Kupang, pers. comm.). Similar reproductive failures have been reported with *Santalum lanceolatum* in southern Australia (Warburton et al. 2000), *Santalum spicatum* in Western Australia (Byrne et al. 2003), *Santalum insulare* in the Pacific islands (Lhuillier et al. 2006), *S. album* in peninsular (Rao et al. 2007) and southern India (Dani et al. 2011) and *Santalum austrocaledonicum* in New Caledonia (Bottin et al. 2007). The factor responsible for these failures was the high level of selfing due to small-sized and highly cloned populations in all regions (Warburton et al. 2000; Ratnaningrum et al. 2015).

This paper reviews previous studies on sandalwood in Indonesia with a focus on population structures (Ratnaningrum et al. 2015), genetic parameters (Indrioko and Ratnaningrum 2015; Ratnaningrum et al. 2015), mating systems (Ratnaningrum et al. 2015, 2016, 2017a, 2018; Fathin and Ratnaningrum 2018; Ratnaningrum and Kurniawan 2019), geneflow and selection (Ratnaningrum et al. 2017b), and reproductive outputs (Ratnaningrum et al. 2016, 2017a, 2018). Based on the previous studies, this paper analyses the effects of population structures on genetic processes, with regard to mating systems, geneflow and selection, and examines their roles in determining the reproductive outputs and population genetic parameters in sandalwood populations along landscape and environmental gradients in Indonesia. The paper provides an initial critical step in designing a conservation strategy for sandalwood in Indonesia based on the management of population structures and genetic processes.

Materials and methods

Study sites and materials

The islands of Timor and Sumba located in the south-east of the Indonesian archipelago are considered the origin of sandalwood. These islands are arid regions with a strong tropical savannah climate (Köppen climate catergory *Aw*), characterised by long drought periods, particularly at lower altitudes. Sandalwood occurs at altitudes of between 100 mASL to more than 2,000 mASL. Since the 1900s, sandalwood was heavily exploited on the islands. As a result, small numbers of trees remain and these are typically dispersed in small groups or stands. Conservation efforts have included attempts to rehabilitate some natural stands, and establish in-situ and ex-situ conservation areas. However, most of these areas have been established using unknown sources of genetic materials, and have therefore resulted in very low survival rates (Kementerian Kehutanan RI 2012; Indrioko and Ratnaningrum 2015).

New landraces of sandalwood have emerged in the Gunung Sewu Global Geopark Network on Java Island in the central part of the Indonesian archipelago (Ratnaningrum et al. 2015). Gunung Sewu is a 1,300 km^2 mountainous limestone zone marked by conic karst hills. The area has two distinct seasons: a rainy season during October to March and the dry season from April to September. As it is adjacent to the Indian Ocean, the area has two types of climate: *Aw*, the semi-arid to arid type characterised by long drought periods, and *Am*, which is an intermediate condition between a tropical and subtropical climate (Simanjuntak 2002; Haryono and Suratman 2010). In Gunung Sewu, the new sandalwood landraces occurred across a range of landscapes (Dinas Kehutanan Propinsi Yogyakarta 2015) (Figure 24.1).

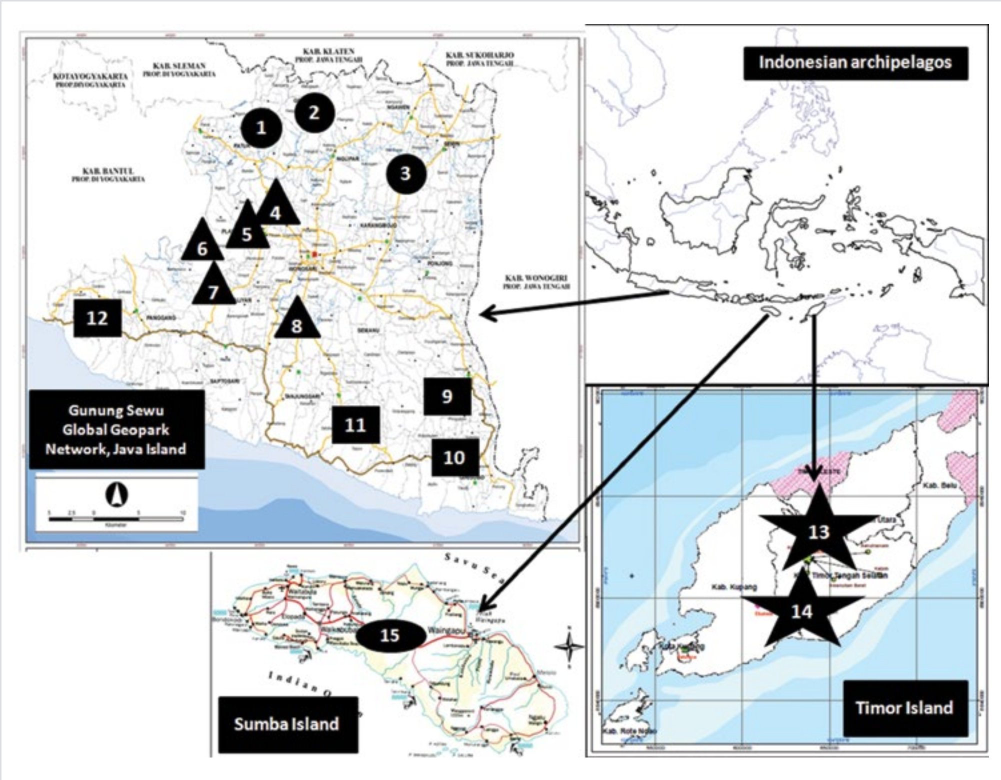

Figure 24.1 Study sites – (a) Sandalwood landraces in the Gunung Sewu Geopark, Java Island: Nglanggeran (1), Sriten (2), Bejiharjo (3), Bunder (4), Wanagama (5), Bleberan (6), Banyusoco (7), Mulo (8), Semugih (9), Botodayakan (10), Tepus (11) and Panggang (12) landraces; and (b) Sandalwood origin in Sumba Island (15) and Timor Island (Netpala, 13 and Soe, 14 populations)

Note: Within each Gunung Sewu zone, landraces are marked by circles (Northern Zone), triangles (Middle Zone) and rectangles (Southern Zone), respectively.

Methods

Measurements on population structures and clonality

The data on population structures include population width, density, effective population size, and the degree of clonality (Indrioko and Ratnaningrum 2015; Ratnaningrum et al. 2015). The data were collected in 2015 following a modified method of that previously applied by Applegate et al. (1990), Warburton et al. (2000) and Rao et al. (2007).

Isozyme analysis

Electrophoretic procedures with vertical polyacrylamide gel were conducted from 2015 to 2017 (Indrioko and Ratnaningrum 2015; Ratnaningrum et al. 2015, 2017b) following the David-Ornstein method (Seido 1993). Three enzymes – shikimate dehydrogenase (SDH; E.C. 1.1.1.25.), esterase (EST; E.C. 3.1.1.) and diaphorase (DIA; E.C. 2.6.4.3.) – were observed to be polymorphic. Interpretable zymmogram phenotypes were found for six loci – shikimate dehydrogenase *Skd-1*, esterase *Est-1*, *Est-2*, and *Est-3*, and diaphorase *Dia-1* and *Dia-2*.

Flowering phenology observation

Observations of flowering and seed production were conducted from 2015 to 2017 (Ratnaningrum et al. 2016, 2017b, 2018) following modified methods of Owens et al. (2001) and Ghazoul (1997).

Pollinator and pollination observation

Pollinator and pollination observations were conducted during the 2017 to 2018 flowering period (Ratnaningrum et al. 2018; Fathin and Ratnaningrum 2018) following modified methods of Ghazoul (1997).

The reproductive outputs measurements

Reproductive outputs were measured from 2016 to 2017 (Ratnaningrum et al. 2016, 2017a) following modified methods of Owens et al. (2001).

Statistical analyses

Multiple linear regressions based on population size and parental clonality examined the relationship between both parameters and the predictor variable of total flower abundance. The same method was applied to estimate the effect of population structures and flower abundance on genetic diversity; and the correlation of population structures, flower abundance and genetic diversity with reproductive outputs. Some of the variables were subjected to logarithmic transformation to obtain normal data distributions. For multiple regressions, a backward stepwise procedure was applied, with the final model including only variables with a significant ($P < 0.05$) effect on the dependent variable. Statistical analyses were carried out with SPSS Statistics (Version 16.0, SPSS Inc.).

Results

Population structures

Each of the sandalwood populations in Gunung Sewu, Timor and Sumba were found on different landscape formations and subject to different evolutionary and ecological histories, resulting in differences in their present-day landscape and habitat characteristics. Each population was also subject to different genetic processes. Characteristics of the different populations were therefore highly varied (Table 24.1).

Table 24.1 Landscape and habitat characteristics of the studied sandalwood populations

Population, area, altitude, climatic type	Landscape history and present-day habitat characteristics	Soil and rock units	Sandalwood history and present-day population characteristics
Nglanggeran; 79.3 ha; 710–750 mASL; *Am* type	A part of the Nglanggeran Formation in the Northern Zone of Gunung Sewu. Now a mountainous landcape, strong undulating, characterised by tropical mountain ecosystems.	Latosols with volcanic and sedimentary rocks, some with deeper solum.	Sandalwood was first documented in the 1970s. Recently occurred in groups of stands across the Nglanggeran mountain regions, in association with the tropical mountain vegetation. Habitat dominated by the association of naturally regenerated mahogany, *Gliricidea* sp., and several *Garcinia* and *Eugenia* spp.
Sriten; 25 ha; 750–890 mASL; *Am* type	A part of the Semilir Formation in the Northern Zone of Gunung Sewu. Now a highland landscape, strongly undulating, characterised by tropical mountain ecosystems. Isolated by mountainous physical barriers.	Latosols with volcanic and sedimentary rocks, mostly with deeper solum.	Sandalwood was first documented in the 1960s. Recently covered three of the area's largest hills in an association with the tropical highland vegetation. Habitat dominated by the association of naturally regenerated mahogany, *Gliricidea* sp., and several *Garcinia* and *Eugenia* spp.
Bejiharjo; 9.6 ha; 150–180 mASL; *Aw* type	A part of the Sambipitu Formation in the Northern Zone of Gunung Sewu. Now an open dry, rocky hilly landscape with caves and ground rivers below. Representing the dryland ecosystems.	The association of red mediterrans and black grumosols with limestone rocks, mostly with a shallow solum.	Sandalwood is a remnant of the 1970s planted stands. Fragmented due to heavy exploitation, urban development and cave tourism activities since the 1990s. Now exists as a small, fragmented group of stands, dispersed throughout open dry, rocky hills above the caves and ground rivers. Sandalwood grew in an association with cajuputi and acacia regenerated from commercial plantations nearby. Younger sandalwood trees were largely derived from root suckers. Sites dominated by dryland herbs such as grasses and *Eupatorium* sp.

Table 24.1 Landscape and habitat characteristics of the studied sandalwood populations *(continued)*

Population, area, altitude, climatic type	Landscape history and present-day habitat characteristics	Soil and rock units	Sandalwood history and present-day population characteristics
Bleberan; 52.9 ha; 150–170 mASL; intermediate between *Aw* and *Am* type	A part of the Wonosari Basin Formation in the Middle Zone of Gunung Sewu. Now a catchment area of the ancient subterranean Oya River in the lowland basin landscape. Representing the tropical lowland ecosystems.	The association of red mediterrans and black grumosols with limestone rocks, mostly with the deeper solum.	Sandalwood was first documented in the 1970s along the catchment area of the ancient subterranean Oya River, at the lowland basin of the middle zone. Sandalwood dispersed widely along the riparian catchment area and nearby, in association with the tropical lowland forest vegetation, which consists of more diverse vegetation including teak, mahogany, *Gliricidea* sp., *Schleicera* sp., cajuputi and acacia. Population is surrounded by several ex-situ conservation areas, sharing the same river.
Mulo; less than 1 ha; 150 mASL; intermediate between *Aw* and *Am* type	A part of the Wonosari Basin Formation in the Middle Zone of Gunung Sewu. Now a limestone cliffs landscape. Isolated by cliff barriers.	Latosols with limestone rocks, mostly with a very shallow solum.	Limestone cliffs ecosystems. Sandalwood was first documented in the 1970s in the naturally regenerated stands surrounding the cliffs and nearby. Recently, small groups of sandalwood grew on the cracks of vertical limestone cliffs, at 3 m to more than 50 m below ground level.
Wanagama; 6 ha; 150–170 mASL; intermediate between *Aw* and *Am* type	A part of the Wonosari Basin Formation in the Middle Zone of Gunung Sewu. Now a lowland basin landscape.	Latosols with limestone rocks, mostly with deeper solum; well-managed.	Sandalwood was first introduced in 1967 using seedlings from Timor. Ex-situ conservation area established in 1992–93, consisting of seven provenances from Timor and Java islands. Site is a part of the Wanagama Forest Research Station belonging to the Universitas Gadjah Mada, well-managed for research activities.
Petir; 78 ha; 70–100 mASL; *Aw* type	A part of the Wonosari-Punung Karst Formation in the Southern Zone of Gunung Sewu. Now a karst hilly landscape with open dry, rocky hills, strongly undulating, characterised by dry, rocky limestone ecosystems.	Latosols with limestone rocks. Solum is deeper at the basins, but very shallow at the limestone hills.	Sandalwood was first documented in the 1960s in karst hilly areas, recently covering more than 20 open dry, rocky hills. Adult plants were mostly derived from root suckers. In the open undulating areas, sandalwood grew in association with dry, rocky limestone vegetation including acacia and cajuputi, but more dominated by shrubs and herbs such as grasses and *Eupatorium* sp.

Table 24.1 Landscape and habitat characteristics of the studied sandalwood populations *(continued)*

Population, area, altitude, climatic type	Landscape history and present-day habitat characteristics	Soil and rock units	Sandalwood history and present-day population characteristics
Botodayakan; 6.75 ha; 100 mASL; *Aw* type	A part of the Wonosari-Punung Karst Formation in the Southern Zone of Gunung Sewu. Now a karst hilly landscape surrounded by a very dense teak forest, less undulating. The flat basin areas were bordered by the rocky hills and slopes.	Latosols with limestone rocks, mostly with deeper solum.	Sandalwood was first documented in 1970s in karst hilly areas. Recently, small groups of sandalwood grew in an association with dry lowland forest vegetation and shaded by a very dense teak canopy The population is surrounded by a very dense teak forest and was bordered by the rocky hills and slopes, functioning as barriers.
Soe; approx. 10 ha; 200 mASL; strong *Aw* type	Savannah landscapes in the lowland arid region of the southern part of Timor Island. Previously it was sandalwood natural forests covering more than 100 ha. Now a remnant of the heavily wild-harvested population.	Red mediterrans soils, mostly with the shallow solum.	Previously it was sandalwood natural forests covering more than 100 ha. Now a remnant of the heavily wild-harvested population. Sandalwood occurred in dispersed small groups of ramets, heavily cloned, and grew in an association with the lowland arid savannah vegetation.
Netpala; 4.09 ha; 1,090 mASL; *Aw* type	Seed production area in the highland arid region of Timor Island. Less undulating, characterised by a highland arid ecosystem.	Ustic cambisol soils, mostly with the deeper solum.	Sandalwood seed production area established in 1992–93, consisting of six provenances from Timor. Located in the highland arid region in the middle part of Timor Island. Well-managed for seed production purposes.
Sumba; strong *Aw* type	Sandalwood rehabilitated stands, using seedlings from Sumba, planted in the savannah landscapes in the middle region of Timor Island.	Red mediterrans soils, mostly with the shallow solum.	Planted in 2013 with genetic materials collected from the remnant of sandalwood natural forests on Sumba Island. Now 3-year-old saplings of sandalwood in a rehabilitated plantation in Kupang, Timor Island.

Source: Ratnaningrum et al. (2015)

Population structures (i.e. population area, density, effective population size, clonality and the offspring recruitment) were highly varied among sites but similar between seasons (Table 24.2). Clonality was dependent on the landscape features and population disturbances. The occurrence of highly clonal parents was manifest through root suckers arising from their horizontal roots occurring near the soil surface.

Flowering and fruiting phenology

There were six flowering developmental phases (Figure 24.2; Ratnaningrum et al. 2016). Sandalwood flowering and seed production in Gunung Sewu varied with climate and altitude. Both reproductive events are also environmentally sensitive since they are altered by changes in rainfall, temperature and soil water status. The higher altitude sites and the rainy season always produced more flowers, however, higher abortion resulted in very low seed sets. At the lower altitude sites and during the dry season, fewer flowers were produced, but a higher pollination and reproductive success resulted in more fruits (Figure 24.3).

Table 24.2 Number of individuals and population structure for eleven sandalwood populations in Gunung Sewu (Java Island), and Timor and Sumba islands

	Number of individuals		N_a		Clonality (%)	
Populations	**Adult***	**Seedling***	**Adult**	**Seedling**	**Adult**	**Seedling**
Gunung Sewu						
GSN1-Nglanggeran**	1,145 (50)	93 (39)	12.31	2.50	24.02	2.17
GSN2-Sriten**	330 (119)	50 (26)	15.76	2.50	20.00	2.33
GSN3-Bejiharjo**	496 (116)	124 (23)	18.55	2.50	76.62	2.17
GSM1-Bleberan**	1,834 (99)	364 (205)	7.03	2.50	34.35	2.50
GSM2-Mulo	41 (35)	12 (0)	41.46	2.00	12.19	NA
GSM3-Wanagama	276 (120)	78 (41)	76.45	2.50	0	2.50
GSS1-Petir**	9,190 (55)	2,945 (52)	50.92	2.17	77.48	2.17
GSS2-Botodayakan**	151 (29)	72 (50)	17.22	2.17	25.83	2.33
Timor						
Tm-Soe***	NA (21)	NA (0)	NA	1.33	80.00	NA
Tm-Netpala***	344 (30)	NA (0)	63.95	2.50	0	NA
Sumba						
Sb-Sumba***	NA (25)	NA (25)	NA	NA	80.00	2.17

N_a = the mean number of allele per locus, NA = Not assessed; * = number in parentheses is the number of sampled individuals; ** = data available in Ratnaningrum et al. (2015); *** data available in Indrioko and Ratnaningrum (2015)

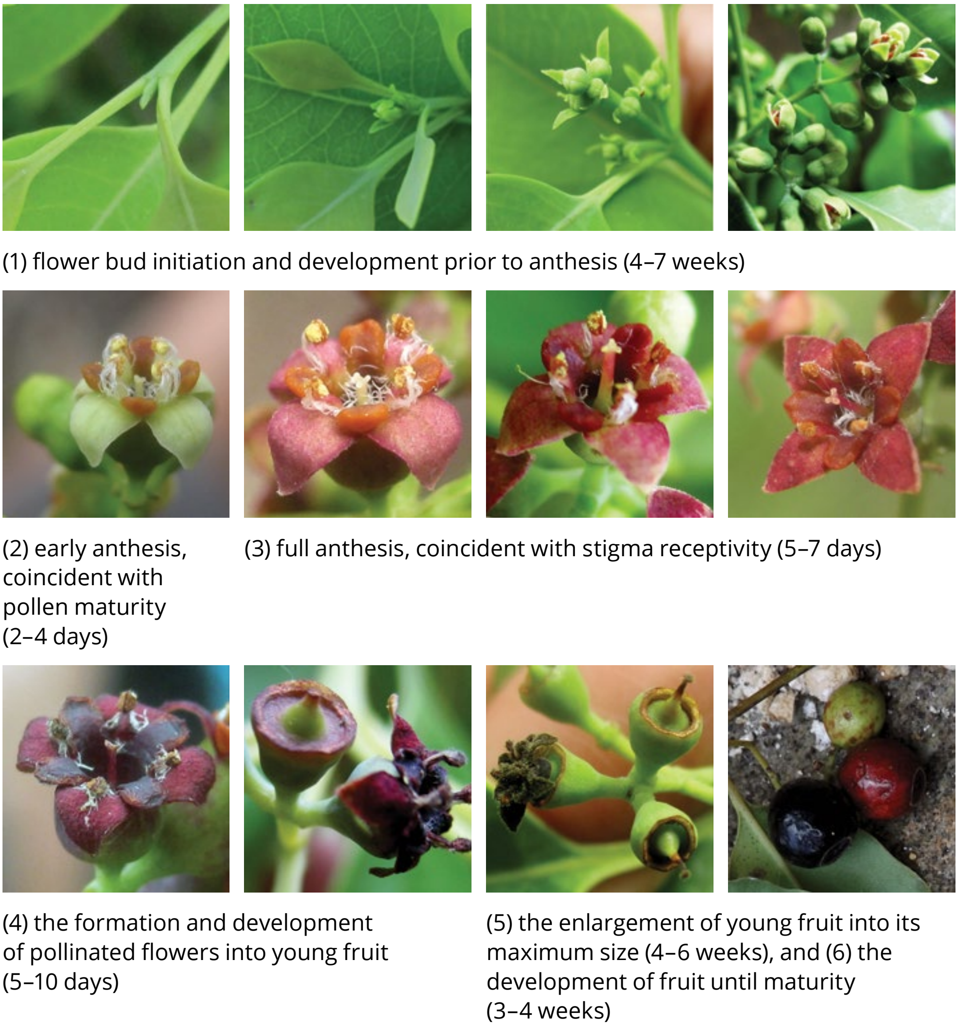

Figure 24.2 Six flowering phases of sandalwood from flower bud initiation to fruit maturity
Source: Ratnaningrum et al. (2016)

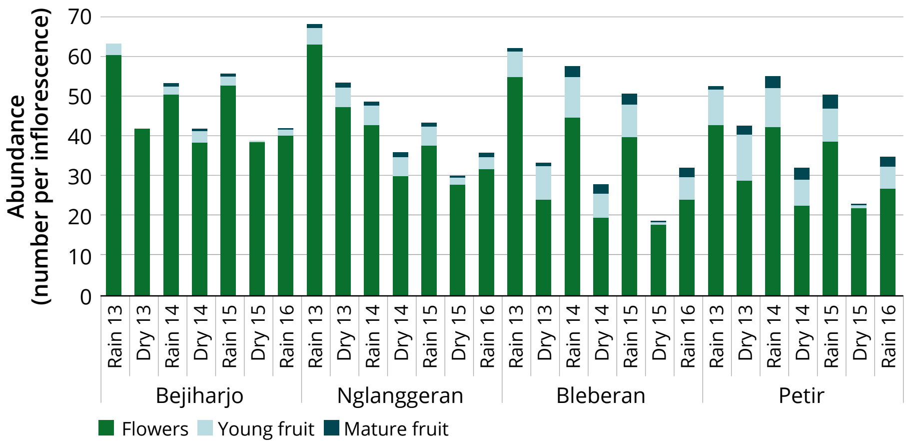

Figure 24.3 The abundance of flowers, young fruits and mature fruits per inflorescence in four sandalwood populations in Gunung Sewu in the rainy and dry seasons during the 2013 to 2015 flowering periods

Note: The bars in *y*-ordinate indicate the number of flowers (green), young fruit (pale blue) and mature fruits (dark blue). The horizontal *x*-line represents the rainy and dry seasons during the 2013 to 2015 flowering periods.

Source: Some of the data of Nglanggeran, Bleberan and Petir from 2013 to 2014 have been published in Ratnaningrum et al. (2016)

Floral initiation and flowering period, as well as the reproductive outputs, varied with altitude and season. Sites with a lower altitude, lower rainfall, highest temperature, lowest humidity and lowest soil moisture flowered earlier and for shorter periods. At all sites, flowering was delayed and more prolonged in the rainy season than during the dry season (Figure 24.3).

Pollination events

The higher and cooler sites (Wanagama, Bleberan) were visited primarily by Dipteran and Hymenopteran pollinators, while pollination at the warmer and lower sites (Petir, Bejiharjo, Nglanggeram) was dominated by Lepidopterans and Dipterans. The higher sites received fewer pollinator visits, but the visitors were more diverse (28 families). In contrast, lower sites received more pollinator visits but with less diversity (20 families) (Figure 24.4). At all sites, more pollinator visits occurred during the rainy seasons, coinciding with the availability of more nectar.

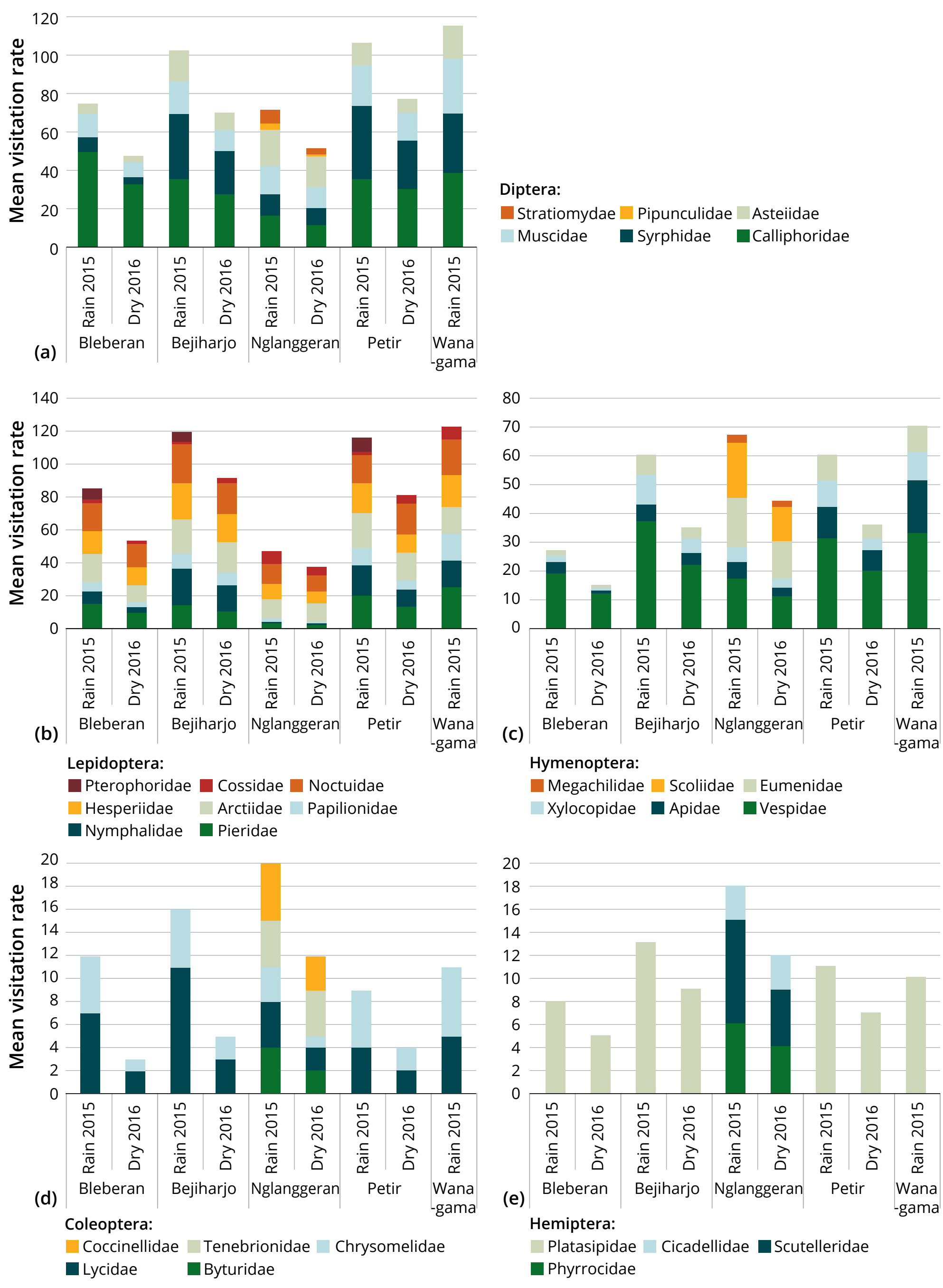

Figure 24.4 The pollinator diversity at the family levels within the order of Dipterans (a), Lepidopterans (b), Hymenopterans (c), Coleopterans (d) and Hemipterans (e), in five sandalwood populations in Gunung Sewu

Source: Data are available in Ratnaningrum et al (2018), and Fathin and Ratnaningrum (2018)

Reproductive outputs

Reproductive outputs among the sites differed more by mating system and the parental genetic diversity. The intraspecific cross-pollination always resulted in the highest reproductive outputs, particularly in the populations that were less cloned and had a higher genetic base (Figure 24.5).

Correlations between variables

From the data collected from the previous studies, a multiple regression analysis was conducted to correlate the components of population structures, genetic parameters, mating systems, floral and pollination traits, and reproductive outputs. Flower abundance plays an important role in determining the reproductive outputs, heterozygosity and mating systems in a population. Flower abundance significantly enhanced the pollinator visitation rate, seed sets and seedling recruitments. However, mass flowering might correlate with the increase of geitonogamy in a population, as the inbreeding parameters increased along with the number of flowers, particularly in the cloned populations and those that had a lower genetic base. Furthermore, more flowers significantly reduced the outcrossing rate, final reproductive outputs and population heterozygosity. Parental clonality increased inbreeding parameters, which reduced the outcrossing rate, population heterozygosity and seedling survival. In contrast, parental heterozygosity (which is strongly affected by flower abundance and clonality) increased outcrossing rate, offspring heterozygosity and seedling survival.

Mating systems also had significant effects on reproductive fitness and heterozygosity. The inbreeding coefficient and selfing rate significantly reduced the offspring heterozygosity, while the outcrossing rate works in an opposite way. Flower

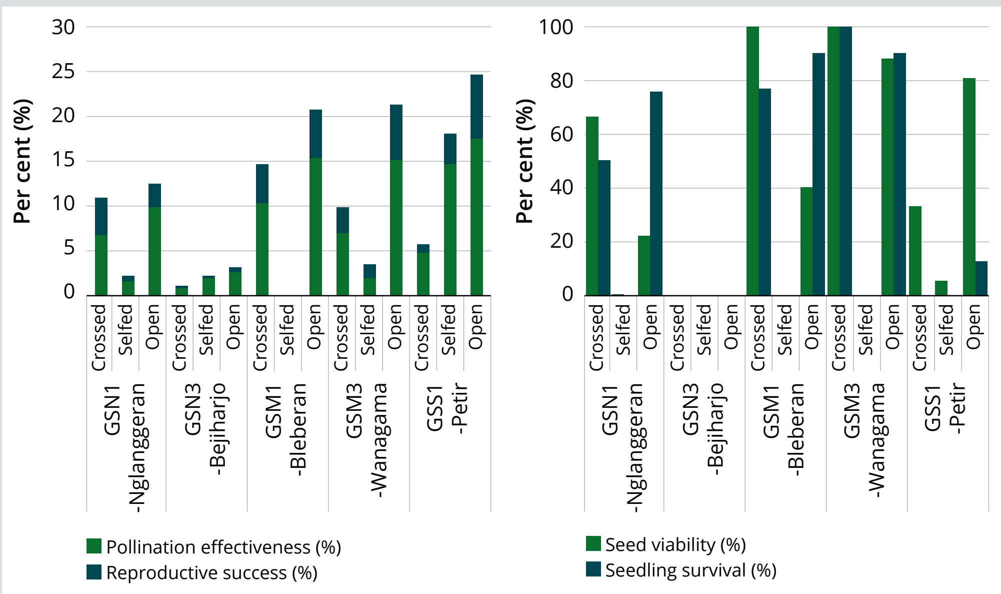

Figure 24.5 Pollination effectiveness, reproductive success, seed viability and seedling survival under cross-, self- and open-pollination treatments in five sandalwood populations in Gunung Sewu, Java Island

Source: Ratnaningrum et al. 2016

abundance is the only variable affected by both sites and seasons. Pollination rate differed only by season but is similar among sites. Other variables differed by sites but were similar between seasons.

Conclusions

Some of the sandalwood populations in Java, Sumba and Timor in Indonesia are genetically and reproductively depleted due to various factors including their geological, evolutionary and anthropogenic disturbance histories. Ongoing genetic reductions and reproductive failures may reduce the species' ability to cope with current and emerging threats, placing populations at great risk of extinction. Moreover, despite the many current and emerging threats and that these will likely increase with time, most of the study sites have still not implemented any sandalwood conservation programs.

Results of this study emphasise the importance of a larger genetic base and geneflow to naturally maintain the genetic and reproductive processes of sandalwood populations in equilibrium conditions. To design a sandalwood conservation strategy, the main recommendation is focused on maintaining the reproductive and genetic processes within each population, but with different strategies according to the parental genetic base, population heterozygosity, mating systems and the degree of fragmentation and clonality of different populations. The continuous, outbreeding and less cloned populations, which have a wider genetic base and higher heterozygosity, may be expected to naturally maintain their genetic and reproductive processes in equilibrium. In more disjunct, inbreeding, cloned and lower genetic base populations, the conservation strategy should focus on improving the genetic base, reducing parental clonality, preventing geitonogamy, enhancing outcrossing and facilitating geneflow. Finally, the sandalwood conservation strategy should be integrated into other regional and national conservation programs, under rehabilitation, reintroduction and community forestry schemes, as well as integration into the conservation management activities of the geopark scheme.

Several recommendations for designing a sandalwood conservation strategy are proposed: (1) mapping of the genetic diversity and genetic differentiation according to the IUCN standard; (2) improving the parental genetic base; (3) preventing parental clonality; (4) enlarging the population size; (5) facilitating natural generative seedling recruitments; (6) optimising outcrossing in populations by flowering, pollinators and pollination management, and outcross planting design; (7) creating landscape connectivity to facilitate geneflow and prevent habitat fragmentation; (8) managing the selection process in populations; (9) establishing sandalwood conservation areas; (10) establishing new plantations of sandalwood; and (11) conducting further genetic and taxonomic studies on the possible occurrence of new variants.

Acknowledgements

These results are a part of the Long-Term Research on Genetic Conservation and Improvement of Indonesian Sandalwood project, which has been conducted by the Faculty of Forestry at the Universitas Gadjah Mada, under the grants of Hibah BPPS year 2012–15 and Hibah Penelitian Disertasi Doktor year 2017 by Kementrian Pendidikan dan Kebudayaan Indonesia, and Hibah Rekognisi Tugas Akhir year 2018 by Universitas Gadjah Mada.

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Acknowledgements and conference details

25 Acknowledgements

Acknowledgement is given to the Vanuatu Department of Forests, who was the host organisation of the Sandalwood Regional Forum in Port Vila. A special mention is given to the three organising committees who worked tirelessly to make the Sandalwood Regional Forum possible.

In addition, Paul Macdonell provided the distribution maps for all the papers in this proceedings, unless stated otherwise.

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26 Participating ACIAR-funded projects

Sandalwood Regional Forum (FST/2016/024)

Improvement and management of teak and sandalwood in PNG and Australia (FST/2014/069)

Enhancing returns from high-value agroforestry species in Vanuatu (FST/2016/154)

Enhancing the formation of heartwood in sandalwood in Vanuatu (FST/2016/054)

Agricultural innovations for communities for intensified and sustainable farming systems in Timor-Leste (AI-Com) (CIM/2014/082)

Domestication and breeding of sandalwood in Fiji and Tonga (FST/2016/158)

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