3-1-2023

Safeguarding sandalwood: A review of current and emerging tools to support sustainable and legal forestry

Ellyse Bunney

Francesca A. McInerney

Eleanor Dormontt

Arif Malik

Nina Welti

See next page for additional authors

10.1002/ppp3.10349
Bunney, E., McInerney, F. A., Dormontt, E., Malik, A., Welti, N., Wilkins, D., ... & Lowe, A. J. (2023). Safeguarding sandalwood: A review of current and emerging tools to support sustainable and legal forestry. Plants, People, Planet, 5(2), 190-202). https://doi.org/10.1002/ppp3.10349

Authors
Ellyse Bunney, Francesca A. McInerney, Eleanor Dormontt, Arif Malik, Nina Welti, David Wilkins, Malcolm Plant, Dhanushka S. Hettiarachchi, Darren Thomas, Ashley Dowell, Tresa Hamalton, and Andrew J. Lowe

Received: 16 August 2022 | Revised: 10 November 2022 | Accepted: 15 November 2022
DOI: 10.1002/ppp3.10349

REVIEW

Plants People Planet PPP Open Access

Safeguarding sandalwood: A review of current and emerging tools to support sustainable and legal forestry

Ellyse Bunney[1,2] | Francesca A. McInerney[1,2,3] | Eleanor Dormontt[4] | Arif Malik[4] | Nina Welti[2] | David Wilkins[5] | Malcolm Plant[6] | Dhanushka S. Hettiarachchi[7,8] | Darren Thomas[9] | Ashley Dowell[10] | Tresa Hamalton[11] | Andrew J. Lowe[4]

[1]Department of Earth Sciences, University of Adelaide, Adelaide, South Australia, Australia
[2]Commonwealth Scientific and Industrial Research Organisation, Waite Campus, Urrbrae, South Australia, Australia
[3]School of Earth and Environmental Sciences, University of Queensland, St. Lucia, Queensland, Australia
[4]Department of Ecology and Evolutionary Biology, University of Adelaide, Adelaide, South Australia, Australia
[5]Department for Environment and Water, Government of South Australia, Port Lincoln, South Australia, Australia
[6]Department of Biodiversity, Conservation and Attractions, Government of Western Australia, Kensington, Western Australia, Australia
[7]Product Specialist, Quintis Sandalwood, West Perth, Western Australia, Australia
[8]School of Science, Edith Cowan University, Joondalup, Western Australia, Australia
[9]Double Helix Tracking Technologies Pte Ltd., Singapore
[10]Southern Cross Analytical Research Services, Southern Cross University, East Lismore, New South Wales, Australia
[11]Tree Improvement and Genetics Division, Institute of Wood Science and Technology, Bangalore, India

Correspondence
Ellyse Bunney, Department of Earth Sciences, University of Adelaide, Adelaide, SA 5005, Australia.
Email: ellyse.bunney@csiro.au

Funding information
Nature Foundation South Australia, Grant/Award Number: 2019-3; Biological Society of South Australia; Nature Conservation Society of South Australia; Bill-Retalic Prize for Science and Justice; Environment Institute, University of Adelaide; Australian Government, Department of Education (Research Training Program Scholarship)

Societal Impact Statement
Sandalwood and other high value tree species are under significant threat from illegal harvest. Illegal logging is an increasing problem contributing to deforestation, biodiversity loss, human rights abuses and funding transnational crime. Successful prosecution of illegal logging is hindered by a lack of methods to provide evidence of the origin of timber. New analytical techniques have been developed to trace timber back to its source. These methods, together with the establishment of sustainable sources of forest resources, can help protect vulnerable species by providing evidence to prosecute illegal harvest and ensure that commercially available forest products come from sustainable sources.

Summary
Sandalwood is highly valued for its fragrant oil and has a long history of cultural and economic importance in many regions of the world. Historical overharvest and poor management have depleted natural populations of sandalwood, which are slow to regenerate. The increasing establishment of plantation sandalwood creates an alternative resource for the sandalwood industry while potentially relieving harvesting pressure on natural stands. Due to the high demand for sandalwood, remaining wild

populations are still under threat from illegal logging and methods to identify the source of harvested sandalwood are needed. Laws and regulations aimed at preventing illegal harvest and possession of sandalwood have been put in place but cannot be enforced without the forensic tools to independently verify claimed origin or product quality. The high value of sandalwood combined with the difficulties in enforcing illegal logging laws makes these species particularly vulnerable to poaching. There is an immediate need to develop tools that can identify illegally sourced and adulterated sandalwood products. This paper reviews the current and developing scientific tools that can help identify and control illegal activity in sandalwood supply chains and provides recommendations for future research. Topics include isotope and DNA analysis for tracing illegally harvested sandalwood, chemical profiling for quality control of sandalwood oils, network and policy development to establish a framework for future regulation of the sandalwood trade.

KEYWORDS
geographic origin, illegal logging, isotopic provenancing, sandalwood, timber tracking, traceability

1 | INTRODUCTION: SANDALWOOD DESCRIPTION, ECONOMICS AND THREATS TO CONSERVATION

The fragrant wood known as sandalwood is obtained from a variety of species in the family *Santalaceae* (Soundararajan et al., 2015; Teixeira da Silva et al., 2016). Sandalwood is one of the most valuable tree species in the world (Dev et al., 2013; Kumar et al., 2012). Most species commonly called sandalwood belong to the genus *Santalum* and have a natural geographic range between 30°N and 40°S, occurring throughout India, Australia, South East Asia, Hawaii and the Pacific Islands (Subasinghe, 2013) (Table 1). African sandalwood, genus *Osyris*, is also heavily extracted for commercial purposes (Bunei, 2017; Mugula et al., 2021).

Sandalwood has a long history of human use and appears in Sanskrit texts as early as 2000 BCE (Rai, 1990). The sought-after wood and oil are still essential in a wide range of industries and activities (Subasinghe, 2013; Teixeira da Silva et al., 2016) and have significant religious and cultural importance, being considered sacred in many parts of the world (Kumar et al., 2012; Rashkow, 2014; Soundararajan et al., 2015). In Hindu, Buddhist and Muslim ceremonies sandalwood is used for incense sticks and as wood for funeral pyres (Sandeep & Manohara, 2019; Teixeira da Silva et al., 2016; Thomson, 2020). Sandalwood is also valued as a quality wood for carving and furniture making (Rashkow, 2014; Thomson, 2020). In the perfume and cosmetics industries, sandalwood oil is prized for its aroma and fixative qualities (Kucharska et al., 2021; Kumar et al., 2012). Some species of *Santalum* produce edible nuts, and the heartwood oil is used for flavouring food products and chewing tobacco (Clarke, 2006; Lee et al., 2019). There is also a long history of using sandalwood in both traditional and modern medicines (Burdock & Carabin, 2008; Subasinghe, 2013). Research into the medicinal properties of sandalwood oil has identified numerous benefits of the active compounds α- and β-santalols, including antibacterial, anti-inflammatory, antioxidant, antihyperglycaemic and chemopreventative effects (Bommareddy et al., 2019; Kucharska et al., 2021; Teixeira da Silva et al., 2016).

Sandalwood species occur in both tropical and temperate environments (Clarke, 2006; Sandeep & Manohara, 2019) and are slow growing, root hemiparasites that obtain nutrients from a host plant as well as producing their own nutrients through photosynthesis (Barbour et al., 2010; Lee et al., 2019; McLellan et al., 2021; Subasinghe, 2013; Teixeira da Silva et al., 2016). Sandalwood can form parasite–host associations with more than 300 species; however, nitrogen-fixing, woody species are the preferred hosts for sandalwood such as *Acacia nicolita*, *Acacia acuminata*, *Casuarina equisetifolia*, *Cynodon dactylon* and *Cassis siamea* (Das, 2021; Doddabasawa et al., 2020). The fragrant oil is extracted mainly from the heartwood of the tree, which begins to develop at around 10 years, but takes at least 25 years to produce optimal levels of heartwood for oil extraction (Brand et al., 2012; Howes et al., 2004; Moniodis et al., 2017). The rate and amount of heartwood growth, as well as the chemical composition of sandalwood oil, can vary greatly between species, region and individual plants (Hettiarachchi, 2008; Moniodis et al., 2017; Subasinghe, 2013). The most valuable sandalwood species is *Santalum album* (*S. album*), commonly known as East Indian sandalwood, which is well known for the superior quality of its oil and favourable proportions of α- and β-santalols (Howes et al., 2004; Kucharska et al., 2021; Subasinghe, 2013). Even so, many different species are harvested commercially around the world; see Table 1 (Lee et al., 2019; McKinnell, 1990; Subasinghe, 2013; Thomson, 2020).

Poor management and over exploitation of sandalwood resources have depleted natural stands, which have seen dramatic global

TABLE 1 Sandalwood producing countries and associated species names, common names, occurrence of sandalwood plantations, occurrence of legal wild harvest and estimated future production or consumption

Country	Species exploited for oil extraction	Common name	Occurrence of plantations yes (Y)/no (N)	Occurrence of legal wild harvest Y/N	Net production (P) or consumption (C)	References
Australia	*Santalum spicatum* (R.Br.) A.DC. *Santalum album* L. *Santalum lanceolatum* R.Br.	Australian sandalwood Indian sandalwood Northern sandalwood	Y	Y	P	Lee et al. (2019); Thomson (2020)
India	*S. album* L.	Indian sandalwood	Y	Y	P	Kumar et al. (2012)
Indonesia	*S. album* L.	Indian sandalwood	Y	Y	P	McKinnell (1990); Rohadi et al. (2004)
Timor-Leste	*S. album* L.	Indian sandalwood	Y	Y	P	Ferreira et al. (2019)
Sri Lanka	*S. album* L.	Indian sandalwood	Y	Y	P	Subasinghe et al. (2017)
New Caledonia	*Santalum austrocaledonicum* Vieill.	New Caledonia sandalwood, Vanuatu sandalwood, Coral Sea sandalwood	Y	Y	P	Subasinghe (2013)
Vanuatu	*Santalum austrocaledonicum* Vieill.	New Caledonia sandalwood, Vanuatu sandalwood, Coral Sea sandalwood	Y	Y	P	Page et al. (2021)
Fiji & Tonga	*Santalum yasi* Seem.	Yasi sandalwood	Y	Y	P	Bush et al. (2020); Huish et al. (2015)
Papua New Guinea	*Santalum macgregorii* F. Muell.	Papua New Guinea sandalwod	Y	Y	P	Rome et al. (2021)
China	*S. album* L.	Indian sandalwood	Y	N	C	Thomson (2020)
Hawaii	*Santalum paniculatum* Hook. & Arn. *Santalum ellpticum* Gaudich	'Iliahi	N	Y	C (N America)	Merlin and VanRavenswaay (1990)

TABLE 2 Status of *Santalum* species on the International Union for Conservation of Nature (IUCN) red list of threatened species (IUCN, 2022; https://www.iucn.org/)

Species	Conservation status
Santalum fernandezianum	Extinct
Santalum involutum, 'iliahi	Critically endangered
Santalum macgregorii	Critically endangered
Santalum yasi	Endangered
Santalum pyrularium, 'iliahi	Endangered
Santalum freycinetianum, Lanai sandalwood	Endangered
Santalum insulare, Polynesian sandalwood	Endangered
Santalum album, Indian sandalwood	Vulnerable
Santalum spicatum, Australian sandalwood	Vulnerable
Santalum paniculatum	Vulnerable
Santalum haleakalae	Vulnerable
Santalum austrocaledonicum, Coral Sea sandalwood	Near threatened

declines over the last 100 years (Barbour et al., 2010; McKinnell, 1990). Natural regeneration of sandalwood stands is slow and remnant populations are isolated, fragmented and show a lack of recruitment (Herford et al., 2015; McLellan et al., 2021). Reduction in range and size of sandalwood populations, due to intense harvest pressure, has resulted in a loss of genetic diversity (Bush et al., 2020; Indrioko & Ratnaningrum, 2015; McLellan et al., 2021; Sandeep & Manohara, 2019). Further pressures on sandalwood survival include agricultural clearing, fire, grazing impacts on seedling survival, climate change and illegal logging (Herford et al., 2015; Sandeep & Manohara, 2019; Subasinghe, 2013). In India, sandalwood is also significantly affected by spike disease caused by bacterial phytoplasma which often results in tree death within 2 years of infection (Mondal et al., 2020; Subasinghe, 2013).

The overharvest of sandalwood species has led to many species now being vulnerable, in decline or extinct (Table 2; International Union for Conservation of Nature [IUCN], 2022) (Subasinghe, 2013). East Indian sandalwood (*S. album*) and *Santalum haleakalea* (Hawaii) are listed as vulnerable on the IUCN red list, *Santalum freycinetianum* is classified as endangered, *Santalum macgregorii* is critically endangered and *Santalum fernandezianum* from Chile has been harvested to extinction (Harbaugh & Baldwin, 2007; Huish et al., 2015; Jiao et al., 2019; Teixeira da Silva et al., 2016). Other species of sandalwood have recently been assessed and added to the IUCN red list, bringing the total number of threatened *Santalum* species to 12 (IUCN, 2022).

Increasing demand, paired with declining supply has caused the price of sandalwood to increase dramatically (George et al., 2020; Rashkow, 2014; Subasinghe, 2013; Thomson, 2020). Between 1992 and 2014, it is estimated that the price of sandalwood increased by a compound rate of 15.1%, which has made sandalwood a lucrative target for poachers and further threatens species' survival (Thomson, 2020).

Current interest in sandalwood involves many countries, government agencies, industries, research disciplines, conservation groups, cultures and communities worldwide. Industry representatives, compliance officers, scientists and sandalwood growers met for the 2020 Sandalwood Workshop, (hosted online by the University of Adelaide, Environment Institute, 5 August 2020) to discuss current work, management challenges and research. This group identified both challenges to and opportunities for the future sustainability of sandalwood, which we present in this paper. Here, we summarise the current status of sandalwood utilisation and management and identify the main legal problems relating to the trade in sandalwood and sandalwood oil. We go on to explore the current and emerging forensic tools that are being developed for sandalwood identification and supply chain monitoring (e.g., DNA and chemical analysis), how these methods can be applied to support policy and law enforcement and what is needed to systemically develop a verification framework for legal sandalwood supply chains. Finally, we aim to highlight research needs relating to sandalwood management to assist conservation, compliance and industry development as well as encourage an interdisciplinary approach to creating new solutions to current challenges. This review is primarily from an Australian perspective but seeks also to provide an international context.

2 | STATUS OF SANDALWOOD SUPPLY

2.1 | Wild harvest trade

2.1.1 | India

The sandalwood trade has a long and rich history, and India has been the major supplier of sandalwood to the world for over 5000 years (Kumar et al., 2012; Rashkow, 2014). Sandalwood stocks have historically been under tight control as they have been an important source of revenue for successive rulers and governments (Bhaskar et al., 2010; Sandeep & Manohara, 2019; Soundararajan et al., 2015). In the Indian state of Mysore, sandalwood was declared a 'royal tree' and the sandalwood trade was managed by the state (George et al., 2020; Rashkow, 2014). The state control of sandalwood continued with successive Indian governments that prevented private landowners from harvesting sandalwood grown on their land, a situation that has changed in recent decades (Bhaskar et al., 2010; Kumar et al., 2012; Rashkow, 2014; Sandeep & Manohara, 2019). Approximately 90% of wild *S. album* occurred in the southern states of Karnataka and Tamil Nadu (Kumar et al., 2012; Venkatesha Gowda et al., 2004). In Karnataka, an average 480,000 sandalwood trees were harvested per year from 1950 to 1970 (Rashkow, 2014). A survey of sandalwood stocks in 1974 revealed that there were only 347,128 trees remaining in the state, and only 4360 of these were large enough to harvest (Rashkow, 2014). Sandalwood populations in Karnataka were also significantly affected by spike disease

(Mondal et al., 2020). The sudden drop in supply from India at this time was a major catalyst for the price of sandalwood to increase (Rashkow, 2014).

2.1.2 | Australia

The Australian sandalwood trade dates back to the late 1800s and has been controlled in Western Australia (WA) by the State Government since the 1920s (Rashkow, 2014; Tonts & Selwood, 2003) when harvest permits, harvest limits and fixed prices were introduced (Tonts & Selwood, 2003). The economic importance of sandalwood to WA, compared with other agricultural products, has fluctuated over the years, and land clearance for agriculture has contributed significantly to a reduction in geographic range of wild *Santalum spicatum* (McLellan et al., 2021; Soundararajan et al., 2015; Tonts & Selwood, 2003).

The decline in sandalwood supply from other countries renewed interest in developing Australia's sandalwood trade (Clarke, 2006). Previously, sandalwood was predominantly exported from Australia as timber, but in recent decades, sandalwood oil and other value-added products have been produced by Australian companies, both for export and domestic use (Tonts & Selwood, 2003).

2.1.3 | South East Asian and Pacific regions

Unsustainable harvesting has resulted in variable supply of sandalwood from the majority of countries in South East Asia and the Pacific region over the last 100 years (Bush et al., 2020; McWilliam, 2005; Rohadi et al., 2004; Soundararajan et al., 2015; Tonts & Selwood, 2003). Restrictions or temporary bans on the harvest and export of sandalwood have, at times, been used to allow over-exploited populations to recover and mature (Gillieson et al., 2008; McWilliam, 2005; Rohadi et al., 2004). New Caledonia has had more consistent sandalwood production due to better management and regulation of harvest from wild trees (Butaud, 2015; Thomson, 2020).

2.2 | Plantations

Markets for sandalwood continue to grow, and in recent decades, plantations of sandalwood have been established to fill the growing demand and to create a sustainable, legal supply of sandalwood (Subasinghe, 2013; Thomson, 2020). Supplementing commercial harvest of wild-grown sandalwood with plantation-grown sandalwood is necessary for supporting the conservation of sandalwood species (Clarke, 2006). Many countries, including Australia, India, China, Fiji, Tonga, New Caledonia, Vanuatu, Malaysia, Thailand, Vietnam and Sri Lanka, have shown interest in developing sandalwood plantations (Subasinghe, 2013; Thomson, 2020). Growing sandalwood is a long-term investment as it takes approximately 25 years for trees to mature and reach optimal levels of oil production. However, sandalwood is commonly harvested as young as 15 years (Bush et al., 2020) and identifying opportunities for early return on plantation investments is being explored as a priority to encourage smallholders to delay harvest (Ota et al., 2022). Expected production of sandalwood in 2040 indicates that India is positioned to be the largest producer globally, followed by Australia and Indonesia, with substantial growth in production in the Pacific and South East Asian regions (Table 1 and Figure 1; Thomson, 2020).

Australia has led the way in the establishment of sandalwood plantations and is in a position to be a major contributor to the global market, due to modest domestic consumption of sandalwood (Subasinghe, 2013; Thomson, 2020). There have been extensive plantations of *S. album* (approximately 12,000 ha of East Indian sandalwood) established in tropical Australia in response to global demand for Indian sandalwood oil and products (Clarke, 2006; Thomson, 2020). In WA, an estimated 21,000 ha of *S. spicatum* plantations have been established (Herford et al., 2015; Thomson, 2020). Due to the hemiparasitic nature of sandalwood, establishment of sandalwood plantations requires host species such as *Acacia* and *Casuarina* to be present (Lee et al., 2019; McKinnell & Levinson, 2008); therefore, sandalwood plantations also promote planting of native species or preservation of existing stands of native vegetation (McKinnell & Levinson, 2008). Other environmental benefits of planting sandalwood include decreased soil salinity and erosion (Tonts & Selwood, 2003).

In India, there has been interest and investment in plantation development, especially in northern regions (Thomson, 2020). Initial attempts to establish plantations in southern India were unsuccessful due to the complication of the hemiparasitic nature of sandalwood and their germination and early establishment requirements (Rashkow, 2014). Unfortunately, subsequent efforts to develop plantations in southern India have been heavily impacted by spike disease and poaching (Clarke, 2006). However, plantations established in northern India are expected to be less affected by spike disease (Thomson, 2020).

In Vanuatu, there has been some commercial plantation establishment and an interest in smallholder plantings by local communities (Gillieson et al., 2008; Page et al., 2021). New Caledonia's sandalwood industry has several replanting initiatives, with *Santalum austrocaledonicum* harvested in the Loyalty Islands being replanted at a rate of 30 trees for every tree harvested (Butaud, 2015; Thomson, 2020). *S. album*, *Santalum yasi* and a hybrid of the two species (which produces a high-quality oil) have also been established in plantations on Fiji and Tonga (Thomson, 2020). More recently, plantations have been established in South East Asian countries such as Cambodia, Vietnam, Thailand and Malaysia (Thomson, 2020).

Despite overwhelming interest in sandalwood farming globally, the length of time it takes for trees to mature inevitably delays return on investment, and it is expensive to protect trees while they reach maturity (Ota et al., 2022; Viswanath et al., 2020). Methods have been developed to assist with mitigating the risk of sandalwood theft such as vibration sensing alarms that are attached to trees and send and alert to forestry staff when the vibrations from tree-cutting are detected (Hamza et al., 2013; Kumar et al., 2020). Ongoing

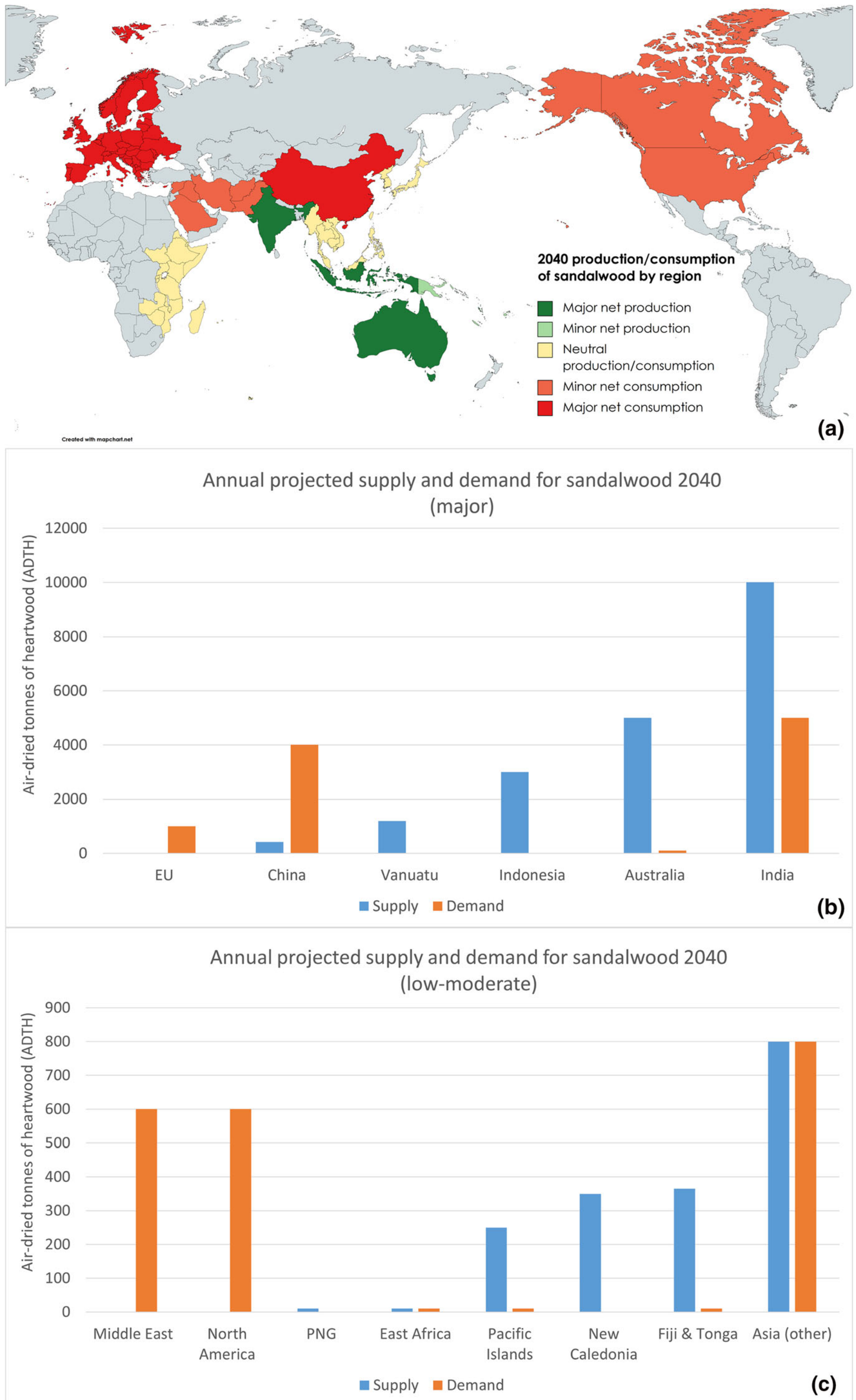

FIGURE 1 Estimated annual sandalwood production and consumption in 2040, by region; (a) map indicating anticipated future annual production and consumption of sandalwood by region; graphs indicating quantity of air-dried tonnes of heartwood (ADTH) of sandalwood produced and consumed annually, by region. Supply and demand data reported in tonnes of oil has been converted to an approximated, equivalent ADTH (based on an oil yield of 1% to 5% from heartwood of sandalwood species). Map created with MapChart (https://mapchart.net). (b) Major producers/consume: production or consumption >1000 ADTH; (c) low-moderate producers/consumers: production and consumption <1000 ADTH. Data from Thomson et al. (2020)

agroforestry research aims to improve financial viability of sandalwood planting by determining optimal timing of tree harvest (Ota et al., 2022; Viswanath et al., 2020).

2.3 | Regulation

In an effort to conserve sandalwood species in Australia and internationally, there have been changes to the regulation of sandalwood harvest and trade (Lingard & Perry, 2018). *Osyris lanceolata* (African Sandalwood) is listed as a protected species under CITES (the Convention on International Trade in Endangered Species of Wild Fauna and Flora) Appendix 2, but populations have continued to decline to the point of local extinction in some countries, despite this protection (Mugula et al., 2021). Laws prohibiting the import and trade of illegal timber products have been introduced in Australia (Illegal Logging Prohibition Act), the European Union (European Union Timber Regulation) and the United States (2008 Amendment to the Lacey Act)

(Gascoigne, 2021). The Australian Illegal Logging Prohibition Act prohibits the import or processing of timber or timber products that have been harvested contrary to the laws of the country where the timber was harvested (Gascoigne, 2021). Due diligence to comply with this direction is the responsibility of those importing and processing the timber, and there are penalties associated with noncompliance (Gascoigne, 2021).

In sandalwood producing countries, such as Australia, India, Indonesia, Vanuatu and Tonga, there are also regulations relating specifically to the harvest, possession and trade of wild sandalwood (Herford et al., 2015). In Australia, documentation and licences are required for the harvest and trade of sandalwood to trace supply routes (Herford et al., 2015). In WA, the commercial harvest quota for *S. spicatum* is set by the *Sandalwood (Limitation of Removal) Order* that states how much green wood and deadwood can be harvested each year and specifies from what locations (Herford et al., 2015). The Government of WA has increased penalties for illegal harvest with a recent change (1 January 2019) in legislation from the *Sandalwood Act 1929* to the *Biodiversity Conservation Act 2016—Section 172*. This change has increased the maximum penalty for illegally taking sandalwood from a $200 fine to a $200,000 fine. There is currently no commercial harvest of wild-grown *S. spicatum* in South Australia (SA), and any clearing on private land requires a native vegetation permit, which is not granted unless absolutely necessary for protected species such as sandalwood (pers comm. South Australian Department of Environment and Water). Likewise, India, Indonesia, Vanuatu and Tonga require licenses to harvest, trade and invest in sandalwood. Additional regulatory tools in these countries include long-term restricted harvest quotas, short-term bans on any harvest and designated protected areas with penalties for noncompliance (Begum & Ravikumar, 2021; Page et al., 2021; Thomson et al., 2020; Yuskianti & Warrier, 2022). Tonga has implemented a system to tag and record individual trees for further traceability (Thomson et al., 2020). The Indonesian government has made policy changes to support the ongoing viability of sandalwood and provide incentives to encourage sustainable farming of sandalwood (Yuskianti & Warrier, 2022).

3 | ILLEGAL ACTIVITIES ALONG THE SANDALWOOD SUPPLY CHAIN

3.1 | Illegal logging in wild stands of sandalwood

Despite legislative changes, illegal harvest of wild sandalwood is a continuing problem globally (Bunei, 2017; Subasinghe, 2013). In India, it has been estimated that 75% of sandalwood leaving Karnataka has been harvested illegally (Rashkow, 2014), and approximately 33% of the global sandalwood market is sourced illegally (Thomson, 2020). Enforcing sustainable forestry practices is further hindered by fraudulent documentation, bribery and money laundering (Gascoigne, 2021).

In sandalwood producing countries, there are active and organised criminal sandalwood harvesting syndicates (Rashkow, 2014) and intricate laundering of sandalwood to avoid penalties (Bunei, 2017). Illegally logged sandalwood can be transported across borders into jurisdictions with fewer protections to evade regulations (Bunei, 2017). Proving a piece of sandalwood has been illegally harvested requires the ability to determine the geographic origin of the wood. A lack of uniform legislation across sandalwood producing states and countries, combined with a lack of tools to independently verify the source of sandalwood products, contributes to the inability to police illegal activity and enforce sustainable harvest laws in Australia and internationally (Soundararajan et al., 2015).

3.2 | Illegal mixing and adulterants in sandalwood oil

Fraud in the form of substitution and mixing has been identified as a problem further along the sandalwood supply chain (Subasinghe, 2013). Due to reduced supplies and increased prices for sandalwood oil, inferior or synthetic oils are labelled as sandalwood or used to dilute sandalwood oils (Hettiarachchi, 2008; Subasinghe, 2013). Due to the therapeutic properties of natural sandalwood oil, mislabelled synthetic substitutes could be especially problematic and may not be safe to use in the same way (Kucharska et al., 2021). An important part of quality control and detecting illegal products involves comparison of sandalwood oils with industry standards (International Organization for Standardization [ISO]) and dictates the acceptable chemical constituents (Clarke, 2006; Kucharska et al., 2021). A study comparing six sandalwood oils on the market to the international standard for *S. album*, found that only one was genuine *S. album* oil (Kucharska et al., 2021). Of the remaining five sandalwood oils tested, three were from the species *Amyris balsamifera* (a species that produces a fragrant oil similar in smell to sandalwood) and two were mixtures of synthetic compounds (Kucharska et al., 2021). While all were labelled sandalwood oil, one of the *A. balsamifera* oils and one of the synthetic oils were specifically labelled as *S. album* (Kucharska et al., 2021).

4 | CURRENT TOOLS AVAILABLE FOR SANDALWOOD AUTHENTICATION

4.1 | Supply chain transparency and product traceability

Successful prosecution of illegal logging cases requires an ability to provide evidence, which independently verifies the species of timber and if the timber is from the geographic origin declared; however, currently, such methods are still in development (Dormontt et al., 2015). Buyers are also unable to independently verify the legality of their timber purchases due to the lack of established value chain tracing systems (Kagawa & Leavitt, 2010; Watkinson et al., 2020). As such, analytical techniques are required to distinguish legal timber from poached products (Kagawa & Leavitt, 2010), and a similar situation exists for sandalwood. These tools can provide quality assurance for industry by tracing supply chains and providing a certification of sustainably sourced timber, as well as provide evidence to prosecute illegal logging (Dormontt et al., 2015; Kagawa & Leavitt, 2010).

4.2 | Tracing geographic origin of sandalwood (provenance)

4.2.1 | Isotopic provenancing

A newly emerging approach to timber tracking is isotopic provenancing of wood (Kagawa & Leavitt, 2010). The isotope ratio quantifies the relative abundance of heavy and light isotopes of an element, which varies systematically due to physical, chemical and biological processes in the environment (Sharp, 2017). Spatial variation in isotope ratios, driven by factors including differences in hydrology, climate, soil chemistry, bedrock type and agricultural practices result in distinct isotopic signature for different geographical regions especially when multiple isotope systems are considered (Cerling et al., 2016; Kelly et al., 2005; Sharp, 2017). Isotopic signatures that are characteristic of a particular region are incorporated into the tissue of organisms grown in that region and may be utilised as a means of identifying from where an organic material originated (Camin et al., 2017). In forensic applications, the isotopic signature of one sample may be compared with another sample to verify whether or not they could have originated from the same place (Camin et al., 2017). Alternatively, the isotopic signature of an unknown sample may be compared with the isotopic signatures of a suite of reference samples of known origin to identify where the unknown sample could have come from Camin et al. (2017). Differentiating geographic origin of timber using multiproxy-isotopic provenancing has been demonstrated in other tree species (Lee et al., 2015; Rich et al., 2016; Watkinson et al., 2020).

Development of a reference database of sandalwood isotope ratios (carbon, oxygen and strontium) would enable this technology to be used to verify claims of legally harvested sandalwood by comparing logs with reference samples from the location identified as the origin on the documentation accompanying the wood (Gasson et al., 2021). Independent verification of the source of sandalwood oil would also be useful to identify illegal products, particularly in the case of illegally sourced *S. album*. Medini et al. (2015) demonstrated the utility of strontium isotopes for provenancing of olive oil. Strontium isotopic signatures could be useful for determining the origin of sandalwood oils because strontium is very stable and should remain unaltered during processing and oil extraction procedures (Medini et al., 2015).

4.2.2 | Genetic provenancing

Tracing the origin of timber products using population genetics relies on the dynamics of genetic drift and gene flow in natural populations that creates genetically identifiable clusters in different regions (Crawford, 2016, unpublished honours thesis). Genetic markers have been developed that can identify the provenance of *S. spicatum* from SA and WA (Crawford, 2016, unpublished honours thesis). DNA barcoding, single-nucleotide polymorphism (SNP), sequence characterised amplified region (SCAR) and microsatellite (SSR) techniques have been studied for verifying geographic origin of timber species; for review, see Jiao et al. (2020). Increased genotyping of specimens within these regions will increase the spatial resolution of identification, and new genetic markers could be added to existing marker sets (Crawford, 2016, unpublished honours thesis). It is important to note that seeds are transported interstate which could complicate results from genetic analysis for verifying the source of sandalwood logs, particularly when applied to plantation sources. Due to an increased interest in planting sandalwood, it would also be useful to develop genetic markers to identify plantation stocks (Dormontt et al., 2015; Jiao et al., 2019, 2020).

4.3 | Individual matching—Log to log and log to stump

The existing genetic markers that are used for determining the provenance of samples (Crawford, 2016, unpublished honours thesis) could also be used to match sandalwood logs with logs or with the stumps of trees left behind after harvesting, as has been done in other species (Jiao et al., 2020; Ng et al., 2020). This has been developed in other species as the stumps have been found to be left behind during illegal harvesting activities because removing stumps is time consuming. Stumps of sandalwood are more commonly removed because they contain valuable quantities of sandalwood oil (McKinnell, 1990). However, a blind experiment could be performed to test the accuracy of matching logs to stumps through comparing DNA. This type of paired analysis could be used to provide forensic evidence for prosecution of illegal logging and could be integrated into supply chain monitoring to ensure compliance (Dormontt et al., 2015).

4.4 | Oil quality control

There are eight *Santalum* species that are commercially utilised for wood and oil globally, and due to the high value and demand for sandalwood oil, it is also one of the most mislabelled or fraudulently sold essential oils (Kucharska et al., 2021). To ensure authenticity and quality control for essential oils, international standards have been established by the ISO to specify the oil properties such as colour and chromatographic profile. International standards have been developed for Indian sandalwood (*S. album*) oil (ISO 3518:2002) (Kucharska et al., 2021) and Australian sandalwood (*S. spicatum*) oil (ISO 22769:2009) (Hettiarachchi, 2008). However, as there is natural variation in oil composition within and between sandalwood species, it will be necessary to categorise these variations for different species. The ISO have reviewed the existing Indian and Australian sandalwood oil standards to accommodate the changing chemical profile from wild and plantation sources of sandalwood. Development of an ISO standard for each species will be useful in the future as alternatives to *S. album* are more frequently sold on the market (Kucharska et al., 2021). The chemical profile of *S. austrocaledonicum* is currently analysed for quality and authenticity as this species is also widely used for oil (Baldovini et al., 2011; Hettiarachchi et al., 2022).

Indian sandalwood oil consists mainly of *cis*-α- and *cis*-β-santalols, where other components are present in minor concentrations (Hettiarachchi et al., 2022). However, Australian sandalwood has mixture of different sesquiterpene alcohols as major components; *t,t*-farnesol is a major component in *S. spicatum* essential oil, making it a unique marker compound for the species; also, there is a higher composition of *cis*-lanceol, *t*-α-bisabolol and *cis*-nuciferol (Baldovini et al., 2011; Hettiarachchi et al., 2022). Change of chemical composition has a considerable effect on aroma and pharmacological properties of the essential oil (Baldovini et al., 2011).

Variation of major components were observed for *S. spicatum* in different geographical regions in WA (Ofori, 2020, unpublished PhD thesis; Moniodis et al., 2017; Moretta, 2001), further investigation into the minor components could reveal more variation to understand the geographical effects.

4.5 | Species verification

4.5.1 | Genetic analysis for species ID

Genetic markers have been developed that can differentiate between sandalwood species (Jiao et al., 2019). DNA barcoding has been applied to identify sandalwood to species level and uses a combination of short DNA sequences from the chloroplast genome to differentiate between *Santalum* species (Jiao et al., 2019, 2020). Due to degradation of DNA in wood, careful selection of a robust and short genome sequence is important to allow for successful amplification in wood samples (Jiao et al., 2019). SNP markers are well known to amplify successfully in samples containing degraded DNA, such as timber, due to short amplicon lengths. A set of SNP markers have been developed to distinguish between seven species of *Santalum* (Crawford, 2016, unpublished honours thesis). Species identification of sandalwood is not only important for authenticity and traceability but also as a tool to inform conservation decisions and monitor genetic diversity of remaining wild populations (Bush et al., 2020; Fatima et al., 2019).

5 | NEXT STEPS AND FUTURE OPPORTUNITIES

Efforts to decrease the illegal harvest and trade of sandalwood have been hindered by the lack of connectivity between interested parties and the limitations of what one group is able to accomplish independently. Additional steps, involving the integration of environmental agencies, sandalwood industry and research and development organisations, are required to decrease illegal activity in supply chains. To develop a systematic approach to screening sandalwood, there needs to be a framework that uses existing legislation and includes steps that apply analytical tools for the independent verification of sandalwood authenticity.

5.1 | Unify legislation

Currently, the protection status of sandalwood species and laws and regulations regarding harvest differ across countries, as well as across states within those countries. The lack of uniform regulation is being exploited to move illegal sandalwood through states with less stringent regulation and does not easily allow for enforcement of illegal logging laws across borders. Unifying legislation across states and internationally will better enable enforcement of illegal logging laws and allow for across border cooperation between government agencies and compliance units. This has been identified as a priority for sandalwood management in India (Soundararajan et al., 2015) and should be considered within Australia and internationally.

5.2 | Mapping of trees

In recent times, there has been a worrying lack of recruitment in natural Australian sandalwood populations, with few to no seedlings being observed (Crawford, 2016, unpublished honours thesis; Herford et al., 2015). This could possibly be a result of the dry conditions experienced in recent times or due to animal browsing, such as camels and goats. Mapping trees with satellite imagery could be used to identify and locate individuals or populations of sandalwood (Rao et al., 2007). This could help monitor recruitment, population demographic health and identify sandalwood populations affected by sudden disturbances such as drought, fire or illegal harvest (Nagendra et al., 2013; Rajan, 2019; Rao et al., 2007).

5.3 | Combined isotopic and genetic reference database for sandalwood

To validate and implement isotopic and genetic provenancing for sandalwood, a reference database of isotopic and DNA data for regions of importance is required (Camin et al., 2017; Dormontt et al., 2015; Gasson et al., 2021). In particular, it would be useful to determine isotopic and DNA profiles for sandalwood in protected areas and also for plantation stocks. Increasing the size of these databases will allow for finer scale geographic identification using a combination of isotope and genetic data (Dormontt et al., 2015). Large collections of samples could be compiled by cooperation between collaborating and interested parties. Additionally, these samples could be used to build the chemical profile reference database for sandalwood oils and used for quality control of single origin sandalwood oils and oil products (Subasinghe, 2013). While isotopic and genetic analysis may have limited capacity to identify products that contain a mixture of sandalwood from multiple sources or from a mix of species, they still have the potential to distinguish mixed sandalwood products that have been intentionally mislabelled, from authentic, single origin or single species sandalwood products. Isotope data from reference collections could be used to develop sandalwood isoscapes and model sandalwood isotope spatial variation to predict isotopic signatures of sandalwood for locations with no reference samples (Hollins et al., 2018; Watkinson et al., 2020).

5.4 | Differentiating plantation and wild populations

In the next 5 years, Australian plantation sandalwood established in the early 2000s will become mature enough to harvest (Herford et al., 2015). A definitive test to determine whether sandalwood is from a plantation or from a wild source will be needed as the sandalwood industry transitions away from harvesting from wild populations. Multi-isotopic signatures could potentially distinguish between plantation- and wild-grown trees because they are sensitive to differences in water availability due to irrigation and nutrient differences due to other agricultural practices (Camin et al., 2017). Additionally, screening the plantation genetic stock could provide a means of identifying plantation-grown sandalwood. Quite often the plantation trees are genetically superior due to selective breeding aimed at improving oil yield and preventing disease, and this could be confirmed with genetic testing (Das, 2021; Srimathi et al., 1980).

5.5 | Promote the use of novel chemical analytical tools

Oil profiles unique to species need to be assessed for standardisation. Once international standards have been developed to categorise the chemical profile of oils produced from different sandalwood species, these tools could be used for quality control, to detect adulterated products and for species ID. Chemical analytic tools should be promoted to quantify active compound compositions contained in sandalwood oils. The use of analytical tools for quality control is especially important to detect synthetic chemicals that may not be safe to use in the same way as natural sandalwood oil (Kucharska et al., 2021).

5.6 | International and interdisciplinary collaboration

Global enthusiasm for sandalwood has produced a large and diverse body of scientific research. Over the last two decades, Indian authors have published the most research, followed by Australia and China (George et al., 2020). There is also an increase in Australian and Chinese authors publishing collaborative research with authors from multiple countries (George et al., 2020). Given the breadth of interested parties at the 2020 Sandalwood Workshop (e.g., Department of Environment and Water [SA]; Department of Biodiversity, Conservation and Attractions [WA]; Department of Agriculture and Fisheries [Queensland]; Commonwealth Scientific and Industrial Research Organisation [CSIRO]; Double Helix Tracking Technologies [Singapore] Pte Ltd.; Quintis [Australia] Pty Ltd.; University of Adelaide; University of Queensland; Southern Cross University; and Institute of Wood Science and Technology [Bangalore, India]), there is an opportunity to create a network of labs and expertise which can collaborate to test, develop and standardise analytical techniques for sandalwood identification and characterisation. Establishing a large collection of georeferenced sandalwood samples will enable the development of new genetic markers and chemical identification methods. Scientific testing with existing and newly developed methods could then be applied to identify illegally sourced sandalwood and ensure there is integrity within supply chains. Industry involvement in collaboration with researchers and policy makers would be highly beneficial to limit possible issues to do with intellectual property and align researcher activities with industry priorities. There is currently no governing body for the sandalwood industry, and there is a lack of formal coordination in the industry on national and international scales (Lingard & Perry, 2018). Previous industry research initiatives have failed to achieve longevity, and engagement with research institutions can be cost prohibitive for small- to medium-scale growers.

6 | CONCLUSIONS

The high value of sandalwood products makes these species a target for illegal logging and other fraudulent activity, which has led to a rapid decline in wild populations to a point where they are now predominantly classified as vulnerable or endangered. Laws are in place to protect wild populations, but their effectiveness is limited because of variations in stringency between jurisdictions and challenges to verifying illegal activities. Harmonising these laws and developing tools to aid law enforcement in theft prevention could decrease illegal activity and help conserve remnant populations of sandalwood. Current forensic methods used to characterise or identify the origin of natural products such as chemical and genetic identification can be developed into a systematic approach to forensic sandalwood identification. The sandalwood industry will also be able to use these forensic identification methods to validate their product supply chains and demonstrate compliance with sustainable harvest laws. Further cooperation between government, industry and research organisations can potentially facilitate the development of reference databases for sandalwood identification and establish standardised testing methods to protect wild sandalwood populations and support the sandalwood industry.

ACKNOWLEDGEMENTS

We would like to thank the following organisations for supporting this research: Nature Foundation South Australia (2019-3), Biological

Society of South Australia, Nature Conservation Society of South Australia, Bill-Retalic Prize for Science and Justice, Environment Institute, University of Adelaide, and Australian Government, Department of Education (Research Training Program Scholarship).

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

Andrew J. Lowe conceived the manuscript. Arif Malik facilitated the Sandalwood workshop and summarised group input and discussions. Ellyse Bunney, Andrew J. Lowe and Francesca A. McInerney developed manuscript framework. Ellyse Bunney reviewed the literature, wrote the manuscript (drawing on the workshop presentations), was primary content contributor to the isotope sections, created all the figures and corresponded with all authors. David Wilkins and Malcolm Plant contributed content on sandalwood regulation and illegal harvest. Ellyse Bunney, Francesca A. McInerney and Nina Welti contributed content on isotope analysis for traceability. Andrew J. Lowe, Eleanor Dormontt, Tresa Hamalton and Darren Thomas contributed content on genetic analysis for traceability. Dhanushka S. Hettiarachchi and Ashley Dowell contributed content on sandalwood oil quality control. Ellyse Bunney, Andrew J. Lowe and Francesca A. McInerney edited the manuscript. All authors reviewed and approved the manuscript.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

ORCID

Ellyse Bunney https://orcid.org/0000-0002-7905-2975
Francesca A. McInerney https://orcid.org/0000-0002-2020-6650
Eleanor Dormontt https://orcid.org/0000-0001-9935-9061
Nina Welti https://orcid.org/0000-0001-9966-5915
Tresa Hamalton https://orcid.org/0000-0002-2427-0174
Andrew J. Lowe https://orcid.org/0000-0003-1139-2516

REFERENCES

Baldovini, N., Delasalle, C., & Joulain, D. (2011). Phytochemistry of the heartwood from fragrant *Santalum* species: A review. *Flavour and Fragrance Journal*, *26*(1), 7–26. https://doi.org/10.1002/ffj.2025

Barbour, L., Norris, L., & Burgess, T. (2010). *Heartwood rot identification and impact in sandalwood (Santalum album)*. Rural Industries Research and Development Corporation.

Begum, S. N., & Ravikumar, K. (2021). The sandalwood trade: An overview. In T. Pullaiah, S. C. Das, V. A. Bapat, M. K. Swamy, V. D. Reddy, & K. S. R. Murthy (Eds.). *Sandalwood: Silviculture, conservation and applications*. Springer. https://doi.org/10.1007/978-981-16-0780-6_10

Bhaskar, D., Viswanath, S., & Purushothaman, S. (2010). Sandal (*Santalum album* L.) conservation in southern India: A review of policies and their impacts. *Journal of Tropical Agriculture*, *48*(2), 1–10.

Bommareddy, A., Brozena, S., Steigerwalt, J., Landis, T., Hughes, S., Mabry, E., Knopp, A., VanWert, A. L., & Dwivedi, C. (2019). Medicinal properties of alpha-santalol, a naturally occurring constituent of sandalwood oil: Review. *Natural Product Research*, *33*(4), 527–543. https://doi.org/10.1080/14786419.2017.1399387

Brand, J. E., Norris, L. J., & Dumbrell, I. C. (2012). Estimated heartwood weights and oil concentrations within 16-year-old Indian sandalwood (*Santalum album*) trees planted near Kununurra, Western Australia. *Australian Forestry*, *75*(4), 225–232. https://doi.org/10.1080/00049158.2012.10676406

Bunei, E. K. (2017). The hunt for the precious wood: Illegal trade of sandalwood as an international criminal enterprise in Kenya. *Society and Business Review*, *12*(1), 63–76. https://doi.org/10.1108/SBR-04-2016-0025

Burdock, G. A., & Carabin, I. G. (2008). Safety assessment of sandalwood oil (*Santalum album L.*). *Food and Chemical Toxicology*, *46*(2), 421–432. https://doi.org/10.1016/j.fct.2007.09.092

Bush, D., Thomson, L., Bolatolu, W., Dutt, S., Hamani, S., Likiafu, H., Mateboto, J., Tauraga, J., & Young, E. (2020). Domestication provides the key to conservation of *Santalum yasi*—A threatened Pacific sandalwood. *Australian Forestry*, *83*(4), 186–194. https://doi.org/10.1080/00049158.2020.1855004

Butaud, J.-F. (2015). Reinstatement of the Loyalty Islands sandalwood, *Santalum austrocaledonicum* var. *glabrum* (Santalaceae), in New Caledonia. *PhytoKeys*, *56*, 111–126. https://doi.org/10.3897/phytokeys.56.5924

Camin, F., Boner, M., Bontempo, L., Fauhl-Hassek, C., Kelly, S. D., Riedl, J., & Rossmann, A. (2017). Stable isotope techniques for verifying the declared geographical origin of food in legal cases. *Trends in Food Science & Technology*, *61*, 176–187. https://doi.org/10.1016/j.tifs.2016.12.007

Cerling, T. E., Barnette, J. E., Bowen, G. J., Chesson, L. A., Ehleringer, J. R., Remien, C. H., Shea, P., Tipple, B. J., & West, J. B. (2016). Forensic stable isotope biogeochemistry. *Annual Review of Earth and Planetary Sciences*, *44*(1), 175–206. https://doi.org/10.1146/annurev-earth-060115-012303

Clarke, M. (2006). *Australia's sandalwood industry: An overview and analysis of research needs*. Rural Industries Research and Development Corporation, Australian Government. 06/131.

Das, S. C. (2021). *Silviculture, growth and yield of sandalwood. Sandalwood: Silviculture, conservation and applications* (pp. 111–138). Springer.

Dev, S. A., Muralidharan, E. M., Sujanapal, P., & Balasundaran, M. (2013). Identification of market adulterants in East Indian sandalwood using DNA barcoding. *Annals of Forest Science*, *71*(4), 517–522. https://doi.org/10.1007/s13595-013-0354-0

Doddabasawa, Chittapur, B., & Lokesh, R. (2020). Parasitism ecology of sandalwood (*Santalum album* L.) for commercial production in the semi-arid tropics. *Current Science*, *119*(4), 699–703. https://doi.org/10.18520/cs/v119/i4/699-703

Dormontt, E. E., Boner, M., Braun, B., Breulmann, G., Degen, B., Espinoza, E., Gardner, S., Guillery, P., Hermanson, J. C., & Koch, G. (2015). Forensic timber identification: It's time to integrate disciplines to combat illegal logging. *Biological Conservation*, *191*, 790–798. https://doi.org/10.1016/j.biocon.2015.06.038

Fatima, T., Srivastava, A., Hanur, V. S., Somashekar, P., & Rao, M. S. (2019). Genetic diversity estimates of *Santalum album* L. through microsatellite markers: Implications on conservation. *American Journal of Plant Sciences*, *10*(03), 462–485. https://doi.org/10.4236/ajps.2019.103033

Ferreira, B., de Almeida, L., & Williams, R. (2019). *National sandalwood report for Timor-Leste*. Sandalwood Regional Forum.

Gascoigne, C. E. (2021). 'Seeing the wood for the trees': Revisiting the consistency of Australia's illegal logging act with the law of the World Trade Organization. *Journal of Environmental Law*, *33*, 395–422. https://doi.org/10.1093/jel/eqab005

Gasson, P. E., Lancaster, C. A., Young, R., Redstone, S., Miles-Bunch, I. A., Rees, G., Guillery, R. P., Parker-Forney, M., & Lebow, E. T. (2021). WorldForestID: Addressing the need for standardized wood reference collections to support authentication analysis technologies;

a way forward for checking the origin and identity of traded timber. *Plants, People, Planet*, *3*(2), 130–141. https://doi.org/10.1002/ppp3.10164

George, A. K., Chavan, S., Kumar, S., & Jayasubha, S. (2020). Progress and future research trends on *Santalum album*: A bibliometric and science mapping approach. *Industrial Crops and Products*, *158*, 112972. https://doi.org/10.1016/j.indcrop.2020.112972

Gillieson, D., Page, T., & Silverman, J. (2008). *An inventory of wild sandalwood stocks in Vanuatu*, Report. Australian Government.

Hamza, H. C., Haseel, V., Nair, M. K. R., Gafoor, S. A., & Indulal, S. (2013). Tree theft control system. In *2013 Texas Instruments India Educators' Conference* (pp. 8–11). IEEE. https://doi.org/10.1109/TIIEC.2013.9

Harbaugh, D. T., & Baldwin, B. G. (2007). Phylogeny and biogeography of the sandalwoods (*Santalum*, Santalaceae): Repeated dispersals throughout the Pacific. *American Journal of Botany*, *94*(6), 1028–1040. https://doi.org/10.3732/ajb.94.6.1028

Herford, I., Rayner, M., Kealley, I., & Morrison, K. (2015). *Review of the Sandalwood (Limitation of Removal of Sandalwood) Order 1996*. Governmente of Western Australia, Department of Parks and Wildlife.

Hettiarachchi, D. (2008). Volatile oil content determination in the Australian sandalwood industry: Towards a standardised method. *Sandalwood Research Newsletter*, *23*, 1–4.

Hettiarachchi, D. S., Brown, A., & Boyce, M. C. (2022). *Chemistry and analysis of Santalum album* (pp. 387–405). Springer.

Hollins, S. E., Hughes, C. E., Crawford, J., Cendón, D. I., & Meredith, K. T. (2018). Rainfall isotope variations over the Australian continent—Implications for hydrology and isoscape applications. *Science of the Total Environment*, *645*, 630–645. https://doi.org/10.1016/j.scitotenv.2018.07.082

Howes, M.-J. R., Simmonds, M. S., & Kite, G. C. (2004). Evaluation of the quality of sandalwood essential oils by gas chromatography–mass spectrometry. *Journal of Chromatography a*, *1028*(2), 307–312. https://doi.org/10.1016/j.chroma.2003.11.093

Huish, R. D., Fakáosi, T., Likiafu, H., Mateboto, J., & Huish, K. H. (2015). Distribution, population structure, and management of a rare sandalwood (*Santalum yasi*, Santalaceae) in Fiji and Tonga. *Pacific Conservation Biology*, *21*(1), 27–37. https://doi.org/10.1071/PC14902

Indrioko, S., & Ratnaningrum, Y. W. (2015). Habitat loss caused clonality, genetic diversity reduction and reproductive failure in *Santalum album* (Santalaceae), an endangered endemic species of Indonesia. *Procedia Environmental Sciences*, *28*, 657–664. https://doi.org/10.1016/j.proenv.2015.07.077

International Union for Conservation of Nature. (2022). The IUCN Red List of Threatened Species. Version 2022-1. https://www.iucnredlist.org. Accessed on 30/09/2022.

Jiao, L., He, T., Dormontt, E. E., Zhang, Y., Lowe, A. J., & Yin, Y. (2019). Applicability of chloroplast DNA barcodes for wood identification between *Santalum album* and its adulterants. *Holzforschung*, *73*(2), 209–218. https://doi.org/10.1515/hf-2018-0047

Jiao, L., Lu, Y., He, T., Guo, J., & Yin, Y. (2020). DNA barcoding for wood identification: Global review of the last decade and future perspective. *IAWA Journal*, *41*(4), 620–643. https://doi.org/10.1163/22941932-bja10041

Kagawa, A., & Leavitt, S. W. (2010). Stable carbon isotopes of tree rings as a tool to pinpoint the geographic origin of timber. *Journal of Wood Science*, *56*(3), 175–183. https://doi.org/10.1007/s10086-009-1085-6

Kelly, S., Heaton, K., & Hoogewerff, J. (2005). Tracing the geographical origin of food: The application of multi-element and multi-isotope analysis. *Trends in Food Science & Technology*, *16*(12), 555–567. https://doi.org/10.1016/j.tifs.2005.08.008

Kucharska, M., Frydrych, B., Wesolowski, W., Szymanska, J. A., & Kilanowicz, A. (2021). A comparison of the composition of selected commercial sandalwood oils with the international standard. *Molecules*, *26*(8), 2249. https://doi.org/10.3390/molecules26082249

Kumar, A. A., Joshi, G., & Ram, H. M. (2012). Sandalwood: History, uses, present status and the future. *Current Science*, *103*(12), 1408–1416.

Kumar, S. S., Ravi, V., Prasad, C. R., & Rao, P. R. (2020). Anti-poaching of trees in forest-based on IoT. *IOP Conference Series: Materials Science and Engineering*, *981*(3), 032014. https://doi.org/10.1088/1757-899X/981/3/032014

Lee, D. J., Burridge, A., Page, T., Huth, J., & Thompson, N. (2019). Domestication of northern sandalwood (*Santalum lanceolatum*, Santalaceae) for Indigenous forestry on the Cape York Peninsula. *Australian Forestry*, *82*(sup1), 14–22. https://doi.org/10.1080/00049158.2018.1543567

Lee, S., Park, B. S., Lee, D., Chung, H., & Lee, K.-S. (2015). Spatial variability in hydrogen and oxygen isotopic composition of Korean Red Pine and its implication for tracing wood origin. *Environmental Earth Sciences*, *73*(12), 8045–8052. https://doi.org/10.1007/s12665-014-3960-8

Lingard, K., & Perry, M. (2018). An assessment of the regulatory framework of the Western Australian sandalwood industry. *Australian Forestry*, *81*(2), 89–101. https://doi.org/10.1080/00049158.2017.1420455

McKinnell, F. (1990). Status of management and silviculture research on sandalwood in Western Australia and Indonesia. In L. Hamilton & C. E. Conrad (Eds.). Technical coordinators*Proceedings of the Symposium on Sandalwood in the Pacific; April 9–11, 1990; Honolulu, Hawaii*. Gen. Tech. Rep. PSW-GTR-122 (pp. 19–25). Pacific Southwest Research Station, Forest Service, US Department of Agriculture.

McKinnell, F., & Levinson, J. (2008). *WA sandalwood industry development plan 2008-2020*. Forest Products Commission.

McLellan, R., Dixon, K., & Watson, D. (2021). Prolific or precarious: A review of the status of Australian sandalwood (*Santalum spicatum* [R. Br.] A. DC., Santalaceae). *The Rangeland Journal*, *43*(4), 211–222. https://doi.org/10.1071/RJ21017

McWilliam, A. (2005). Haumeni, not many: Renewed plunder and mismanagement in the Timorese sandalwood industry. *Modern Asian Studies*, *39*(2), 285–320. https://doi.org/10.1017/S0026749X04001581

Medini, S., Janin, M., Verdoux, P., & Techer, I. (2015). Methodological development for^{87}Sr/^{86}Sr measurement in olive oil and preliminary discussion of its use for geographical traceability of PDO Nîmes (France). *Food Chemistry*, *171*, 78–83. https://doi.org/10.1016/j.foodchem.2014.08.121

Merlin, M., & VanRavenswaay, D. (1990). The history of human impact on the genus *Santalum* in Hawai'i. In L. Hamilton & C. E. Conrad (Eds.). Technical coordinators*Proceedings of the Symposium on Sandalwood in the Pacific; April 9-11, 1990; Honolulu, Hawaii. Gen. Tech. Rep. PSW-GTR-122* (pp. 46–60). Pacific Southwest Research Station, Forest Service, US Department of Agriculture.

Mondal, S., Sundararaj, R., & Yashavantha Rao, H. (2020). A critical appraisal on the recurrence of sandalwood spike disease and its management practices. *Forest Pathology*, *50*(6), e12648. https://doi.org/10.1111/efp.12648

Moniodis, J., Jones, C. G., Renton, M., Plummer, J. A., Barbour, E. L., Ghisalberti, E. L., & Bohlmann, J. (2017). Sesquiterpene variation in West Australian sandalwood (*Santalum spicatum*). *Molecules*, *22*(6), 940. https://doi.org/10.3390/molecules22060940

Moretta, P. (2001). *Extraction and variation of the essential oil from Western Australian sandalwood (Santalum spicatum)*. (Doctoral thesis). University of Western Australia.

Mugula, B. B., Kiboi, S. K., Kanya, J. I., Egeru, A., Okullo, P., Curto, M., & Meimberg, H. (2021). Knowledge gaps in taxonomy, ecology, population distribution drivers and genetic diversity of African sandalwood (*Osyris lanceolata* Hochst. & Steud.): A scoping review for conservation. *Plants*, *10*(9), 1780. https://doi.org/10.3390/plants10091780

Nagendra, H., Lucas, R., Honrado, J. P., Jongman, R. H., Tarantino, C., Adamo, M., & Mairota, P. (2013). Remote sensing for conservation monitoring: Assessing protected areas, habitat extent, habitat condition, species diversity, and threats. *Ecological Indicators*, *33*, 45–59. https://doi.org/10.1016/j.ecolind.2012.09.014

Ng, C. H., Ng, K. K. S., Lee, S. L., Tnah, L. H., Lee, C. T., & Zakaria, N.-F. (2020). A geographical traceability system for Merbau (*Intsia palembanica* Miq.), an important timber species from peninsular Malaysia. *Forensic Science International: Genetics*, *44*, 102188. https://doi.org/10.1016/j.fsigen.2019.102188

Ota, L., Page, T., Viranamangga, R., Kalsakau, T., & Herbohn, J. (2022). How financially viable is smallholder forestry? A case study with a high-value tropical forestry species. *Small-Scale Forestry*, *21*(3), 505–525. https://doi.org/10.1007/s11842-022-09511-1

Page, T., Doran, J., Tungon, J., & Tabi, M. (2021). Restoration of Vanuatu sandalwood (*Santalum austrocaledonicum*) through participatory domestication. *Australian Forestry*, *83*(4), 216–226. https://doi.org/10.1080/00049158.2020.1855382

Rai, S. N. (1990). Status and cultivation of sandalwood in India. In L. Hamilton & C. E. Conrad (Eds.). Technical coordinators *Proceedings of the Symposium on Sandalwood in the Pacific; April 9-11, 1990; Honolulu, Hawaii. Gen. Tech. Rep. PSW-GTR-122* (pp. 66–71). Pacific Southwest Research Station, Forest Service, US Department of Agriculture. https://doi.org/10.1080/00049158.2020.1855382

Rajan, N. M. (2019). Vulnerability analysis of Indian sandalwood tree using GIS. *Arabian Journal of Geosciences*, *12*(14), 1, 416–17. https://doi.org/10.1007/s12517-019-4520-z

Rao, M. N., Ganeshaiah, K., & Shaanker, R. U. (2007). Assessing threats and mapping sandal resources to identify genetic 'hot-spot' for in-situ conservation in peninsular India. *Conservation Genetics*, *8*(4), 925–935. https://doi.org/10.1007/s10592-006-9247-1

Rashkow, E. D. (2014). Perfumed the axe that laid it low: The endangerment of sandalwood in southern India. *The Indian Economic & Social History Review*, *51*(1), 41–70. https://doi.org/10.1177/0019464613515553

Rich, S., Manning, S. W., Degryse, P., Vanhaecke, F., & Van Lerberghe, K. (2016). Provenancing East Mediterranean cedar wood with the $^{87}Sr/^{86}Sr$ strontium isotope ratio. *Archaeological and Anthropological Sciences*, *8*(3), 467–476. https://doi.org/10.1007/s12520-015-0242-7

Rohadi, D., Maryani, R., Widyana, M., & Azhar, I. (2004). A case study of the production-to-consumption system of sandalwood (*Santalum album*) in South Central Timor, Indonesia. In *Forest products, livelihoods and conservation: Case studies of non-timber forest product systems* (Vol. 1, p. 187). CIFOR.

Rome, G., Turia, R., Oa, L., Page, T., Applegate, G., & Saliau, C. (2021). Sandalwood trade and development in Papua New Guinea. *Australian Forestry*, *83*(4), 208–215. https://doi.org/10.1080/00049158.2020.1855005

Sandeep, C., & Manohara, T. (2019). Sandalwood in India: Historical and cultural significance of *Santalum album* L. as a basis for its conservation. *NeBIO*, *10*(4), 235–241.

Sharp, Z. (2017). *Principles of stable isotope geochemistry*. Upper Saddle River, NJ.

Soundararajan, V., Ravi Kumar, G., & Murugesan, K. (2015). Trade scenario of sandalwood and its valued oil. *International Journal of Novel Research in Marketing Management and Economics*, *2*(3), 52–59.

Srimathi, R., Kulkarni, H., & Venkatesan, K. (1980). Selection of sandal (*Santalum album* L.) for spike resistance and other qualities. *Indian Journal of Forestry*, *3*(4), 303–305.

Subasinghe, S. (2013). Sandalwood research: A global perspective. *Journal of Tropical Forestry and Environment*, *3*(1), 1–8. https://doi.org/10.31357/jtfe.v3i1.1117

Subasinghe, S., Samarasekara, S., Millaniyage, K., & Hettiarachchi, D. (2017). Heartwood assessment of natural *Santalum album* populations for agroforestry development in Sri Lanka. *Agroforestry Systems*, *91*(6), 1157–1164. https://doi.org/10.1007/s10457-016-0001-5

Teixeira da Silva, J. A., Kher, M. M., Soner, D., Page, T., Zhang, X., Nataraj, M., & Ma, G. (2016). Sandalwood: Basic biology, tissue culture, and genetic transformation. *Planta*, *243*(4), 847–887. https://doi.org/10.1007/s00425-015-2452-8

Thomson, L. (2020). Looking ahead–global sandalwood production and markets in 2040, and implications for Pacific Island producers. *Australian Forestry*, *83*(4), 245–254. https://doi.org/10.1080/00049158.2020.1841441

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

Tonts, M., & Selwood, J. (2003). Niche markets, regional diversification and the reinvention of Western Australia's sandalwood industry. *Tijdschrift voor Economische en Sociale Geografie*, *94*(5), 564–575. https://doi.org/10.1046/j.1467-9663.2003.00283.x

Venkatesha Gowda, V., Patil, K., & Ashwath, D. (2004). Manufacturing of sandalwood oil, market potential demand and use. *Journal of Essential Oil-Bearing Plants*, *7*(3), 293–297. https://doi.org/10.1080/0972-060X.2004.10643410

Viswanath, S., Dhanya, B., Purushothaman, S., & Rathore, T. (2020). Financial viability of sandal (*Santalum album*) based agroforestry practices in Southern India. *Indian Journal of Agroforestry*, *12*(2), 14–22.

Watkinson, C. J., Gasson, P., Rees, G. O., & Boner, M. (2020). The development and use of isoscapes to determine the geographical origin of *Quercus* spp. in the United States. *Forests*, *11*(8), 862. https://doi.org/10.3390/f11080862

Yuskianti, V., & Warrier, R. R. (2022). *Status of sandalwood in Indonesia and neighbouring countries* (pp. 127–142). Springer.

How to cite this article: Bunney, E., McInerney, F. A., Dormontt, E., Malik, A., Welti, N., Wilkins, D., Plant, M., Hettiarachchi, D. S., Thomas, D., Dowell, A., Hamalton, T., & Lowe, A. J. (2023). Safeguarding sandalwood: A review of current and emerging tools to support sustainable and legal forestry. *Plants, People, Planet*, *5*(2), 190–202. https://doi.org/10.1002/ppp3.10349