Australian Government

Australian Centre for International Agricultural Research

Final report

Project full title	**Domestication and breeding of sandalwood in Fiji and Tonga**
project ID	FST/2016/158
date published	October 2021
prepared by	David Bush
co-authors/ contributors/ collaborators	Waisea Bolatolu, Bronwyn Clarke, Heimuli Likiafu, Jalesi Mateboto, Lex Thomson
approved by	Dr Nora Devoe
final report number	FR2021-083
ISBN	978-1-922787-08-8
published by	ACIAR GPO Box 1571 Canberra ACT 2601 Australia

Contents

1 Acknowledgments

We would like to acknowledge the many people who contributed to the formulation, development, and delivery of this project. In Fiji this includes our late colleague and friend Mr Ponijesi Bulai, Mr Sonu Dutt, Mr Noa Vacacegu and Mrs Sanjana Lal; and from Tonga Mr Tevita Faka'osi, Mr Steven Hamani, Mr Pasimati Motuliki, Mr Spencer Hefa, Mr Viliami Kato and Mrs Leody Vainikolo. From SPC, we thank Ms Elina Young and Mr Sairusi Bulai. Dr Joe Brophy (UNSW) and Dr John Doran (CSIRO) are thanked for their assistance with gas chromatograpghy of essential oil samples.

We would like to acknowledge our colleague Dr Tony Page (USC) who leads and is involved in several other ACIAR sandalwood projects in the Pacific. Collaboration with Tony and his network of sandalwood researchers was very fruitful, leading to the collaboration on the Pacific Sandalwood Growers' manual and the work undertaken on *Santalum album* population diversity in Timor-Leste, an additional objective added late in this project. Mr Luis Almeida and Mr Rob Williams from the Ministry of Agriculture and Fisheries, Timor-Leste, also collaborated strongly to deliver this activity.

We would like to thank Dr Tony Bartlett, the ACIAR Forestry Program Manager who originally supported the concept for this project and its predecessor, and the strong support of Dr Nora Devoe, who has been the Forestry Program Manager during the later stages of the project. We would also like to thank Prof. Roger Sands who led an insightful and valuable end-of-project review.

2 Executive summary

Santalum yasi is a sandalwood native to Fiji, Tonga and Niue. The heartwood is highly valuable as its quality rivals that of Indian sandalwood (*S. album*) with the distilled oil fetching around USD 2000 per kg. It has been overharvested in the wild and is now endangered. However, cultivation of *S. yasi* has increased in the last two decades. The sale of a single mature tree can make a meaningful financial impact for families and community groups, including those on outer islands where non-durable products can be difficult to market. Though *S. album* and its spontaneous hybrid with *S. yasi* are also frequently cultivated throughout Fiji and Tonga, an early decision, made by the project team in consultation with stakeholders, was to focus on *S. yasi*. Building a high-value, market niche for *S. yasi* will differentiate it from *S. album,* which is being cultivated on a large scale in Australia and elsewhere.

A conservation and domestication strategy was written that advocates establishment of broadly-based conservation plantings and community-based seed production stands that will increase the diversity and productivity of pure *S. yasi* plantings. A total of six stands (three each in Fiji and Tonga) were established, against an original target of eight. Establishment of the stands proved to be challenging, with numerous setbacks and delays leading to late establishment in both countries. *Santalum yasi* seeds exchanged between Fiji and Tonga arrived too late to be integrated into the plantings, though seedlings are now being raised from this resource.

A major objective was development of a strategy outlining the key steps required to develop a sustainable sandalwood industry that includes processing, value-adding and marketing rather than export of wood only. *The South Pacific Sandalwood Industry Plan for Fiji and Tonga* sets out issues that need to be addressed, including securing sufficient resource on which to base an industry, skills development, processing, and marketing.

A further technical objective was to gather data on sandalwood growth performance – a priority identified in the Industry Strategy. The study involved a re-measure of 156 mature, cultivated, and wild trees inventoried in 2015. The study demonstrated that *S. yasi* grows slowly, as expected, at a rate that is very similar to other sandalwood species. No significant differences were detected in growth rate between the *S. yasi*, *S. album* and their hybrids. This is a very useful dataset and finding. Further measurement of trees of known age, genetic origin and grown on a common set of sites are recommended. A comprehensive inventory of planted resources in Fiji and Tonga is also strongly recommended, as a step towards setting planting targets required to build a resource large enough to support processing and value-adding.

An analysis of heartwood development, oil yield and oil composition of *S. yasi*, *S. album* and their hybrid was undertaken by non-destructively coring 82 trees in Fiji and Tonga. The results of this study showed that trees less than 15 years old have unreliable heartwood development, an important finding for growers who are tending to harvest trees at around this age, and for the domestication program which would need to wait at least until trees are 15 years old for sampling and selection on heartwood and oil traits. Analysis of the oil composition showed that trees with acceptable heartwood tend to have acceptable oil quality and a higher proportion of the desirable β-santalol fraction than *S. album*: this may be a useful point of market differentiation for the product.

An additional Objective added late in the project, substituting for some activities that could not be completed due to COVID-19 travel restrictions was a DNA-based population genetics study of native *S. album* in Timor-Leste in association with project CIM/2014/082. The results showed that although heavily harvested, there is still significant diversity remaining. The information from this study will be used to manage the conservation stands already established and in the formulation of a domestication and breeding program for sandalwood in Timor-Leste.

Further cooperation with other ACIAR sandalwood projects saw the completion of the Pacific Sandalwood Growers' manual – an update of a previous manual focused on growing S. *austrocaledonicum* in Vanuatu. The manual now additionally covers *S. album*, *S. lanceolatum*, *S. macgregorii* and *S. yasi* and should be widely applicable to growers throughout the Pacific.

Capacity building activities mainly focused on development of technical skills for professional staff in Fiji and Tonga. A series of workshops was carried out to provide training on propagating *S. yasi* by cutting and grafting. Further hands-on training with Ministry staff on field inventory was carried out, including development of skills in record keeping using measure sheets and photography, locating and re-locating trees using GPS and coring trees for non-destructive sampling of heartwood. During this project a large turnover of professional and technical staff in both Fiji and Tonga highlighted the ongoing need for broad forestry technical skill development in both countries. This will be critically important for the ongoing implementation of the conservation and domestication plan for *S. yasi* and for other forestry development projects that require research skills.

3 Background

Santalum yasi (known as yasi in Fiji and 'ahi in Tonga) is a hemi-parasite, dependent on the roots of host plants for its nutrients. It is found naturally in Fiji and Tonga, with a very small occurrence reported on Niue. The species produces a highly valued, sandalwood oil-yielding heartwood that has been over-exploited in the wild, resulting in the fragmentation and local extinctions of natural populations. This has been the fate of all of the main commercial sandalwood species, particularly the most commercially valuable, *S. album*, (commercially known as Indian sandalwood; Ai-kameli in Timor-Leste) which is native to Timor-Leste, parts of Indonesia, northern Australia, Sri Lanka and India. The annual harvest volume of *S. album* has declined by an order of magnitude in the last 50 years, although it might still be around 5000 - 6000 t/year (Coakley 2013; Page et al. 2012a). However, the global demand for sandalwood has been maintained and is projected to continue growing (Thomson 2020), which places upward pressure on prices: the stumpage value of a single stem can be well over a thousand dollars (and for very mature trees, the price paid may be tens of thousands of dollars).

S. yasi is readily cultivated on a wide range of sites in Fiji and Tonga and is highly regarded as one of the best alternatives to *S. album* in terms of market acceptance. This makes it highly suitable for the development of plantation industries in Fiji and Tonga. The product is high-value, low-volume and non-perishable, which is an advantage to communities on some of the less-accessible outer islands for whom transporting perishable agricultural produce is not economically viable. As has been found in Vanuatu with the indigenous sandalwood, *Santalum austrocaledonicum,* individual farmers or villagers can generate substantial income from a limited land base. Though over 20,000 ha of sandalwood plantations, using *S. album* and the lower value *S. spicatum,* have been planted in Australia, the development of *S. yasi* as another source of supply, and the opportunity to differentiate *S. yasi* as a unique niche product, is therefore likely to be a profitable enterprise for growers and processors in Fiji and Tonga. Observations from Fiji and Vanuatu also suggest that plantations of indigenous sandalwood species are more resilient to destructive cyclones than *S. album*.

ACIAR SRA (FST/2015/020) surveyed the wild and planted populations in Fiji and Tonga and found that locally, there is low genetic diversity and inbreeding, leading to seedlings of suboptimal genetic quality being deployed. However, there is still quite a large amount of genetic diversity present in the species in its wild and planted distribution throughout Fiji and Tonga, and this could be much better utilised and managed through a domestication and breeding program to underpin viable plantation industries. The benefits of domestication and tree breeding can be quite substantial, and improvements of traits of low-medium heritability, such as stem growth, can be expected to be significant, perhaps between 10-20% in the first generation when inbreeding is present. Genetic and oil quality gains can also be made by selecting the best provenances, while ongoing gains in each generation are to be expected from recurrent selection, breeding and maintenance of genetic diversity.

A major issue in the development of plantation sandalwood is the yield and quality of oil. Published oil yields for *S. album* range between about 1.5% and as high as 9%. Yields of other sandalwood species tend to be lower than about 2%, though high variability is common. The international standard for *S. album* oil (ISO 2002) is typically used to assess the relative quality of sandalwood oils, the chief components being the santalol oil fractions. The standard designates a commercially acceptable oil as that having an α-santalol component accounting for 41– 55% of total oil and β-santalol accounting for 16–24%, meaning an oil should have at least 57% total santalol content to be commercially acceptable (Bush et al. 2020a). While other commercial sandalwood species have difficulty attaining this standard, *S. yasi* is often substituted for *S. album*, implying that its oil constitution may be similar to *S. album*. Further investigation of this, as well as the oil quality of the *S. yasi* x *album* hybrid is warranted. In other sandalwood species, and generally in tree species, the proportion of heartwood at harvest age as well as the overall yield of oil and the relative composition of its constituent components can be highly variable. Studies in other tree species indicate that these traits are often of moderate to high heritability, and their inclusion in breeding programs can therefore be expected to have a substantial influence on the overall value of the crop.

A further question that is not well studied in *S. yasi* or other sandalwoods is the development of oil yield and quality with tree age. There is a tendency, in both Fiji and Tonga to cut trees as soon as they are perceived to have merchantable heartwood. This is driven by the need to generate income and the risks associated with theft of mature sandalwood trees. This often results in trees of around 15 years of age being harvested. This is younger than the usually-suggested harvest age for sandalwoods - usually 20 years or older. Examining the heartwood development, oil yield and oil quality of trees of around 15 years of age would therefore provide answers to two questions: (i) is it important for growers to wait longer to get acceptable heartwood development and oil characters and (ii) can selections be made for oil characters at around 15 years of age? The second question is important in terms of domestication and breeding, because making selections on the key wood and oil traits will be major determinants of the breeding cycle length.

This project seeks to conserve the existing genetic resources of *S. yasi* and to enhance the availability of better quality and more diverse planting material to underpin Fiji and Tonga's emerging sandalwood plantation industries. It will make use of previous plantings and molecular data to access germplasm of known origin and performance and it will make preliminary determinations on the genetic aspects of oil yield and quality. These activities will be carried out within the framework of an updated conservation and domestication plan for the species, that will outline the framework for short-, medium- and long-term activities that will be required to carry out the genetic improvement work that will improve the profitability of the species and ensure its long-term survival.

Although development of a sustainable, plantation based sandalwood industry in Fiji and Tonga would be a good first step for securing the species and the livelihoods associated with it, there is considerable scope for capturing value through processing and value adding in Fiji and Tonga. Since 2000, *S. yasi* exports from Fiji and Tonga combined have averaged about 100 MT of heartwood per annum worth about USD 5 Million. This figure grossly under-represents the potential value of *S. yasi* to the economies of Fiji and Tonga, and its unique potential to provide cash income to villagers living in remote islands and locations. Based on estimates of *S. yasi* currently planted and naturally regenerating (Thomson et al. 2020b), the industry has the potential to increase in value by 3.5 times, and this would be doubled again through appropriate local value-adding and niche marketing such that the industry will be minimally worth USD 35 million per annum (in present $ values). If the Forestry Ministries in each country and private sector work together to increase the current rate of replanting three-fold, then *S. yasi* would grow into a USD 100 million per annum sustainable, green growth industry for Fiji and Tonga. However, several strategic steps are required to develop such a value adding industry. Identification of the required policy, economic and research and development interventions required will be an important enabling activity.

Like *S.yasi* in Fiji and Tonga, *S. album* is a native species in Timor-Leste that has been overharvested over hundreds of years. There is also a significant opportunity for smallholders to grow sandalwood in agroforestry systems, using leguminous fodder-tree hosts, that will diversify their farm incomes (Almeida et al. 2021). However, it is thought that genetic diversity might now have diminished, through population fragmentation, to the point where additional *S. album* genetic resources might need to be imported from elsewhere to form the basis of a domestication program. An additional objective of this study was therefore to carry out a DNA-based molecular marker study similar to that carried out for *S. yasi* (Bush et al. 2016) to determine the level of diversity, relatedness and implications for conservation and breeding of *S. album* in Timor-Leste.

4 Objectives

The project forms part of ACIAR's overall investment in Pacific sandalwood research and development. The primary aim was to establish the foundation for conservation and domestication of native sandalwood (*S. yasi*) in Fiji and Tonga to support the development of a sustainable planted sandalwood industry through addressing objectives 1-4:

Objective 1: Improve understanding of the breeding biology and genetic diversity of key traits in *S. yasi.*

Objective 2: Enhance the genetic conservation status of *S. yasi* in Fiji and Tonga.

Objective 3: Develop strategies to enhance the quality and availability of *S. yasi* germplasm and support development of sandalwood industries in Fiji and Tonga

Objective 4: Disseminate the practical outcomes and implications relating to objectives 1-3 to growers and practitioners

An additional objective was added in the final year of the project, after travel restrictions associated with the global COVID-19 epidemic restricted travel and some activities relating to the four original objectives. Following the success of the molecular genetic study of *S. yasi*, *S. album* and hybrids undertaken as a precursor to this project (project FST/2015/020, Bush et al. 2016), a project variation was agreed to. This enabled collaboration with CIM/2014/082, *Agricultural Innovations for Communities* in Timor-Leste to undertake a population diversity study. An objective of this project is development of *S. album,* which is endemic in Timor-Leste, for smallholder livelihood diversification.

Additional Objective 5: Use DNA molecular markers to assess the population structure and genetic diversity of *S. album* from Timor-Leste

5 Methodology

The methods proposed and/or used to deliver on each of the objectives were as follows:

Objective 1: Improve understanding of the breeding biology and genetic diversity of key traits in *S. yasi.*

1.1 Breeding biology and interactions

S. yasi is assumed to have a mixed mating system and as it is known that spontaneous hybrids between *S. yasi* and *S. album* are common, it is also thought that intra-specific crosses between *S. yasi* provenances will be possible. However, both assumptions will be confirmed by analysis of seedling progeny of trees (germinants raised for the conservation and seed production stands) that have been planted in mixed provenance and/or mixed species plantings. The molecular marker system developed in project FST/2015/020 will be used to make the assessment. Some general and specific methods used to carry out this activity are detailed in Bush et al. (2016).

1.2. Develop recommendations for breeding strategy

The findings from the molecular analysis of sandalwood “inventory trees” growing throughout Fiji and Tonga undertaken in 2015 (Bush et al. 2016) and the results of the heartwood and oil variation study (based on a subset of the inventory trees) were used to inform the breeding strategy update. The outcome of the preliminary strategic session held at the project inception meeting was to focus attention on domestication and conservation of *S. yasi* rather than *S. album* or the interspecific hybrid. New information on the rate of development of heartwood, the chemical yield and composition of santalol compounds and population structure were taken into account. The originally-proposed activity also involved the use of molecular markers to study aspects of the breeding biology of *S. yasi* – for example the proportion of trees that are self-compatible, information on whether offspring of pure *S. yasi* mothers are inbred, and the rate of spontaneous hybridisation with *S. album.* This study would have been carried out on the planted progeny included in the trials established in this project. This study did not go ahead as the trials were established too late to be sampled.

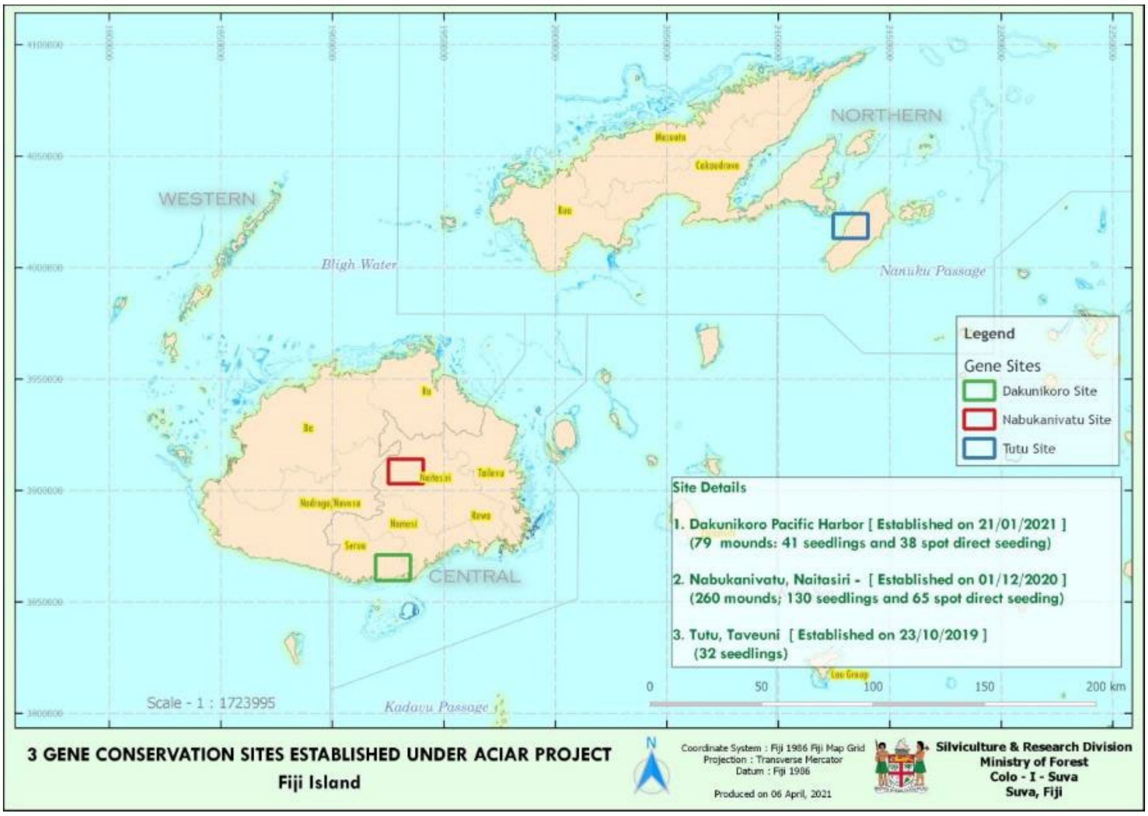
Objective 2: Enhance the genetic conservation status of *S. yasi* in Fiji and Tonga.

2.1. Updated conservation and domestication strategy

The existing conservation strategy developed under SPRIG was updated to reflect new information on levels of inbreeding and diversity attained using molecular marker data from the SRA study. The strategy focused on pure *S. yasi* rather than the introduced *S. album* and *S. yasi* hybrids, based on the outcome of initial policy discussions held at the project inception meeting. The study is based on a classical recurrent selection and breeding approach, though it also emphasises the importance of conservation for this endangered species. Planting genetically diverse production stands adjacent to fragmented wild stands is advocated to encourage geneflow and outcrossing to the wild stands – a concept known as *circa situm* conservation. The unique need to take account of host-sandalwood interactions (genotype-genotype interaction) in addition to genotype-environment interactions is also emphasised as a key determinant of success in sandalwood breeding. The breeding strategy was peer reviewed and published in *Australian Forestry*.

2.2. and 3.4 Seed production and conservation stands in Fiji and Tonga

In Fiji, three (of four originally planned) sites were established (Figure 5.1) at Tutu Estate, on Taveuni (an agricultural training centre) during 2019 and 2020; Dakunikoro, near Pacific Harbour on the south coast of Viti Levu in 2021; and Nabukanivatu, Naitasiri in the central Viti Levu uplands in 2021. The stands were established using a mixture of pure *S. yasi* seed collected from project inventory trees and seedlings purchased from private growers, judged to be *S. yasi* on the basis of their leaf morphology, which is usually a reliable indicator.



In Tonga, three genetic conservation stands/ seed orchards were established (Figure 5.2), one at the MAFF Forestry Station (established September 2020), Tokomololo; one on farmers land in Vaini village, Tongatapu (established December 2020); and one at the MAFF Forestry Station Vava'u (established March 2021). The Tongan plantings did not follow the original design methodology and included a mix of *S. album* and *S. yasi*, due to lack of available *S. yasi* seed at the start of the nursery phase.

maps

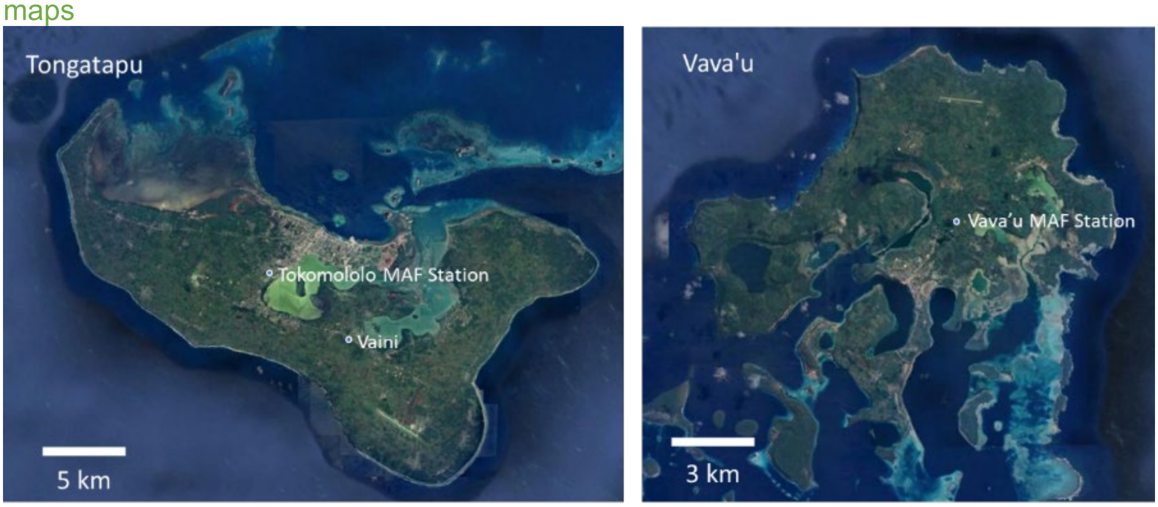


Figure 5.2 Map showing the locations of three conservation and seed production stands in Tongatapu (Tokomololo and Vaini) and Vava'u, (Vava'u MAF Station), Tonga

Objective 3: Develop strategies to enhance the quality and availability of *S .yasi* germplasm and support development of sandalwood industries in Fiji and Tonga

3.1. Strategic plan

Following preliminary discussion to define the scope of the strategic plan and identify key issues held at the project inception meeting, a *South Pacific Sandalwood Industry Plan for Fiji and Tonga* was written with participation from all project partners and some other stakeholders. An additional, peer-reviewed Participatory Value Chain Analysis, conducted jointly with participants from this project, the PARDI2 project and private sector actors (Thomson et al. 2020a) provided important background and stakeholder engagement. The Industry Plan sets out high-level developmental goals and milestones for R&D (throughout the value chain), harvest regulation and governance, product, marketing and general policy and governance development. The recommendations include points of engagement for government and large and small private-sector stakeholders. The formulation and writing of the plan was led by Dr Lex Thomson who conducted a series of small workshops and interviews with stakeholders to canvas opinions and define the main issues.

3.2. Oil variation

Quantitative genetic variation in oil yield and quality was assessed at the provenance and individual-tree levels, including *S. yasi*, *S. album* and the interspecific hybrid. Sampling was conducted throughout Fiji and Tonga, including at the Vunimaqo gene bank in Fiji, which is the largest mature planting of *S. yasi* of known age and managed with consistent silviculture (i.e., a common-garden planting). Sampling was conducted by non-destructively coring individual trees (Figure 5.3). Oil analysis was carried out by solvent extraction and gas chromatography with mass spectrometry (GC-MS) using already-developed analytical and quantitative genetic methods by the University of NSW. Capacity building activities were undertaken with field and scientific staff to familiarise them with the appropriate selection and coring methods for wood sampling in both Fiji and Tonga. A more-detailed method is given in Bush et al. (2020a).

Figure 5.3 Set of 4-mm core samples taken from trees sampled in Tonga. A starch stain has been applied to delineate the sap wood. A portion of the heartwood was ground, extracted and its oil yield and composition analysed using gas chromatography – mass spectrometry

3.3. Growth studies

Growth studies were conducted on 156 trees that had been identified and measured during FST/2015/020, including the Vunimaqo conservation stand in Fiji. The trees were relocated using a combination of GPS and photos taken during 2015 and then re-measured during 2018/19. Linear equations and mixed models fitted to the results were used to assess the growth rates of the three taxa (*S. album*, *S. yasi* and *S. yasi* x *album*) and determine whether regional differences in growth could be detected. Some trees of known age from the Vunimaqo, Fiji planting were available to ground truth the fitted equations. The data were compared with measures gathered from other sandalwood taxa grown elsewhere in the world. This differed from the original Method which was to assess early growth in newly-established field trials: delayed establishment of the trials meant that this was not possible. Capacity building activities were undertaken with field staff in Fiji and Tonga on operating GPS, photographic identification, and the use of inventory sheets to re-locate, measure and document trees that had previously been surveyed in 2015. Inventory books of the original and updated measures were distributed as both hard and soft copies to collaborators in Fiji and Tonga.

Objective 4: Disseminate the practical outcomes and implications relating to objectives 1-3 to growers and practitioners

Extension activities included the development of written materials including a fact sheet (Appendix 1) and an expanded version of the Vanuatu sandalwood growers' manual, as well as capacity building of extension staff. The Pacific Sandalwood Growers' manual expanded the original Vanuatu manual to include *S. album*, *S. lanceolatum*, *S. macgregorii* and *S. yasi* in addition to *S. austrocaledonicum* which is the native species that is grown commercially in Vanuatu. The expansion of the manual was led by Bronwyn Clarke in close consultation with Tony Page who is the lead editor of the updated manual and has had a long involvement in ACIAR sandalwood domestication projects throughout the Pacific. The updated manual provides general information common to all species as well as species- and country-specific advice on management, host selection and marketing.

Training workshops for key MFF and MAFFF staff and community-based sandalwood development champions were held in Fiji and Tonga covering cutting and grafting techniques for sandalwood and practical training on inventory and coring trees to non-destructively take wood samples.

Objective 5: Use DNA molecular markers to assess the population structure and genetic diversity of *S. album*

Leaves from wild and cultivated trees throughout Timor-Leste were collected and preserved using silica gel. This collection represented 15 separate seed sources or putative provenances, with some samples collected from *in situ* wild trees and/or plantings and some from an *ex situ* conservation stand. The leaves were sent to Australia for analysis. DNA was extracted from leaf tissue samples and then assayed using the DaRTseq medium density protocol at Diversity Arrays Technology Pty. Ltd Canberra. This yielded a total of 61,120 single nucleotide polymorphism (SNP) markers for 402 trees from Timor-Leste, and 379 *S. album* and other sandalwood taxa from Fiji and Tonga.

The data were analysed using R statistical and other software to provide estimates of population differentiation, diversity, inbreeding and structure. The report made recommendations for the ongoing management, domestication and conservation of the Timor-Leste *S. album* population. More detailed Methods are presented in Bush et al. (2021).

6 Achievements against activities and outputs/milestones

Objective 1: To improve understanding of the breeding biology and genetic diversity of key traits in S. yasi

Meeting this objective was dependent on the successful establishment of field trials in Fiji and Tonga. The field trials were to be sampled for DNA analysis to gather information on the breeding biology of *S. yasi* through the analysis of co-ancestry of progeny of known mothers. The objective was not met and was constrained by two impediments: (i) incomplete and delayed establishment of field trials, in both Tonga and Fiji, and (ii) travel of Australian counterparts to both countries needed to be undertaken to gather the samples.

Though three trials were established in Fiji, the plantings were not finalised until early 2021 in some cases, by which time the decision not to proceed with this the DNA sampling had been made – partly because of the young age of the field trials (which included direct-sown seeds in some cases), but mainly because international travel had ceased due to travel restrictions associated with the global COVID-19 pandemic. Similarly, insufficient *S. yasi* seedlings had been planted in Tonga to gather meaningful data by the end of the project. The method of establishing the conservation stands and orchards in both countries was to include unpedigreed bulk seedlots. In Fiji these were *S. yasi*, but in Tonga an extreme shortage of *S. yasi* seed led to the substitution of *S. album*.

Some of the resources that were to be used to carry out the genotyping (DNA analysis) were diverted by way of an ACIAR contract variation in late 2020 to Additional Objective 5 - a similar DNA-based study - which commenced in late 2020 and was completed in September 2021 (Bush et al. 2021).

No.	Activity	Outputs/ milestones	Completion date	Comments
1.1	Study the breeding biology for *S. yasi* and its interactions with related sandalwood species	Leaf samples collected and analysed	Not completed	The scope of this activity was limited by lack of trial material suitable for study. New Objective 5 (a study of *S. album* population genetics) was carried out instead.
1.2	Develop recommendations for the breeding strategy for *S. yasi* and its interactions with related sandalwood species	Report describing results including recommendations for the breeding strategy	Not completed	The breeding strategy has been completed with a conference paper (currently in press with ACIAR publishing) and a journal paper published. However, the strategy should be updated when DNA data associated with this activity become available in future.

Objective 2: To enhance the genetic conservation status of S. yasi in Fiji and Tonga

The domestication and conservation strategy commenced with a position being reached to focus on pure *S. yasi* rather than hybrid breeding in Fiji and Tonga in November 2017. The strategy was presented as a conference paper to the Regional Sandalwood Forum in 2019 and then as a refereed journal paper in Australian Forestry in early 2021 (Bush et al. 2020b). However, progress on assembling both clonal and seedling-based material for the conservation and seed stands was very slow. This was due to a number of factors, including: propagation being more difficult than expected; project funding in Fiji not being made available to the project to carry out field sampling until after August 2018, and then again being withdrawn for much of 2020; numerous staff changes in both Fiji and Tonga with new staff assigned to the project not having attended the earlier capacity building exercises, and; sampling and seed crops on Tongatapu and ‘Eua in Tonga were severely set back by TC Gita and then again by TC Harold.

The original design called for a seed exchange between Fiji and Tonga, with the resultant seedlings being included in the conservation plantings. The seed exchange was only finalised in early 2021, so the international seedlings were not included in these plantings. The exchanged seeds are a valuable resource, and it will be important to include them in new plantings and/or use them to augment the existing plantings.

No.	Activity	Outputs/ milestones	Completion date	Comments
2.1	Revise the conservation and genetic improvement strategy for *S. yasi*	1. An agreed position on the approach for the development of *S. yasi* 2. Revised conservation and genetic improvement strategy for *S. yasi* in Fiji and Tonga	1.Completed February 2017 2. Completed September 2018	1. Agreement was reached in November 2017 2. A conservation and genetic improvement strategy is complete. Conference paper presented Bush et al (in press) and journal paper in *Australian Forestry* Bush et al. (2020a).
2.2	Assemble conservation stands of *S. yasi* on two secure sites in each of Fiji and Tonga	1.4 sites identified and secured 2 & 3. *S. yasi* and pot host material collected 4. Seedling and clones raised in nurseries and ready for planting 5. Planting sites prepared for planting 6. Sites planted to take advantage of wet season. 7. Weeding and other site maintenance carried out as needed after planting	Partial completion of these tasks by February 2021.	Six sites, three each in Fiji and Tonga were established. The sites differ from the original design in that they will do double duty as conservation and seed production stands. The genetic diversity of these plantings is not known and should be assessed using DNA markers. It would be beneficial to augment the plantings with more-diverse selections including seedlings grown from the seed exchanged by Fiji and Tonga.

Objective 3: To develop strategies to enhance the quality and availability of S. yasi germplasm and support development of sandalwood industries in Fiji and Tonga

The South Pacific Sandalwood Industry Plan for Fiji and Tonga was formulated following consultation (led by Lex Thomson) with stakeholders and a value-chain analysis conducted collaboratively with the ACIAR PARDI2 (Pacific Agribusiness Research in Development Initiative) AGB/2014/057 (Thomson et al. 2020a). The industry plan was published in 2020 (Thomson et al. 2020b).

The wood coring and oil analysis (undertaken in collaboration with Joseph Brophy, UNSW) was completed in early 2020. The data were integrated with those from a re-measure of inventoried trees (Activity 3.3) to gain inference on heartwood and oil trait development in sandalwood of different ages. This study was published in Australian Forestry (Bush et al. 2020a).

Planting stock production and establishment of the community-based orchards was slower than expected, as discussed under Objective 2. By the project's end, six sandalwood stands had been planted in Fiji and Tonga, each of which is expected to perform the functions of conservation stands and seed production.

No.	Activity	Outputs/ milestones	Completion date	Comments
3.1	Develop a ten-year strategic plan for large-scale development of sandalwood in Fiji and Tonga	A document summarising the recommendations and broadly outlining the strategic objectives, policy and development activities required to develop the sandalwood industry in Fiji and Tonga with a 2025 planning horizon	October 2020	The South Pacific Sandalwood Industry Plan for Fiji and Tonga was completed following workshops and stakeholder feedback. The study was published as a CSIRO Technical Report in October 2020 (Thomson et al. 2020b).
3.2	Investigation of genetic variation in *S. yasi* oil characters to identify best provenances and to determine whether the trait can be genetically improved.	Report describing genetic parameter estimates for oil-related traits including recommendations on how these estimates can be integrated into the breeding strategy	June 2020	The study on heartwood development, oil yield and oil quality was completed in 2019 and published in *Australian Forestry* (Bush et al. 2020a).
3.3	Conduct growth studies within *S. yasi* trials	A report detailing the growth study findings and implications for growers and the breeding strategy	August 2020	This activity was originally meant to focus on growth of the newly established trials. As establishment was very delayed, a study based on inventory of trees measured in 2015 in Fiji and Tonga was carried out. Results were used to estimate the ages of wild and cultivated trees that had been cored for the oils study (Bush et al 2020a) and overall growth rates were published in a conference paper (Bush et al. in press)

3.4	Establishment of community-based seed orchards that can produce enough seed to supply a substantial proportion of the local demand.	*S. yasi* seed orchards will be established on at least two islands/island groups in each of Fiji (Viti Levu, Vanua Levu, Kadavu and/or Lau) and Tonga (Vava'u, Ha'apai, Nuku'alofa and/or 'Eua)	Partial completion February 2021	This milestone was partially met in early 2021. Six sites were established (three each in Fiji and Tonga). The stands, designated for both seed production and conservation, were established at the Tutu Agricultural Training Centre in Taveuni, Fiji and on private property in Vaini, Tonga. Plantings at the Tokomololo and Vava'u MAFF facilities in Tonga and at Pacific Harbour in Fiji will also be capable of producing seed.

Objective 4: To disseminate the practical outcomes and implications relating to objectives 1-3 to growers and practitioners

The main activities under Objective 4 were workshops held early in the project covering cutting, grafting, propagation (Figure 6.1, Table 6.1) and GPS techniques. A fact sheet was produced early in the project (Appendix 1) and was circulated by extension officers in Fiji and Tonga. Two workshops that were to be held towards the end of the project and completion of a video were not possible due to COVID pandemic travel restrictions during the project's last year. Efforts were redirected to updating and expanding the Vanuatu sandalwood Grower's Manual to encompass other sandalwood species in the Pacific including *S. album*. This publication is currently in production and is projected to be available in late 2021.

Figure 6.1 Cutting and grafting workshop held at the MAF Nursery, Colo-I-Suva, Fiji. Participants from both Fiji and Tonga attended the workshop which was led by Dr Lex Thomson on in-field collection of scion material from candidate trees and cutting and grafting techniques.

No.	Activity	Outputs/ milestones	Completion date	Comments
4.1	Develop extension materials for *S. yasi* growers	1. Information leaflets and a short video dissemination with seedling supply 2. A sandalwood grower's manual 3. Extension workshops in Fiji and Tonga	1. Information leaflet completed. Video not completed 2. Sandalwood grower's manual complete: in press 3. Extension workshops held between November 2017 and May 2018 (Table 6.1)	1. Although much footage was taken, video of seed orchard establishment was not shot due to travel restrictions in the last year of the project. We agreed to invest effort in collaboratively updating the Vanuatu sandalwood growers' manual to make it regionally appropriate not only for Fiji and Tonga, but also for PNG, Timor-Leste and anywhere else in the Pacific that people might want to cultivate sandalwood. The manual was sent to ACIAR Publishing for typesetting and production in late 2020 and is projected to be available in late 2021. 2. The Growers Manual should be published in late 2021 or early 2022 3. Five workshops were run on cutting and grafting skills that also covered off on the conservation and domestication program for *S. yasi*. These workshops were targeted for extension workers and researchers already engaged in promoting sandalwood cultivation. An additional workshop on GPS skills was held in Tonga (Table 6.1).

Table 6.1 Summary of training and capacity building workshops held

Event	Date	People trained
Cutting and grafting training, Colo I Suva, Fiji	28 November 2017	13 Fiji, 3 Tonga (+ 1 ACIAR observer)
GPS tree location Colo I Suva, Fiji	28 November 2017	13 Fiji, 3 Tonga
Cutting and grafting, Vanua Levu	15 February 2018	3, Fiji
Cutting and grafting, Western district, Fiji	23 Feb 2018	4, Fiji
GPS tree location 'Eua, Tonga	9-10 May 2018	4, Tonga
Ahi cultivation and propagation workshop, Tokomololo, Tonga*	11 May 2018	31 Tonga

*This workshop held jointly with ACIAR PARDI project

Objective 5: **Use DNA molecular markers to assess the population structure and genetic diversity of *S. album***

Additional Objective 5 was added to the project in 2020 when it became clear that some of the project's original Objectives could not be met due to late establishment of field trials and travel restrictions. This activity involved a successful collaboration with ACIAR project CIM/2014/082, resulting in a detailed study on a large number of samples collected both *in situ* from wild and planted stands and also from an existing *ex situ* conservation stand recently established in Timor-Leste. Staff from the Timor-Leste Ministry of Agriculture and Forests who are engaged in collaboration on the ACIAR AiCom project collected 300 samples in late 2020. These were augmented by 102 additional samples that had already been sent to Australia. Samples of *S. yasi*, introduced *S. album* and interspecific hybrids from Fiji and Tonga were also included to provide data on the affinities of the Timor-Leste and Pacific wild and introduced taxa. The samples were genotyped in Australia and analysed, resulting in a technical report. Collaborators from Timor-Leste became highly involved in the analysis and interpretation of the molecular data, which has shed light on the population structure and diversity of the Timor-Leste *S. album* population.

No.	Activity	Outputs/ milestones	Completion date	Comments
5.1	Assess the population structure and diversity of *S. album* native to Timor-Leste using molecular markers	A report detailing the results of a DNA-based analysis of the Timor-Leste *S. album* population including the practical implications for domestication and conservation	30 September 2021	Report published as CSIRO Technical Report Bush, D., Almeida, L., Page, T., Williams. R., (2021) Genetic structure of Timor-Leste *Santalum album*.

6.1 Summary of achievements to date (for ACIAR website)

ACIAR FST-2016/158 *Domestication and breeding of sandalwood in Fiji and Tonga* is focused on conserving and developing *Santalum yasi,* a threatened, commercially valuable sandalwood species (called “yasi” in Fiji and “ahi” in Tonga). A conservation and domestication strategy was developed for the species, with six conservation and seed production stands established from diverse genetic sources. The seed stands will produce seed to supply smallholders with seedlings of improved quality. The stands will also serve as repositories of genetic material that guard against further losses in the wild resulting from illegal harvesting.

Between 2015 and 2020, the project carried out growth measurements of around 250 wild and planted trees in Fiji and Tonga. This inventory showed that *S. yasi* grows slowly, at around 1 cm of basal diameter per year. Over 80 trees from Fiji and Tonga with stem diameter >10 cm have been cored and the heartwood essential oils analysed. This study has shown that though trees around 15 years old may have developed heartwood and oils, it would be better to wait until 20+ years for harvest. The study has confirmed earlier indications that *S. yasi* has an attractive and commercially valuable oil profile and that when mature, many trees have an excellent oil yield.

The project has developed an industry strategy outlining the steps that should be taken in the coming decade to further develop the sandalwood value chain in Fiji and Tonga. A Pacific Sandalwood Growers' Manual has been developed in collaboration with other ACIAR sandalwood projects.

7 Key results and discussion

Objective 1 To improve understanding of the breeding biology and genetic diversity of key traits in *S. yasi*

The key result relating to Objective 1 was the increased understanding in variation of heartwood and essential oil characteristics of *S. yasi*. Relationships among traits including solvent-extracted oil yield, oil composition, lower bole diameters under and over bark and heartwood diameter were examined. These relationships were carried out on trees sampled from a wide range of sites in Fiji and Tonga, on trees that were also included in the growth re-measure. This allowed us to estimate the likely age of the trees and infer a relationship between heartwood and oil development with diameter, and with age given that trees were found to grow at around 1 cm per year in basal diameter in both Fiji and Tonga, on average.

Many of the results that were projected to be obtained from Objective 1 were not, due to the late establishment and compromised designs of the field-based plantings. The original design for Objective 1 would have seen open-pollinated progeny of *S. yasi* established in the ground. From these, it would have been possible to make inferences about the relatedness and breeding biology of the mother trees. This information remains to be obtained and is an important determinant of how the breeding population should be managed – for example whether avoidance of selfing needs to be managed in seed orchard designs depends on whether and what proportion of the species is self-compatible. The single nucleotide SNP-based study that was carried out on *S. album* in Timor-Leste (Additional Objective 5) (Bush et al. 2021) demonstrated the appropriateness of modern marker systems for conducting such studies: a highly detailed matrix of relatedness among the Timor *S. album* population was obtained.

Objective 2 To enhance the genetic conservation status of *S. yasi* in Fiji and Tonga

Development of an updated breeding strategy for *Santalum yasi* was a major output of the project. The strategy was initially released as a conference paper at the 2018 Sandalwood Forum in Vanuatu and then published as a research paper in Australian Forestry (Bush et al. 2020b). The strategy drew on molecular-marker-based research (Bush et al. 2015) and insights from the study on heartwood development (Objective 3 of this project, Bush et al 2020a) and the objective of conserving and developing *S. yasi* rather than exotic sandalwood and hybrids.

As extant stands of *S. yasi* lack genetic diversity and are likely to be suffering from inbreeding depression, the species still has significant genetic diversity overall, a finding made using SSR markers by Bush et al. 2015 and confirmed using a powerful set of SNP markers (Bush et al. 2021). The best way to conserve this species is through an active domestication program that will adequately sample and conserve the genetic base in *ex situ* and *circa situm* plantings. The approach to *S. yasi* tree breeding can be characterised as a low-input strategy involving the early use of molecular markers for population parameter determination. Long-term success will have strong interdependent links with the conservation of the remaining genetic resources. A strategy based on recurrent selection and breeding for key traits—including heartwood volume and oil yield per year, oil quality and environmental adaptability related to cyclone resistance and the tolerance of pests and diseases—is recommended (Figure 7.1).

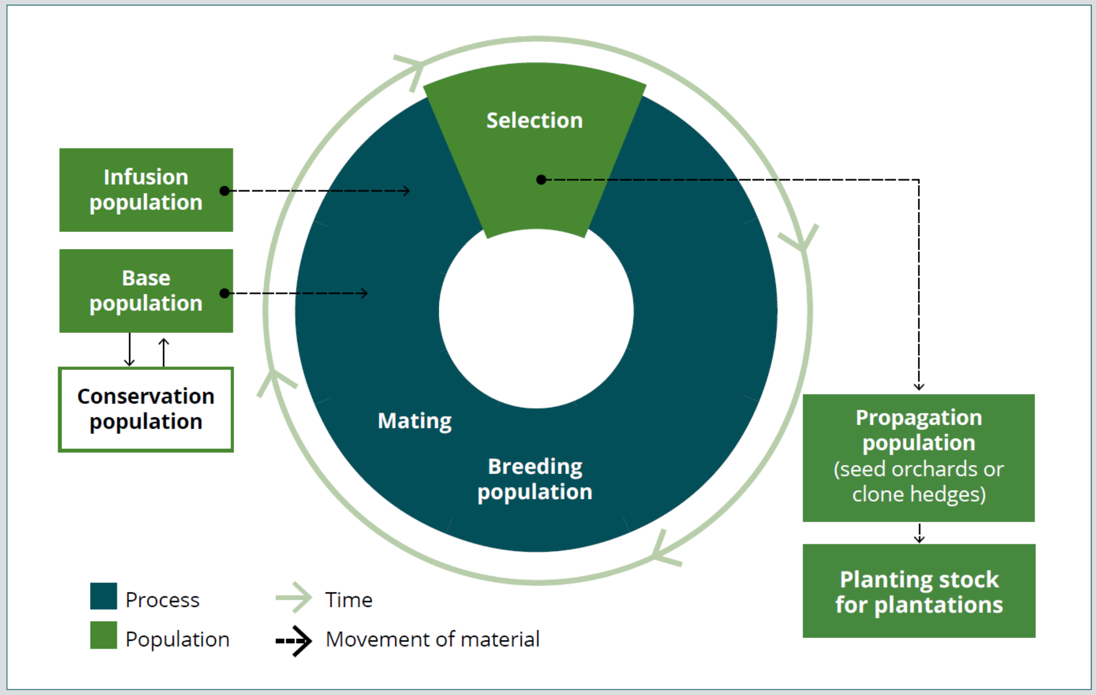


Figure 7.1 Representation of the conservation and domestication strategy for *S. yasi* (Source: Bush et al. in press)

The establishment of genetic conservation stands based on collections of the species throughout its natural range in Fiji and Tonga has commenced, though these will need to be augmented with further accessions from a broader range of sources and the diversity of the unpedigreed sources that have been included so far checked using molecular markers.

Challenges associated with the conservation and domestication of *S. yasi* (and all other sandalwood species) include the advanced age required before oil characterisation can be undertaken; the need to assess genotype–host-plant interactions; and the need for comparatively sophisticated equipment and destructive harvesting to carry out oil assessments (as confirmed by the heartwood and oils study conducted by this project).

Capacity development of professional staff in the Pacific Islands is an additional prerequisite for implementing an effective strategy. Research into the variation and heritability of heartwood formation and oil characteristics, and a better understanding of the breeding biology of *S. yasi* and geneflow between it and exotic Indian sandalwood (*S. album*), are high priorities. It will be more than a decade—probably around 20 years—before *S. yasi* individuals in planned, well-designed trial plantings have sufficient heartwood development to enable oil-trait assessment.

Establishment of further trials and augmentation of those established in this project is an ongoing priority. The strategy will both provide a safeguard against the further loss of diversity and promote wide outcrossing. Releasing fragmented populations from inbreeding depression is expected to increase general vigour.

Figure 7.2 Steven Hamani and Spencer Hefa (MAFF, Tonga) relocating trees initially inventoried in 2015 using GPS. The trees were re-measured, and many were also non-destructively cored.

Objective 3 To develop strategies to enhance the quality and availability of *S. yasi* germplasm and support development of sandalwood industries in Fiji and Tonga

A major activity carried out by the project was the formulation of the South Pacific Sandalwood Industry Plan for Fiji and Tonga (Thomson et al. 2020b). This plan was formulated following the jointly conducted (with the PARDI2 project) participatory value chain study (Thomson et al. 2020a) which was carried out with stakeholders to identify the capacity for growth of the *S. yasi* industry in Fiji. This study examined the likely market in detail, and aspects including the flow of benefits from a sandalwood industry to stakeholders (see for example Figure 7.3).

Figure 7.3 Flow of benefits arising from different sandalwood product classes to different value chain segments (Thomson et al. 2020a)

The industry strategy seeks to address the opportunity that the value of sustainable *S. yasi* planting is currently not recognised and could potentially be increased by 2000% from USD 5 to 100 million per annum in the long term. Key recommendations are:

1. Government of Fiji needs to establish a strong regulatory environment for management and utilisation of *S. yasi* (using Tonga regulations as a model to ensure consistent and high industry standards)

2. Develop improved seed orchards of *S. yasi* using diverse germplasm from multiple wild sources in Fiji (Bua, Macuata, Vanua Balavu, Lakeba/Ono-I-Lau, Nausori Highlands and Kadavu) and Tonga (Vavaʻu, Haʻapai and ʻEua/Tongatapu). Selectively thin these in early years to remove slower growing and unhealthy trees, and later on (after c. 10 years) thin trees with low heartwood development, low oil content and/or inferior oil profiles

3. Increase the production of high quality *S. yasi* seedlings from Government and private nurseries to at least 50,000 per year in Fiji and 25,000 per year in Tonga using high quality and diverse pure *S. yasi* germplasm, and distribute seedlings when in prime condition, i.e., c. 25 cm tall with an Alternanthera or pinto peanut pot host. About three times this number of permanent hosts (including *Citrus*, *Calliandra*, *Casuarina*, *Flueggea* and *Pongamia*) will also need to be provided

4. Establish a dedicated Sandalwood Advisory Service in both Fiji and Tonga Government Forestry Ministries—to be staffed by a minimum of two experienced professionals, one with forestry and one with business credentials—providing high quality and appropriate technical and commercial information to smallholder growers on how best to profitably cultivate and manage *S. yasi* plantations and agroforestry systems

5. Establish a Sandalwood Task Force comprising Government and Private Sector members from Fiji and Tonga that should meet regularly. The key objectives will be to advise on development and monitoring of planted resources; share information on *S. yasi* technologies, resources, and market intelligence; promote rational development of *S. yasi* value-adding; and seek out reputable international partner(s) to develop value-added *S. yasi* products.

The industry plan will take time to implement, with development of an expanded, mature resource base an initial priority.

Apart from feeding into the overall conservation and domestication plan for *S. yasi*, the study of heartwood development, oil yield and oil quality has important implications for the commercial development of the species. The finding that *S. yasi* grows slowly, but not at significantly different rates, in Fiji and Tonga was not surprising. We did not find evidence to support the commonly held belief that *S. yasi* grows more slowly than *S. album* or their interspecific hybrid. Possible explanations for this include that the study of trees of mixed ages, from mixed sites and with various hosts contained too much statistical “noise” to differentiate between the growth rates. It is also possible that the early growth of *S. album* is superior, and given the finding that *S. yasi* tends to be inbred, it would not be surprising to find that outcrossed hybrids are more vigorous. Properly designed field trials remain the only way to definitively address these research questions. There was evidence to suggest that heartwood diameter (i.e., the portion of the stem that potentially contains the valuable oil) is related to diameter under and over bark (Figure 7.4). Tree size and age are therefore quite good indicators of the likely presence of heartwood, which develops first in the upper portion of the roots and then is located at positions higher up the stem as the tree ages.

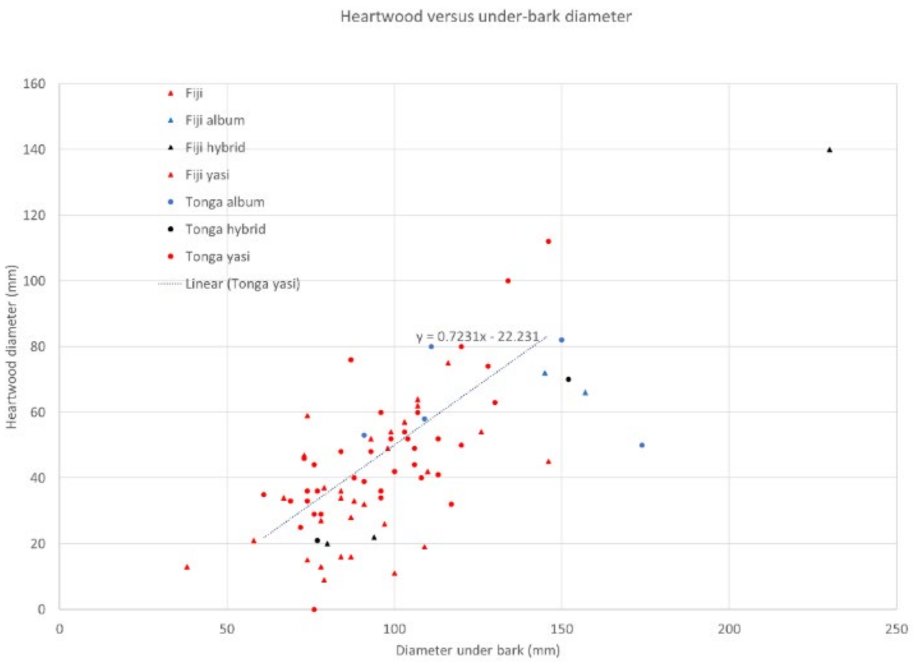


Figure 7.4 Relationship between tree size (diameter under bark) and the diameter of the valuable heartwood portion of the stem. (Source: Bush et al. 2020b)

Chemical essential oil extract analysis of cores showed that yield was highly variable (0.05% to 11.8%) (Figure 7.5) and only weakly correlated to under-bark diameter at 30 cm above ground. Oil yield and percent composition of santalol oil components was strongly positively correlated. For those trees with oil yields >1% w/w, the oil composition was generally favourable relative to the international standard for *S. album* oil, with large proportions of santalols, particularly β-santalol. We did not find evidence from this sample that oil yields from hybrid or *S. album* trees were any lower of higher than *S. yasi*. This is at odds with the commonly-held grower perception that *S. album* and/or the hybrids grow faster than *S. yasi* – a result that would not be surprising in the case of the hybrids which might express heterosis or "hybrid vigour" relative to often-inbred *S. yasi*. A possible explanation is that this growth study was conducted on trees that were from a diverse range of sites and ages, making differences more difficult to detect and/or prove statistically significant. Common garden trials established using common genotypes across a range of sites will provide a better opportunity for studying these differences with higher statistical precision.

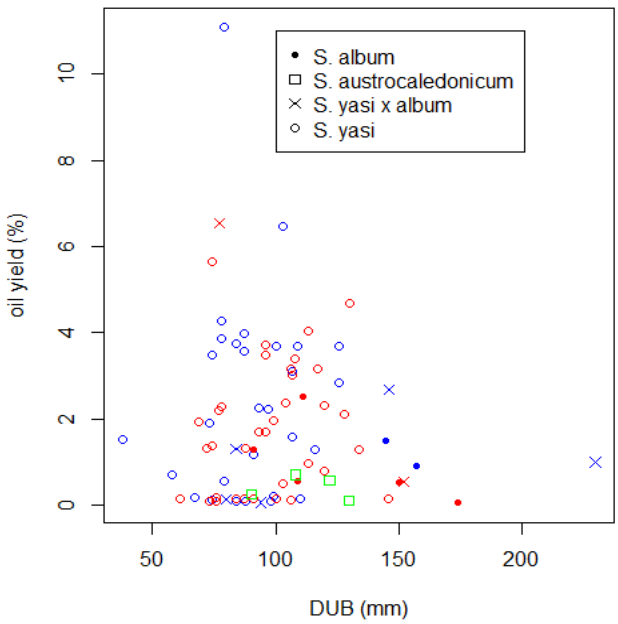


Figure 7.5 Relationship between size of tree (diameter under bark of the sample core or disc at 30 cm above ground) and oil yield (percent of wood air-dry weight). Red, blue and green symbols denote trees from Tonga, Fiji and Vanuatu, respectively (Source: Bush et al. 2020a)

An encouraging finding was that the yield of β-santalol was typically above that defined for commercial acceptance by the *S. album* industrial standard (ISO 2002). As this chemical constituent is the defining perfumery compound associated with sandalwood, it may be possible to take advantage of this distinctive trait to help build the market niche proposed for *S. yasi*. Some samples were found to contain minor constituents of potentially non-desirable oil compounds (E,E-farnesol). Further analyses of steam-distilled oils are recommended to confirm and further research this finding.

Objective 4 To disseminate the practical outcomes and implications relating to objectives 1-3 to growers and practitioners

A major achievement under this Objective was a major update of the Vanuatu Sandalwood Growers' Manual (Page et al. 2012b) to encompass a wider range of sandalwood species and conditions throughout the Pacific (Figure 7.6). The update was coordinated by this project with close involvement of other ACIAR sandalwood projects and numerous authors across the Pacific, particularly Dr Tony Page (University of the Sunshine Coast). The revised Pacific Sandalwood Growers Manual was updated to include country-specific recommendations for planting, marketing and host selection. The updated publication is currently in-press with ACIAR Publishing (Page et al. in press).

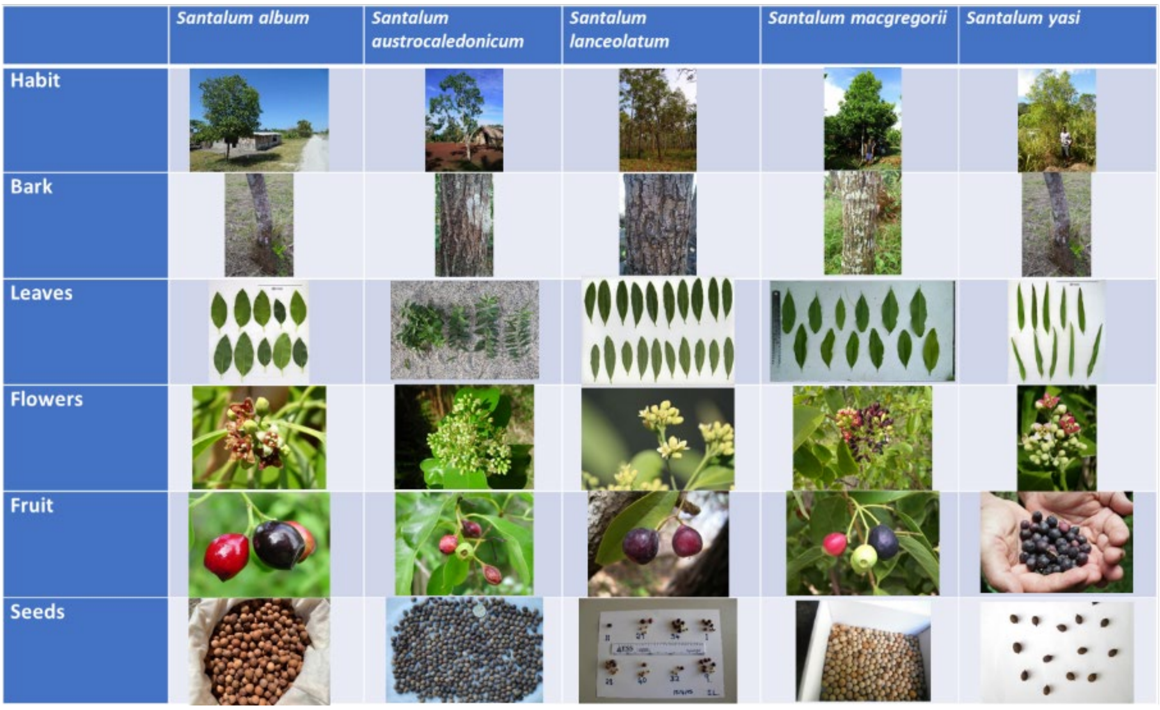


Figure 7.6 Example of a draft illustration from the updated Pacific Sandalwood Growers Manual which has been expanded from coverage of *S. austrocaledonicum* for growers in Vanuatu to five sandalwood species that can be grown under broadly similar silvicultural, management and marketing systems throughout the Pacific

An additional opportunity for capacity building and communication about the methods and benefits of sandalwood farming arose with the selection of a conservation and production site at the Tutu Agricultural College in Taveuni. The planting established there will be used to educate young farmers attending the college on the sandalwood agroforestry system in addition to its conservation and seed production functions.

Additional Objective 5: DNA molecular markers to assess the population structure and genetic diversity of *S. album* in Timor-Leste

A single nucleotide polymorphism (SNP) molecular marker study was conducted to examine the diversity and relatedness among individual trees in natural and planted *Santalum album* from Timor-Leste. These trees form the base population which is both the target of a conservation program and the genetic resource on which domestication of the species is based. Domestication and breeding of the species is a high priority in Timor-Leste as sandalwood has the potential to significantly diversify smallholder agricultural income as it is in Fiji and Tonga. The focus in Timor-Leste is growing sandalwood in an agroforestry system with fodder-tree legume hosts.

Overall, the molecular marker study provided good news for the breeding and conservation program of *S. album* in Timor-Leste, with moderate diversity still remaining despite heavy harvesting in the past. Some evidence of human movement and possible anomalies in the provenance of seed used to establish and/or the nursery production or layout of the *ex situ* planting were also found. The population differentiation between the Fiji/Tonga introduced *S. album* and the wild *S. album* from Timor-Leste was surprisingly very large, indicating that the Fiji/Tonga material is certainly not from Timor-Leste. Speculatively, it would seem more likely that it may have been introduced from the opposite end of the geographic range in India (Figure 7.7).

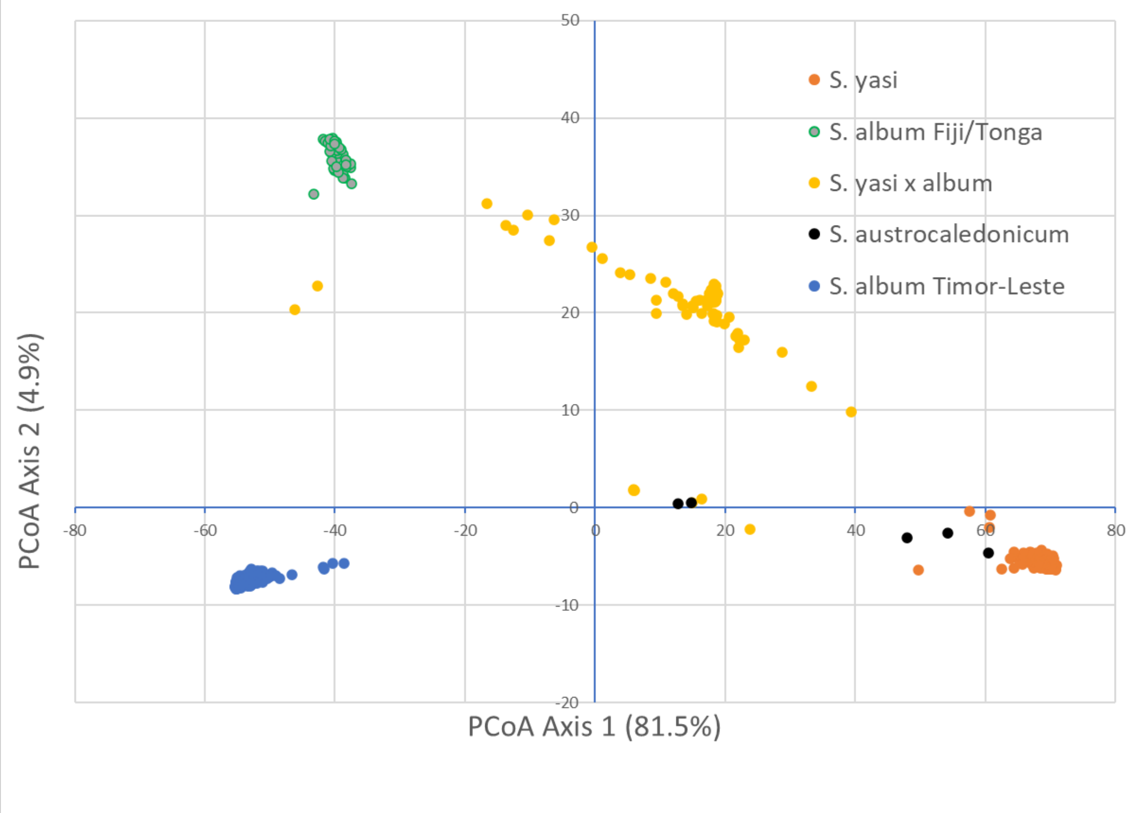


Figure 7.7 Plot of the first two principal components axes based on a Euclidean distance matrix of 20827 SNP markers. Each point represents one of 675 individual trees from 5 population samples. The Fiji/Tonga exotic population of *S. album* is strongly differentiated from the wild Timor-Leste population: both are clearly separate to *S. yasi* as expected, while most *S. yasi* x *album* hybrids sampled in Fiji and Tonga lie in a position intermediate to the two parental populations.

Although population structure within the Timor-Leste *S. album* was clear, significant admixture of populations within some of the putative Timor-Leste provenances was indicated (Figure 7.8). This is likely due to recent human movement of seed and planting stock within Timor-Leste, or possibly seed collections being carried out from multiple locations that were thought to represent a narrower geographic range. Genetic diversity of the Timor-Leste population was moderate overall. While some provenances lacked diversity and contained only close relatives (e.g., Com and Lore that are situated around 30 km apart comprised a cluster of close relatives), other seed sources appeared to have predominantly outcrossed trees (e.g., Zumalai and Lalawa). The SNP data allowed a full pedigree matrix to be assembled which will facilitate management of relatedness among the sampled trees for the purposes of conservation, domestication, and breeding. One of the first activities that could be guided by this new information is the thinning of the Natarbora conservation stand (ETA-N), using the co-ancestry data to check that nearby trees are not close relatives. STRUCTURE analysis also allowed trees within seed sources of apparently mixed origins to be grouped together with populations that are their most likely origin.

Overall, the analysis revealed that while the Timor-Leste *S. album* population has been heavily harvested and has no doubt suffered from genetic depletion in some locations, there is still at-least moderate genetic diversity remaining. Careful selection of unrelated trees from within the existing conservation stand and wild or planted stands throughout Timor-Leste will result in a breeding population that is of sufficient size and diversity to be sustainable. This is good news, because it had been hypothesised that the remaining genetic base in Timor-Leste may be too narrow, requiring the importation of *S. album* accessions from elsewhere in the natural range. While this may not be necessary, it is argued that sampling from the West Timor population, which being based on the same land mass is likely to be an extension of the Timor-Leste population profiled here, would be of benefit for both conservation and domestication purposes. Further assessment of commercial traits, preferably in common-garden trials such as the ETA-N planting will also provide guidance on whether importation of germplasm from outside Timor-Leste is necessary and/or desirable.

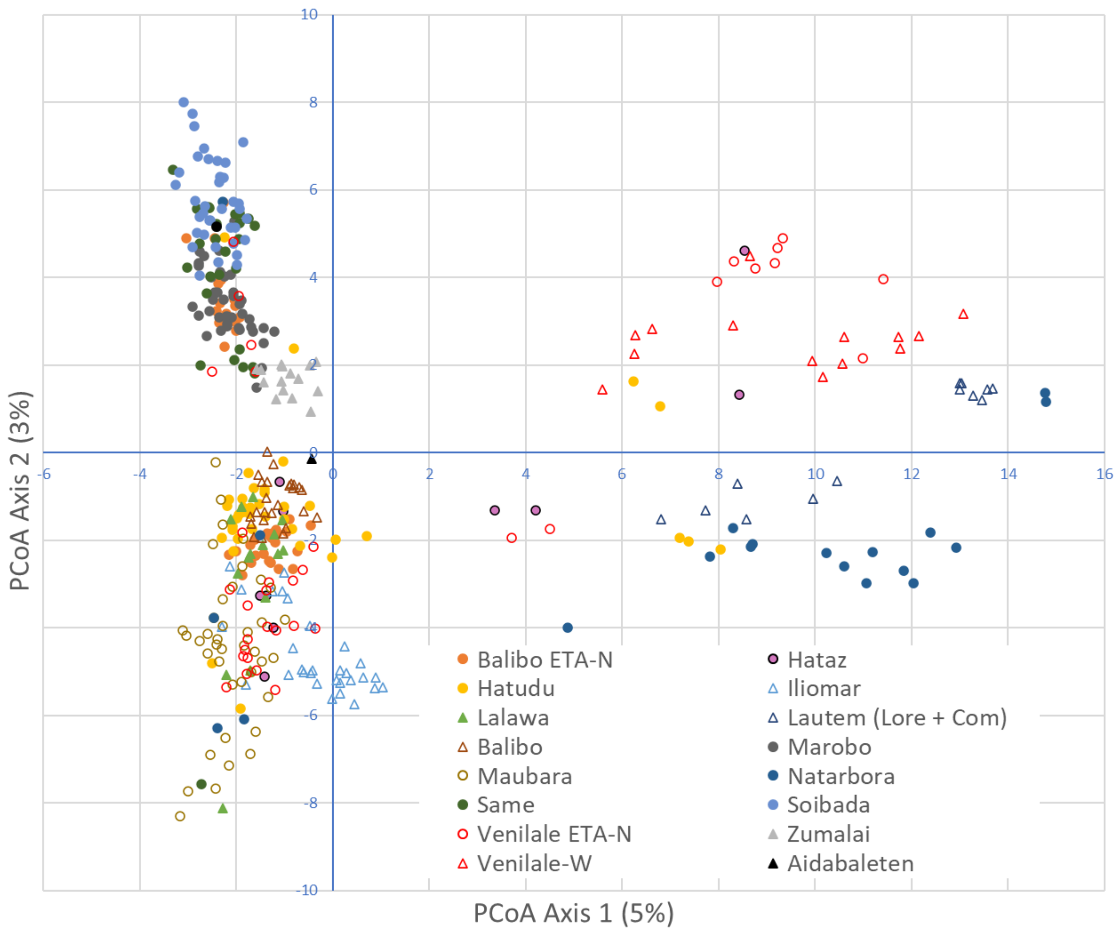


Figure 7.8 Plot of first two principal components axes based on a Euclidean distance matrix of 9700 SNP markers. Each point represents one of 402 individual trees from 15 populations sampled within Timor-Leste.

8 Impacts

8.1 Scientific impacts – now and in 5 years

Scientific impacts have been made in the areas of breeding biology, conservation and domestication population management, quantification of productivity from repeat measurement of previously-measured trees, and essential oil assessment of heartwood sampled from mature trees. Analysis of the data collected from inventoried trees in Fiji and Tonga shows that a good relationship between diameter at the initial measurement in 2015 and the updated 2018/19 measurement exists and that growth rates of sandalwood in Fiji and Tonga appear to be very similar to those of *S. austrocaledonicum* in Vanuatu and other sandalwood species. Core data and gas chromatography from the 2018 sampling in Tonga and 2019 sampling in Fiji has demonstrated that *S. yasi* can have very favourable oil profiles, but that trees of around 15 years of age cannot be relied upon to be sufficiently mature for harvest. A key message arising is that patience is required until the trees are at least 20 years old to maximise returns. The finding also has implications for making selections on the basis of wood and oil trait performance in the *S. yasi* breeding population: there will be a long wait of up to 15 years until oil parameters can be assessed. It may be worth assessing whether sampling from very low in the bole or the upper roots can give an earlier indication of performance, though this type of sampling will be harder to achieve using currently-available equipment. These findings serve as a baseline for further studies. Within the next five years, it will be important to assess newly-established trials. It would also be useful to keep monitoring the inventoried trees to study their growth rates. Those that returned low oil yields should be re-assessed in around five years to determine whether maturation has improved the oil yield as hypothesised.

Two peer-reviewed conference papers arising from the project were prepared for the 2019 Regional Sandalwood Forum (Port Vila, Vanuatu) and will be published in proceedings by ACIAR (Bush et al. in press; Thomson et al. in press). The project also assisted with preparation of two further reports from Fijian and Tongan delegates Bolatolu and Lesabula in press: Motuliki in press). Journal papers on the breeding and conservation strategy (Bush et al. 2020b), heartwood oil analysis (Bush et al. 2020a) and participatory value chain analysis (Thomson et al. 2020a; a joint PARDI project output) were published in a special issue of Australian Forestry in late 2020. These publications contain recommendations for ongoing research and development: their impact in five years' time will be realised if the recommendations are followed. Examples of actions that are recommended include further establishment of conservation and seed stands and inventory of planted sandalwood resources in Fiji and Tonga.

Technical reports produced by the project include the South Pacific Sandalwood Industry Plan for Fiji and Tonga (Thomson et al. 2020b) and a report on genetic structure of Timor-Leste *Santalum album* (Bush et al. 2021). The latter study should have a major impact on the domestication and conservation management of native sandalwood in Timor-Leste and can be used as a basis for shaping a future strategy. An immediate impact will be made on the thinning of the *ex situ* conservation planting that has been established at Natarbora (Figure 8.1) by the Ministry of Agriculture and Fisheries under the auspices of the Ai-Com project (Agricultural Innovations for Communities) (ACIAR project CIM-2014-082). The study will provide guidance on management of relatedness of trees and future targeting of unrelated material for further expansion of the breeding base.

Figure 8.1 Ministry of Agriculture and Fisheries (Timor-Leste) staff inspect the ai-kameli (*Santalum album*) agroforestry and genetic conservation stand at Natarbora, Timor-Leste. The planting contains a broad sample of populations established using seed collected from throughout Timor-Leste. It will be thinned for seed production and managed for conservation and domestication of the species. Host species include leguminous fodder trees (Photo: Rob Williams)

8.2 Capacity impacts – now and in 5 years

The project has undertaken a number of capacity building and training activities focused on development of cutting and grafting nursery skills and GPS positioning skills and mapping (see Table 6.1). An initial training workshop on sandalwood field selection using GPS and photographic identification, scion selection and cutting and grafting to stock plants was held as an activity associated with the project inception meeting in Fiji in November 2017. A second major training workshop was held jointly with the PARDI2 project in Tonga in May 2018. During the course of the project, the need for further capacity building in seed propagation and general nursery culture skills has been identified if Fiji: capacity is lower than expected based on previous experience.

MAF staff in Timor-Leste became closely involved in the analysis of molecular markers assays of the Timor-Leste *S. album* population, particularly the practical aspects of using the data to manage their planted conservation and breeding population. This was a new technology exposure for these staff, and they have identified a need for more training in this area.

An activity that was planned in the project proposal was provision of support for tertiary training (University BSc or equivalent) for a prospective employee of MFF in Fiji identified in precursor project FST2015-20. The identified student has commenced part-time study, however the scholarship was not awarded.

The impacts from capacity building that were undertaken during this project are difficult to ascertain. Certainly GPS and coring training undertaken in both countries was deemed to be highly useful and professional staff have been able to use and build on the skills attained during the course of this project. Similarly, cutting and grafting skills were useful for staff that received the training. However, a major issue that has become apparent during the course of this project is that staff turn-over has been rapid, with a number of participants that received training early in the project being repositioned in their organisations and not able to make practical use of the learning. This also had consequences for the project with replacement staff joining later in the project not having had the training required to carry out some important technical functions.

8.3 Community impacts – now and in 5 years

The project has set up conservation stands *cum* seedling seed orchards on both government and community-controlled land in Fiji and Tonga. The project has interacted with numerous village communities in Fiji and Tonga that provided the inventory trees.

The promotion of *S. yasi* (sandalwood) cultivation in Fiji has been evaluated using the PARDI2 agribusiness assessment tool.

8.3.1 Economic impacts

Since 2000, *S. yasi* exports from Fiji and Tonga combined have averaged about 100 MT of heartwood per annum worth about USD 5 Million. This figure grossly under-represents the potential of *S. yasi* to the economies of Fiji and Tonga, and its unique potential to provide cash income to villagers living in remote islands and locations. Based on estimates of *S. yasi* currently planted and naturally regenerating, the industry has the potential to increase in value by 3.5 times, and this would be doubled again through appropriate local value-adding and niche marketing such that the industry will be minimally worth USD 35 million per annum present value (Thomson et al. 2020b).

The economic impacts from this project will flow from (i) the expected productivity gains associated with a structured domestication and genetic improvement program for *S. yasi* making high genetic-quality planting stock readily available and (ii) the longer-term strategy of focussing on the development of *S. yasi* as a specialised and niche, market-differentiated product. It is difficult to accurately predict the value-add associated with these factors, but it would be reasonable to expect a minimum 15% lift in growth productivity when moving from an inbred land-race population to seed orchard stock.

The market differentiation will both increase the value of the end product and assist it to maintain a good high price in a market supplied by a relatively large volume of *S. album* that will be available from Australia and elsewhere. Information about the current level of planting of *S. yasi* and the number of households, communities and private sector firms that might take up planting have not been formally determined. However, based on knowledge from the partners' extension teams and visits made to sandalwood-growing villages and regions during the implementation of FST/2015/020 and this project, it is estimated that around at least 5000 households in Fiji and 1500 households in Tonga are either currently involved in growing sandalwood or would be in a position to rapidly take it up.

Thomson (unpublished, 2015) estimated the planted area (equivalent) of *S. yasi* and hybrid sandalwood is around 600 ha (with more than 80% in Fiji; the main growing areas are Kadavu, Lau, Vanua Levu (Bua, Macuata and Buca Bay), Viti Levu (Coral Coast, Tailevu and Naitasiri) and Rotuma. Sandalwood planting has continued in its popularity during the last five years and the area of plantations is likely to now be greater than 600 ha. It is expected that the seed stands established in Fiji by this project will be productive within around four years. Generally, first-generation seed stands can be expected to produce at least 10% genetic gain over land race (i.e., unimproved, unselected) seed sources. As the seed stands that have been established were based on a combination of pedigreed and unpedigreed materials it will be important to either (i) use molecular markers to determine that they have sufficient diversity and manage inbreeding and/or (ii) augment the existing plantings with a range of more diverse material.

In the longer term (20-year timeframe) we provisionally estimate that the area of sandalwood planted could be expanded up to five-fold within ten years, assuming that the necessary policy and market development steps (including processing facilities and access to markets) are completed. Our most conservative estimate is that the area might double, the economic impacts in Fiji. To make firmer estimates will require both (i) a resource inventory and (ii) plantation capability and suitability studies.

8.3.2 Social impacts

The economic development of *S. yasi* will have positive societal benefits as it is very amenable to propagation by smallholders and community groups, providing diversification of income. Sandalwood cultivation is being embraced by villages and community groups as a cash crop that can be used to generate revenue for future projects. The industry development plan written as an output of this project seeks to maximise the opportunity for adding value and building brand recognition for sandalwood in Fiji and Tonga. Seed collection and seedling propagation, de-sapping of heartwood, and sales are activities that have major involvement of women. By encouraging the development of the sandalwood industry, the project will have positive societal benefits for these sections of the community.

8.3.3 Environmental impacts

The project is likely to have positive environmental impacts overall. The establishment of a conservation and domestication strategy for sandalwood will improve the profitability of planting sandalwood, an activity that has been growing in popularity over the last decade. The establishment of conservation stands and exchange of *S. yasi* seeds between Fiji and Tonga will also help to ensure that genetic diversity is conserved, thereby protecting the species from further genetic degradation. The project has advocated the planting and economic development of the native *S. yasi* rather than introduced *S. album*, the latter of which poses a threat to *S. yasi* as a “genetic pollutant”. This policy has been strongly embraced in Fiji, and is being promulgated through the MAFF extension services. It should be further reinforced in Tonga where further *S. album* planting has been encouraged due to a shortage of *S. yasi* seed – it is probably better to plant some sandalwood resource to discourage wild harvest in future and to maintain enthusiasm for planting. Some of the impacts from this project, such as the policy of focusing on wild *S. yasi* should have immediate positive benefits. The supply of seed from the established seed stands will take around five years to commence.

8.4 Communication and dissemination activities

The main communication activity for this project was the development of a growers’ manual, as no comprehensive written information on cultivation of *S. yasi* is available to growers in Fiji and Tonga. In collaboration with the ACIAR-supported sandalwood projects in other Pacific countries, this project led the development of an update of the Vanuatu sandalwood growers manual (Page et al. 2012b) to encompass *S. yasi* as well as other Pacific sandalwood species (*S. album, S. austrocaledonicum, S. macgregorii, S. lanceolatum*) and their hosts. The *Pacific sandalwood: growers’ guide for sandalwood production in the Pacific* (Page et al. in press) is currently in production at ACIAR Publishing and it is projected that it will be released later this year.

9 Conclusions and recommendations

9.1 Conclusions

While wild stocks of native sandalwood are threatened and are in urgent need of protection and conservation, cultivation of sandalwood presents as a major opportunity in Fiji and Tonga. The development of a sustainable sandalwood industry depends on steps being taken to conserve the remaining wild population and develop it as a basis for domestication. Immediate expansion of the resource base using genetically diverse, and, as soon as possible, genetically improved planting stock is required. This will underpin further development of the sandalwood value chain in Fiji and Tonga, allowing capture of the benefits of value-adding, rather than unprocessed or only slightly processed logs being exported and processed offshore. The benefits to smallholder growers, isolated people on outer islands, villages and community groups from growing this high value crop could grow substantially over the next 20 years if a resource of a large enough size to support downstream wood processing and distillation of essential oil can be established. The plantings established by this project are a good first step in the overall conservation and domestication strategy. However, the plantings need to be increased in number and diversity to be effective and fulfil the objectives of the conservation and domestication strategy. The development of a Growers' Manual applicable to sandalwood in Fiji and Tonga, together with effective extension programs, should help to increase the uptake of already-popular sandalwood planting. Government programs that have clear targets of increasing the sandalwood resource in each country will be required to attract the comparatively large investment required to support downstream processing such as oil distillation.

There are several technical challenges that have been partially addressed and/or identified by this project that need to be tackled to further progress industry development. This study has confirmed that *S. yasi* and other sandalwood species tend to take a long time to mature, and the need to generate cash flow tends to drive smallholders to harvest at an age (approximately 15 years) when heartwood development is incomplete. This results in a poor return over the length of the rotation, relative to that if the harvest had been delayed for around five years or longer. The lack of planted resources across a range of sites of known ages makes the study of heartwood and oil development difficult, and establishment of plantings where such studies can be undertaken is an important priority. Ideally, these trials need to be carefully designed with attention to host selection, as the host species certainly interacts with the sandalwood in terms of growth traits and may also influence wood and oil trait development – an area that is not well researched. Genetic variation of host species should therefore be minimised in sandalwood trials to reduce interaction between host and sandalwood genotypes – a unique situation among plantation forest trees.

The heartwood and oil study undertaken as part of this project also makes it clear that undertaking selection on wood and oil traits will take a long time unless a new technique to make early estimates of oil yield and quality (possibly by sampling very low in the bole or upper root system) can be developed. This will increase the intergenerational and the overall breeding cycle time periods. Further analysis of the development of heartwood throughout the root system and bole would therefore be beneficial.

Difficulties experienced in achieving some of the objectives of this project are attributable to a number of causes including a late start, within-country financial restrictions and travel restrictions caused by the COVID-19 global pandemic towards the end of the project. However, a shortage of suitably trained professional staff in both Fiji and Tonga was also a major issue: project staff were frequently removed to other roles causing delays and the need for retraining of staff on project-specific tasks, particularly those around plant propagation. The need for capacity building in tree improvement, silviculture and other forest research fields is significant in both Fiji and Tonga. The success of forest tree conservation and domestication programs is highly dependent on a stable continuum of professional staff that can pass on corporate knowledge over decades.

9.2 Recommendations

This project has made some positive initial steps towards building a sustainable sandalwood plantation industry in Fiji and Tonga. While important foundations have been laid, it will be important to follow up to ensure that the conservation and domestication program is placed on a long-term footing. The following recommendations are made:

1. The trial plantings that underpin the conservation and domestication strategy should be expanded and increased, at least to the eight plantings that were originally proposed in this project. These plantings are critical to the long-term conservation of the species and development of a more-productive, improved *S. yasi* seed source. These plantings will also be required to further progress the *S. yasi* breeding biology objectives. As the plantings comprised a mix of trees from known and unknown origins, determining the diversity and relatedness of the plantings will be an important next-step.
2. Further capacity building of professional staff is required to underpin the practical *S. yasi* conservation program in Fiji and Tonga. Staff turnover during the course of this project was considerable, and problems with transfer of corporate research knowledge and practical know-how became evident. Further training of Government staff on research principles, priorities and collaborative practices would be extremely beneficial.
3. The Industry Strategy—an output of this project—places emphasis on undertaking an inventory of planted sandalwood resources in Fiji and Tonga. This activity is critically important to setting planting targets and planning the value adding infrastructure required to further develop the industry. A well designed sandalwood inventory in each country, with individual plants measured and with GPS data, is a high priority.
4. Further study on heartwood and essential oil development is recommended. It would be ideal to carry out whole-tree determinations of heartwood development on commercially harvested trees to assess the rate of heartwood and oil development in individual trees
5. Interactions between this project and other ACIAR sandalwood projects were mutually beneficial. There would be further benefits to exchange of information and coordination of research among ACIAR sandalwood projects. This might extend to further use of DNA marker-based techniques, host-species interactions, capacity building of staff and coordination of industry strategy, conservation and domestication approaches and development of marketing, processing and upper value-chain development activities.

10 References

10.1 References cited in report

Almeida L, Page T, Williams R, Hettiarachichi D, Boyce M, Sacaio M, Alves A, Patrocinio L, Pereira I, Cristovão J (2021). Variation in heartwood development and essential oil phytochemistry across natural populations of sandalwood (*Santalum album* L.) in Timor-Leste. Agricultural Innovations for Communities (Ai-Com). Report for ACIAR project CIM-2014-082. AiCom, Dili, Timor-Leste.

Bolatolu W, Lesubula M (2021 in press) Sandalwood development in Fiji. In: *Sandalwood Regional Forum: Proceedings of a regional meeting held in Port Vila, Vanuatu, 11–13 November 2019* (eds. Page T, Meadows J, Kalsakau T), pp. 9-19. ACIAR, Port Vila, Vanuatu.

Bush D, Almeida L, Page T, R. W (2021) Genetic structure of Timor-Leste *Santalum album*. p. 49. CSIRO, Canberra.

Bush D, Brophy J, Bolatolu W, Dutt S, Hamani S, Doran J, Thomson L (2020a) Oil yield and composition of young *Santalum yasi* in Fiji and Tonga. Australian Forestry, 84, 238-244.

Bush D, McCarthy K, Meder R (2011) Genetic variation of natural durability traits in *Eucalyptus cladocalyx* (sugar gum). Annals of Forest Science, 68, 1057-1066.

Bush D, Thomson L, Broadhurst L, Dutt S, Bulai P, Faka'osi T, Havea M, Napa'a S, Vainikolo L (2016) Assessing genetic diversity of natural and hybrid populations of *Santalum yasi* in Fiji and Tonga. ACIAR, Canberra, Australia.

Bush D, Thomson L, Dutt S, Hamani S, Bolatolu W, Likiafu H, Tauraga J, Mateboto J, Young E (2020b) Domestication provides the key to conservation of *Santalum yasi* – a threatened Pacific sandalwood Australian Forestry, 83, 186-194.

Bush D, Thomson L, S D, Hamani S, Bolatolu W, Tauraga J, Mateboto J, Young E (in press) Conservation, domestication and breeding of *Santalum yasi* in Fiji and Tonga. In: *Sandalwood Regional Forum Proceedings of a regional meeting held in Port Vila, Vanuatu, 11–13 November 2019* (eds. Page T, Meadows J, Kalakaua T), pp. 136-147. ACIAR, Port Vila, Vanuatu.

Coakley T (2013) Sandalwood markets and threats. In: *International Sandalwood Foundation: Proceedings of the International Sandalwood Symposium; Oct 21–24; Honolulu, Hawaii* (eds. Nageswara-Rao M, Soneji J, Harbaugh-Reynaud D), pp. 71–81. Lulu Press; Raleigh (NC)

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

International Standards Organization (2002) Oil of sandalwood (*Santalum album* L.). p. 6. International Standards Organization, Geneva.

Motuliki P (2021 in press) Sandalwood development and production in the Kingdom of Tonga. In: *Proceedings of a regional meeting held in Port Vila, Vanuatu, 11–13 November 2019* (eds. Page T, Meadows J, Kalsakau T), pp. 20-26. ACIAR, Port Vila, Vanuatu.

Page T, Tate H, Bunt C, Potrawiak A, Berry A (2012a) Opportunities for the smallholder sandalwood industry in Vanuatu. ACIAR, Canberra.

Page T, Tate, H, Tungon J, Tabi M, Kamasteia P (2012b) Vanuatu sandalwood growers' guide for sandalwood production in Vanuatu. Australian Centre for International Agricultural Research.

Page, T, Bush, D, Clarke B, Thomson, L (in press) Pacific sandalwood: growers' guide for sandalwood production in the Pacific. ACIAR, Canberra.

Thomson LAJ (2020) Looking ahead – global sandalwood production and markets in 2040, and implications for Pacific Island producers. Australian Forestry, 83, 245-254.

Thomson L, Bush D, Lesubula M (2020a) Participatory value chain study for yasi sandalwood (*Santalum yasi*) in Fiji. Australian Forestry, 83, 227-237.fi

Thomson L, Likiafu H, Lal S, Mateboto J, Tauraga J, Bush D (2020b) South Pacific Sandalwood Industry Plan for Fiji and Tonga: Report for ACIAR Project FST-2016/158. p. 23. CSIRO, Canberra.

10.2 List of publications produced by project

Bush D, Almeida L, Page T, R. W (2021) Genetic structure of Timor-Leste *Santalum album*. p. 49. CSIRO, Canberra.

Bush D, Thomson L (2018) Conserving and making efficient use of forest genetic resources. In: Thomson L, Doran J, Clarke B (eds) Trees for Life in Oceania. ACIAR, Canberra. pp. 15-22.

Bush D, Thomson L, Dutt S, Hamani S, Bolatolu W, Likiafu H, Tauraga J, Mateboto J, Young E (2020) Domestication provides the key to conservation of *Santalum yasi* – a threatened Pacific sandalwood Australian Forestry, 83, 186-194.

Bush D, Thomson L, S D, Hamani S, Bolatolu W, Tauraga J, Mateboto J, Young E (2021 in press) Conservation, domestication and breeding of *Santalum yasi* in Fiji and Tonga. In: *Sandalwood Regional Forum Proceedings of a regional meeting held in Port Vila, Vanuatu, 11–13 November 2019* (eds. Page T, Meadows J, Kalakaua T), pp. 136-147. ACIAR, Port Vila, Vanuatu. Bush D, Brophy J, Bolatolu W, Dutt S, Hamani S, Doran J, Thomson L (2020) Oil yield and composition of young *Santalum yasi* in Fiji and Tonga. Australian Forestry, 84, 238-244.

Page, T, Bush, D, Clarke B, Thomson, L eds. (in press) Pacific sandalwood: growers' guide for sandalwood production in the Pacific. ACIAR, Canberra.

Thomson L, Bush D, Lesubula M (2020) Participatory value chain study for yasi sandalwood (*Santalum yasi*) in Fiji. Australian Forestry, 83, 227-237.

Thomson L, Bush D, Bulai P (2018) Species accounts: *Santalum yasi*. In: Thomson L, Doran J, Clarke B (eds) Trees for Life in Oceania. ACIAR, Canberra. pp. 210-213.

Thomson L, Likiafu H, Lal S, Mateboto J, Tauraga J, Bush D (2020) South Pacific Sandalwood Industry Plan for Fiji and Tonga: Report for ACIAR Project FST-2016/158. p. 23. CSIRO, Canberra.

Thomson L, Bush D, Lesubula M (2021 in press) Participatory value chain study for yasi sandalwood (*Santalum yasi*) in Fiji. In: *Sandalwood Regional Forum* (ed. Page T), Port Vila, Vanuatu.

11 Appendixes

11.1 Appendix 1: Project fact sheet

Domestication and breeding of sandalwood in Fiji and Tonga

Overview

Santalum yasi is commercially-valuable sandalwood species native to Fiji (*yasi*) and Tonga (*'ahi*). It produces an exceptionally high quality sandalwood oil-yielding heartwood. The species has been over-exploited in the wild, resulting in fragmentation and local extinctions of natural populations. However, the demand for sandalwood products remains high, and prices are buoyant. As *S. yasi* is quite easily cultivated, and because it produces a non-perishable, high-value, low-volume product there is considerable scope for development of a substantial *S. yasi* industry throughout Fiji and Tonga.

To achieve this vision, the industry in Fiji and Tonga must transition from dependence on wild harvesting to an efficient, smallholder agroforestry-based systems, 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 in global markets. In order to do this, the remaining *S. yasi* diversity needs to be secured and the quality of germplasm and plants improved. Recent research identified inbreeding in many of the existing stands, which may diminish performance of planted trees unless breeding work is carried out to improve the material available for plantation establishment.

This project aims to establish the foundation for conservation and domestication of native sandalwood (*S. yasi*) in Fiji and Tonga to support the development of a sustainable planted sandalwood industry (Fig. 3).

Fig. 1: *Santalum yasi* stump showing heartwood

Fig. 2: *Santalum yasi* (A&B), *S. album* (C&D) and *S. album* x *S. yasi* hybrid (E&F) fruit and seed

Research

The project objectives are:

1. To improve understanding of the breeding biology and genetic diversity of key traits in *S. yasi* in Fiji and Tonga. This will guide the implementation of a breeding strategy.
2. To develop strategies to enhance the quality and availability of *S .yasi* germplasm.
3. To establish conservation and seed production stands to maintain genetic diversity and produce high quality germplasm for commercial planting.
4. To build the capacity of research and extension staff from government organisation in Fiji and Tonga.

Fig. 3: *S. yasi* planted under pines in Tonga. The aim of current research is to increase the availability of good quality planting stock to underpin a plantation industry

Australian Government
Australian Centre for International Agricultural Research
Pacific Community
Communauté du Pacifique
CSIRO

Achievements and impact

To inform decisions on how to manage the remaining *Santalum yasi* natural resource and promote a successful plantation industry it was necessary to determine what the genetic diversity of the remaining populations of *S. yasi* are and what impact hybridisation with *S. album* was having on these populations. A project was undertaken to assess the genetic diversity of natural and hybrid populations of *S. yasi* in Fiji and Tonga.

- A large number of trees were sampled across the two countries and leaf samples were sent to Australia/CSIRO for morphological and DNA analysis with the following findings:
  - Morphological markers are, in most cases, effective for differentiating the two species and their hybrids.
  - Genetic markers provided greater certainty in differentiating the two species and their hybrids.
  - *S. yasi* has significant genetic diversity but were inbred, indicating that the highly fragmented wild populations may no longer be self-sustaining.
  - Widespread inter-specific hybridisation does not seem to have occurred
  - It is possible that *S. yasi* growth might improve significantly if inbreeding can be reduced
- Recommendations for the way forward based on these results:
  - Genetically diverse gene conservation stands and seed production areas be assembled
  - Active measures be taken to conserve *S. yasi* in its pure form.

Fig. 3: Sampling of *yasi* trees in Fiji

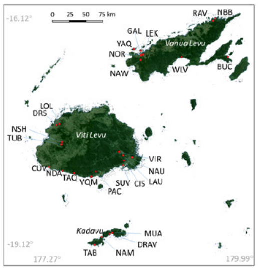


Fig. 4: Fiji *yasi* sample locations (additional samples not shown on here were taken from Vanua Balavu, northern Lau Group)

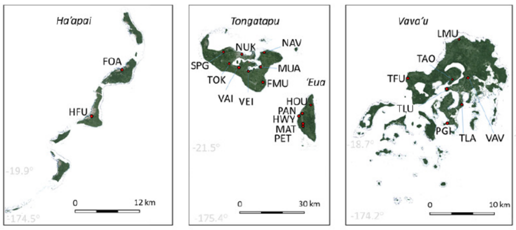


Fig. 5: Tonga *'ahi* sample locations

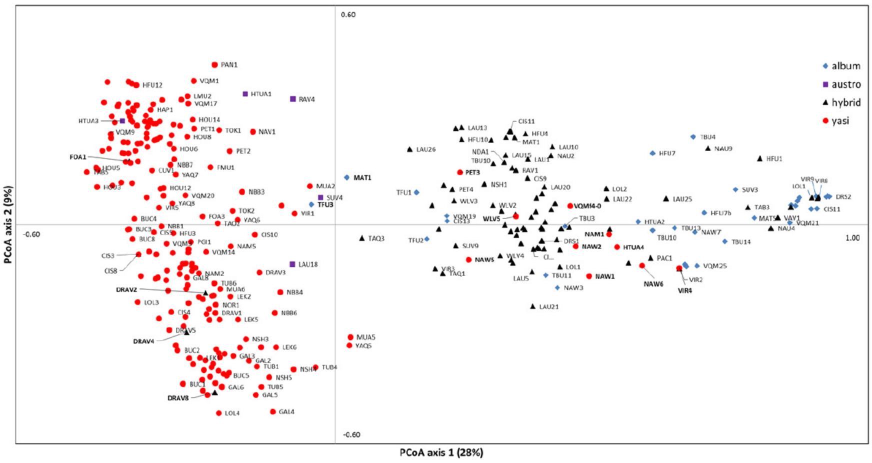


Figure 6: Clusters of trees are considered to be more closely related in DNA analysis *Santalum* species in Fiji and Tonga. The diagram shows the natural *S. yasi* (red) is distinct from hybrids between it (black) and exotic *S. album* (blue).