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Review

Prolific or precarious: a review of the status of Australian sandalwood (*Santalum spicatum* [R.Br.] A.DC., Santalaceae)

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Abstract. Across its entire range in Australia's western and southern rangelands, Australian sandalwood (*Santalum spicatum* [R.Br.] A.DC.) is on a path towards 'extinction in the wild'—the International Union for the Conservation of Nature's penultimate category of conservation risk. Sandalwood populations have substantially diminished or become locally extinct, predominantly a consequence of land clearing for agriculture, introduced grazers, disruption of key ecological processes (e.g. seed dispersal, fire regimes) and 175 years of intensive commercial exploitation for its fragrant, high value timber. The status of the world's last wild-harvested species of sandalwood is significant to both conservation and rangeland management, and the implementation of a science-based sustainable yield approach to management of this species is vital. By highlighting the scale and precipitous rate of decline and identifying key drivers affecting mortality and recruitment, this review outlines the conservation and restoration needs of the species *in situ* to conserve remaining wild populations, and the need to transition to science-based resource management actions such as farm-based plantation production.

Keywords: parasitic plants, hemiparasitic, forestry, threatened species, forest products.

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Introduction

Australian sandalwood (*Santalum spicatum* [R.Br.] A.DC) (hereinafter referred to as sandalwood) is one of the most valuable timbers in the world (Fox 2000; Underwood 2005). This has resulted in 175 years of extensive and intensive commercial harvesting, with permanent detrimental impacts on natural populations (Loneragan 1990; Kealley 1991; Fox 2000; Anderson 2005). The harvest of live and dead trees from wild populations has primarily been for export throughout Asia where the wood and oil are used in religious and traditional ceremonies. The fragrant sandalwood wood and oil are revered within Buddhism, Hinduism and Islam, traditionally burnt during prayers and meditation in the form of incense or joss-sticks (agarbatti), and for cultural uses such as smoking ceremonies, embalming and funeral pyres (Applegate and McKinnell 1993). The wood is also used for carving, and the oil (primarily extracted from the wood) in the production of cosmetic products, (e.g. perfume, skin lotion, powder, soap and hair oil), for repelling insects, waterproofing, and medicinal, culinary and pharmaceutical products (Fox 2001; Clarke 2006).

The population of sandalwood, like all of the world's most fragrant *Santalum* species, has significantly declined across its natural range over the past two centuries (Harbaugh and Baldwin 2007). It is listed as a 'Vulnerable' threatened species in South Australia (SA) (Government of South Australia 1972; Kellermann 2011), largely as a result of the rapid decline of populations following intensive sandalwood exploitation during a period of state-sanctioned harvesting between 1925 and 1941 (Pobke 2007; Gillam and Urban 2010; Jeffery 2010). Sandalwood harvesting is now prohibited in SA, with its threatened species status based on being endemic to Australia, a high degree of threat, and low potential for recovery (Pobke 2007). Although the majority of sandalwood's distribution is in Western Australia (WA), it is not currently listed as a threatened species under the International Union for the Conservation of Nature (IUCN 2012) Red List criteria under WA or national legislation, and is thus outside protective conservation legislation in much of what remains of its geographic range. Sandalwood in WA is characterised by the same vulnerable threatened species criteria as has been attributed in SA, i.e. is lost from much of its range, and there is very little evidence of sustained recruitment.

The objectives of this review are to: (1) synthesise information on this species, drawing on government agency documents and reports, peer-reviewed literature, unpublished theses and

transcripts of parliamentary inquiries to more accurately define the current and historic distribution and abundance of wild sandalwood populations; (2) evaluate the conservation status of the species across its range and identify threats contributing to its decline; and (3) prioritise on-ground actions to arrest further decline and boost recruitment. Having detailed the cumulative impact of interacting threats, we identify the necessary interventions that need to be implemented to ensure the species is conserved to avoid extinction of the last remaining wild populations.

Sandalwood ecology

Sandalwood is an obligate root-parasitic small tree, sparsely distributed across southern and western Australia (Herbert and Gardner 1921; Herbert 1925; Gardner 1928; Hewson and George 1984) (Fig. 1). First described in Western science by British naturalist Robert Brown in 1810 as *Fusanus spicatus* R.BR., it was subsequently reclassified as *Santalum spicatum* (R.Br.) A.DC. by Alphonse De Candolle in 1857 (Sprague and Summerhayes 1927). Usually growing 3–4 m in height but capable of reaching more than 6 m (Herbert and Gardner 1921), the tree is characterised by an open structure with an irregular spreading canopy and green-grey, relatively fleshy leaves.

Sandalwood is considered the slowest growing *Santalum* species, taking up to 90–115 years to reach the ecologically mature size sought after commercially (with an over-bark trunk diameter of >127 mm, at 150 mm aboveground level) in the arid and semi-arid rangelands (Loneragan 1990). Based on annual stem diameter growth rates of approximately 1 mm per year (FPC 2016), or as little as 0.5 mm per year (Brand *et al.* 2014), some trees have been estimated to be more than 250–300 years old. Sandalwood is hemiparasitic and, while attaching its roots via haustoria to a wide range of host species (Fox 1997; Woodall and Robinson 2002), exhibits a recognised preference for nitrogen-fixing *Acacia* species (Herbert 1925; Loneragan 1990). Although capable of coppicing and regenerating vegetatively in some locations, sandalwood most commonly regenerates from seed (Herbert 1925; Fox 1997), particularly when seed is buried just below the soil surface close to a suitable host plant (Brand and Jones 2001).

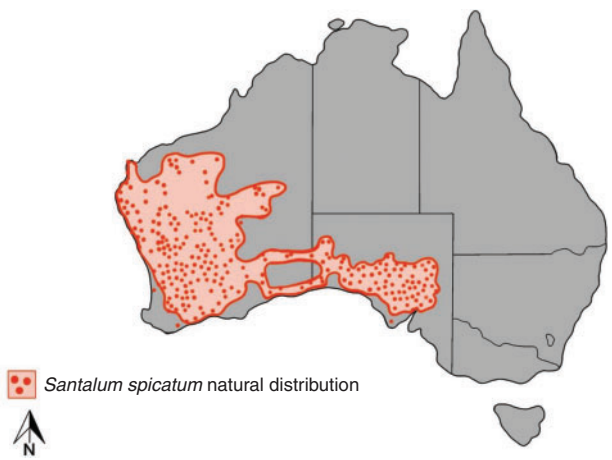

Fig. 1. Natural distribution of Australian sandalwood (*Santalum spicatum*) across southern and western Australia. Distribution based on records of the Western Australian State Herbarium (Spooner 1999; Atlas of Living Australia 2020; and Applegate and McKinnell 1993).

Sandalwood occurs in isolated populations, partly determined by the plant's particular abiotic (e.g. climate and soil) and biotic (e.g. host availability) requirements, and often with an aggregated distribution. Establishment of new cohorts may be constrained by the species' flowering and seed production character traits, which include variable flowering (in quantity and duration), sporadic fruit-set and maturation, low fruit-to-flower ratios, variability in viable seed production and more recently, constraints to seed dispersal (Barrett 1987; Loneragan 1990; Fox 1997). Limited seed dispersal is attributed to the large size of the nuts (1.5–2.5 cm in diameter), which when ripe, fall directly under parent trees where germination and survival rates are low (Brand 2000). Sandalwood flowers at about 3–4 years of age, and begins fruiting between 5 and 10 years old, depending largely upon favourable rainfall conditions (Loneragan 1990; Brand 1999). Seed viability decreases rapidly after seed set, lasting little more than 2–3 years in the wild under optimal conditions (Kealley 1987).

Sandalwood exhibits typical traits of K-selected tree species, being slow-growing (Loneragan 1990), long-lived, strongly competitive, with a low reproductive rate, and with seeds containing sufficient stored energy to support seedlings in their initial growth prior to growing haustoria and establishing connections with host roots. These traits have enabled the species to persist for millennia in environments with low and highly variable rainfall but, together with other traits such as sporadic fruit set (Fox 1997), limited seed dispersal, and the inability to accumulate a soil seed bank due to the rapid loss of seed viability (Kealley 1987; Loneragan 1990) have contributed to its increasing vulnerability.

Economic value

Although valuable for ecological and ethnobotanical reasons, sandalwood is best known for its economic value, having frequently been referred to as 'wooden gold' (Talbot 1983). Sandalwood was classified as a 'forest product' in 1844, almost immediately after its commercial value was realised. Wild plants were declared the property of the WA Government in 1881 wherever it occurred on Crown lands, despite its cultural importance to Aboriginal communities, and harvesting was placed under the control of the WA Forests Department in 1923 (Robertson 1958). In the same year, it was declared one of WA's 'Principal Forest Trees' by the WA Conservator of Forests Charles Lane-Poole, with the 'forest product' status differentiating it from the majority of the plants of WA (Lane-Poole 1922; Robertson 1958; Statham 1990). Sandalwood has been almost continuously commercially harvested since 1845, as highlighted during the WA Government's Parliamentary Inquiry into the Sandalwood Industry (2012–2014) conducted by the Standing Committee on Environment and Public Affairs (SCEPA), during which it was referred to as essentially 'an agricultural resource' (SCEPA 2014*a*). Being designated a 'Forest Product', sandalwood is managed and harvested as a commercial product under the provisions of the Western Australian *Forest Products Act 2000* (as well as the *Biodiversity Conservation Act 2016*, which legislates 'the conservation and protection of biodiversity' as well as its 'ecologically sustainable use'). Annual harvesting limits are

set by the WA Government under the *Sandalwood* (*Limitation of Removal of Sandalwood*) *Order* (*2015*), which currently allows for 2500 tonnes of sandalwood to be harvested annually, comprising 1250 tonnes of greenwood (live sandalwood trees) and 1250 tonnes of deadwood (dead trees) (DPAW 2015).

Australian sandalwood is one of the world's two most commercially valued and traded sandalwood species, the other being Indian sandalwood (*Santalum album*) now only sourced from managed, commercial plantations (Lingard and Perry 2018), and has been exported in a variety of forms, including as whole trees, logs, roots, butts, pieces, chips, powder, shavings and oil (Richmond 1983). Wild harvest of Australian sandalwood currently supplies an estimated 40–60 per cent of the global market for sandalwood (Anderson 2005; Clarke 2006; Lingard and Perry 2018).

The high level of demand and high prices obtained for sandalwood by the WA Forest Products Commission (FPC) (AU$17000/tonne; FPC 2019), provide substantial profit to the FPC (approximately AU$2.3 million in 2019–2020). This contrasts with the loss of approximately AU$1.2 million in 2019–2020 accruing from the exploitation of all other WA native forest species combined (FPC 2020).

Threatening processes

Many of the species' characteristic K-selected life-history traits render sandalwood particularly sensitive to the impacts of multiple threatening processes, which simultaneously and cumulatively interact to considerably affect the plant at several life stages, resulting in changes to the age/size structure of the population and reductions in population size. These threatening processes include over-exploitation, land clearing, grazing pressure, loss of natural dispersers, drought, fire and climate change (Loneragan 1990; Kealley 1991; DEC 2012; DPAW 2015).

Wild sandalwood populations have significantly declined, with many local populations declared extinct (Loneragan 1990; Kealley 1991; Casson 1992; Anderson 2005). Sandalwood has been extirpated throughout approximately 13 million ha of its original extent in WA, largely due to targeted harvesting and land clearing (Loneragan 1990) (Fig. 2).

Many studies and reports, principally from WA Government agencies and scientists, have acknowledged the critical status of the sandalwood population, its local and regional extirpation, the impacts of multiple key threatening processes, and its failure to regenerate at rates capable of maintaining local and regional populations, resulting in ongoing decline of the species (Loneragan 1990; Kealley 1991; Brand 2000; Anderson 2005; Brand *et al.* 2014; FPC 2016, 2017).

The naturally low recruitment of sandalwood was first recognised as a potential issue for the sustainability of a harvesting industry by the WA Department of Wood and Forests in 1896 (Statham 1990) and has been re-emphasised as a matter of concern many times since, particularly in the last 80 years (Richmond 1983; Loneragan 1990; Kealley 1991; Brand 2000, SCEPA 2012*d*, 2014*b*; Brand *et al.* 2014; DPAW 2015; FPC 2016).

Changing climatic conditions

Although capable of surviving in some of Australia's most arid environments, sandalwood recruitment and growth is strongly affected by drought (Kealley 1987; Loneragan 1990; SCEPA 2014*a*) and is increasingly being challenged by changing climate, which contribute to reduced growth and higher mortality, particularly declining rainfall and increasing rainfall variability, and increasing evapotranspiration rates. At least 264 mm of annual rainfall, including a season break of more than 12.5 mm in May/June, is required for successful seed germination (Sawyer 2013). Successful regeneration is dependent on three successive years of above average rainfall (Underwood 1954; Loneragan 1990; Kealley 1991) to allow for successful flowering, seed production, germination and seedling establishment on viable hosts (sandalwood recruits require 6–12 months for their root systems to locate and attach haustoria to the roots of host plants (Loneragan 1990; Kealley 1991)). Increasingly, climatic conditions required for successful regeneration are not being met (Loneragan 1990). Australia's western and southern rangelands are experiencing a significantly changing climate, including declining winter rainfall, increasing rainfall variability and the increasing frequency, duration and severity of drought (Anderson 2005; SCEPA 2012*d*; CSIRO 2014, CSIRO and Bureau of Meteorology 2015; DPAW 2015). Past climate shifts were most likely not as significant as present climate change on the survivability of the species due to the extraordinary longevity of parent plants (evidenced by trees being regularly aged at 200–300 years). However, fragmentation, extensive land alteration, grazing by exotic herbivores and over-exploitation of age cohorts of sandalwood that have resulted in lack of parent plants and recruitment mean that climate resilience of the species has been substantially compromised to provide future regenerative capacity. Recent silvicultural restoration attempts by the FPC in sandalwood supply areas in the southern rangelands have also experienced widespread germination failures due to insufficient rainfall for seedling establishment (FPC 2019, 2020).

Grazing (total grazing pressure)

Sandalwood is adversely affected by grazing pressure, particularly from feral herbivores and livestock, (goats, sheep, cattle, camels and rabbits), and native species such as kangaroos (Herbert 1925; Loneragan 1990; Kealley 1991; DEC 2012; DPAW 2015). Sandalwood foliage is highly palatable (Kealley 1987, 1991; DEC 2012), and seedlings and young plants are often preferentially grazed (Mitchell and Wilcox 1988). Feral goats are particularly selective and destructive (FPC 2016), and sandalwood regeneration is virtually non-existent where goats are abundant (Kealley 1991; SCEPA 2012*d*).

Loss of seed dispersers

Limited seed dispersal also constrains regeneration (FPC 2016). Without facilitated dispersal, the heavy, single-seeded sandalwood fruit remain under the parent tree where if seeds germinate, seedlings are out-competed by the parent tree (Casson 1992; Brand 2000; DPAW 2015). Limited seed dispersal has been attributed to the local extinction of seed distributing and caching marsupials such as Boodies/Burrowing Bettongs (*Bettongia lesueur graii*) and Woylies/Brush-tailed Bettongs (*Bettongia penicillata ogilbyi*) across sandalwood's natural range (Murphy *et al.* 2005; Chapman 2015). These animals

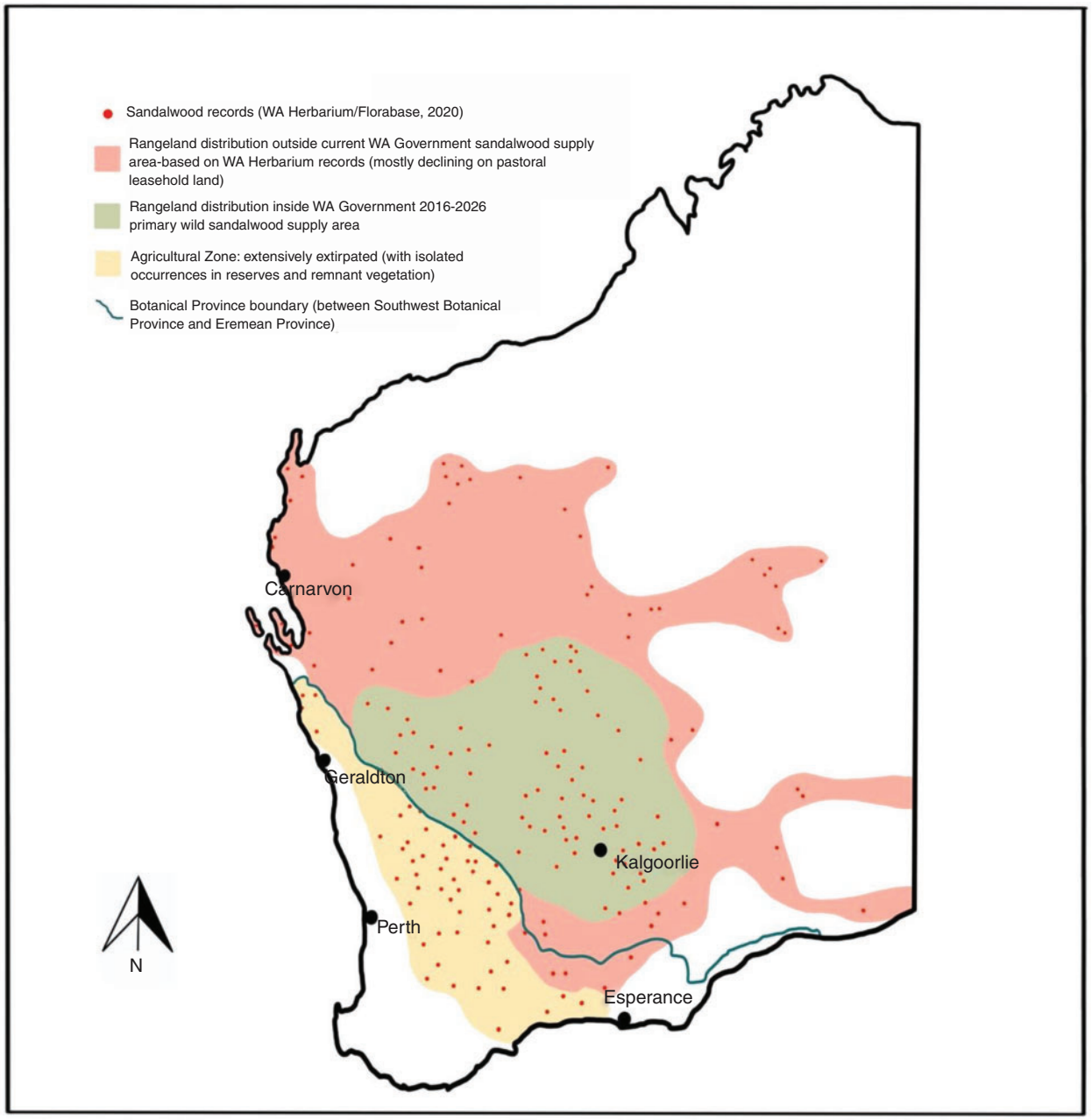

Fig. 2. Distribution of sandalwood in WA. Significantly, due to the key threat imposed by introduced and native herbivores, almost all of the rangelands including the Sandalwood Supply Area zones, are considered as 'Land used for Pastoralism' (Hacker *et al.* 2019). Distribution based on records of the Western Australian Herbarium (Spooner 1999; Richmond 1983; Talbot 1983; Loneragan 1990; Kealley 1991; Casson 1992; DPAW 2016; Atlas of Living Australia 2020).

collect, disperse and cache seeds away from the parent tree, and their foraging behaviour disturbs the soil under potential host trees, facilitating sandalwood establishment on their preferred hosts (Murphy *et al.* 2005). Many of these natural seed dispersing species were extirpated across much of WA by the early 1900s due to the combined impacts of habitat clearing (for agriculture), feral predators (especially cats and foxes), introduced grazing animals, hunting, disease, hydrological change and changed fire regimes (Burbidge and McKenzie 1989; Abbott 2006). Boodies have been recorded collecting and caching sandalwood seed as recently as the 1940s (Leake 1962); however, Boodies and Woylies were largely extirpated by the 1950s (Burbidge *et al.* 1988). Sandalwood seed continues to be dispersed by emus (*Dromaius novaehollandiae*), which drop the kernels away from the parent tree (George 1984; Loneragan 1990; Fox 1997). However, ingested seeds are often destroyed during digestion and if intact, are mostly deposited on the surface of the soil where they desiccate and

fail to germinate (Cunningham 1998; R. C. McLellan and D. M. Watson, unpubl. data).

Fire

Fire has a negative impact on sandalwood regeneration (Herbert 1925; Kealley 1991; Loneragan 1990; SCEPA 2012*d*). Sandalwood is considered fire sensitive partly due to its inability to resprout under most environmental conditions (Brand 1999). Fire will likely have an increasingly detrimental impact on sandalwood populations, with climate change models projected for Australia's southern semiarid and arid rangelands indicating the likelihood of more frequent fire-weather and more extreme fire behaviour (Watterson *et al.* 2015).

Harvesting

Sandalwood has been over-harvested over a long and sustained period (Loneragan 1990; Kealley 1991; Anderson 2005; DEC 2012; SCEPA 2014*a*, 2014*b*; DPAW 2015). Sandalwood was first harvested and exported from WA in 1844 as a trial shipment to Bombay, India, to 'test the market' (Statham 1990). The positive economic result encouraged further commercial shipments. By late 1845, 200 tonnes had been exported to Singapore, Mauritius and Ceylon (Statham 1990), and within months, sandalwood was the primary export income, comprising a quarter of the annual GDP for the WA colony (Richmond 1983). Harvest and exports subsequently fluctuated, with annual exports reaching a maximum of 14355 tonnes in 1920 (Fig. 3). Approximately 2000 tonnes of sandalwood (of the 2500 tonnes p.a. quota) are currently legally harvested annually (FPC 2020).

Sandalwood was almost completely extirpated from WA's south-western agricultural zone as a consequence of commercial harvesting (Talbot 1983; Casson 1992; Fox and Reeve 1993) (Fig. 3). As a result, having reached an initial peak in 1882, sandalwood exports rapidly declined over subsequent years due to 'the increasing difficulty cutters were having in locating new stands of sandalwood, it having been almost cut out in accessible areas' (Talbot 1982). Throughout much of this early period of harvesting, there was virtually no management or regulatory control (Kealley 1991), and indeed harvesting was carried out in the agricultural zone and the arid and semiarid rangelands with little knowledge and understanding of the ecology, abundance and distribution of the species until the 1980s (DEC 2012).

Reported export totals (Fig. 3) do not include quantities of sandalwood uprooted and burned during land clearing for agriculture, harvested on private land for some periods or illegally harvested.

Since its first commercial exploitation (in 1845), numerous documents, originating particularly from WA Government's forestry and conservation agencies but also from industry representatives, members of parliament, independent scientists and civil society, have expressed serious concerns about the impact of overexploitation, the lack of sandalwood regeneration and the potential 'future exhaustion of supplies' (Robertson 1958) (Table 1).

Some of the warnings listed in Table 1 subsequently resulted in policy and management changes, but many did not (Robertson 1958). For example, since the 1950s, improvements have been made in data gathering, research and management (Kealley 1991), and in silvicultural research and innovation (FPC 2004, 2016; Sawyer 2013). However, harvesting (with some populations re-harvested multiple times) has continued at unsustainable rates due to the species' failure to regenerate (Anderson 2005). It is highly likely that harvesting contributes to the lack of recruitment (Anderson 2005), as reduction in the total tree number, particularly prolifically seed-bearing mature trees, reduces seed 'rain'.

The WA Government introduced its first *Management Plan for Sandalwood* in 1991, which among other management

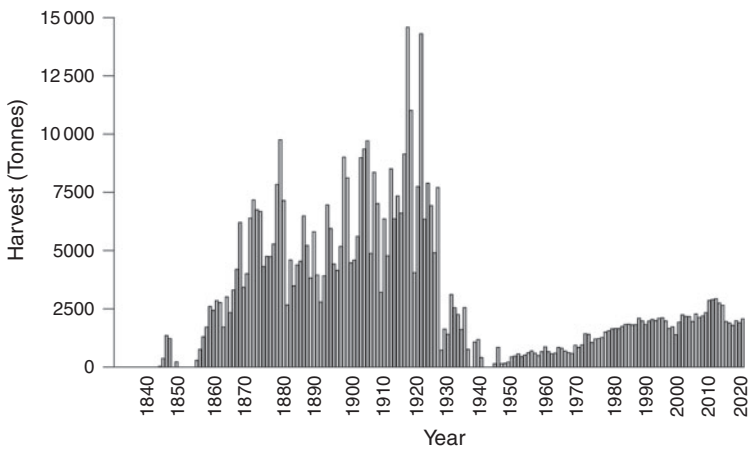

Fig. 3. Sandalwood harvested (by year) in WA, 1844–2020. Peaking in 1920, when more than 14000 tonnes were exported, sandalwood exports have fluctuated considerable. Gradually increasing again since the 1950s, approximately 2000 tonnes are currently exported per annum. Sources: Statham 1990; reports and records of the Western Australian Forests Department, the Australian Sandalwood Company, the Department of Conservation and Land Management (CALM), and the Forest Products Commission (FPC).

Table 1. Government, industry and community warnings about the overexploitation, regional extirpation, and potential extinction in the wild of sandalwood, 1895–2020

The WA Government, its forestry and conservation agencies, and other key sectors have repeatedly raised concerns about the impact of key threats and the associated decline in the sandalwood population

Year	Issues/action	Source
1844	Governor John Hutt issued orders for settlers to not burn sandalwood, considers it a forest product, and ordered landowners to stockpile timber for future sale/export.	Forests Department, Talbot 1983
1876	First actions by the WA Government to prevent overexploitation of sandalwood, established sandalwood reserves, and prohibited the cutting of undersized trees.	Forests Department, Talbot 1982, 1983
1893	WA Government considered, then rejected new legislation and regulations aimed at conserving sandalwood.	WA Forests Department report, Robertson 1958
1895	50 years after the first exports. First sandalwood research conducted by the newly formed Department of Wood and Forests. Concerns raised about the excessive rates of exploitation and the future survival of the species.	Statham 1990
1900	WA Woods and Forests Department encouraged private landholders to establish sandalwood plantations.	Underwood 1954
1919	Concerned about the sustainability of the industry, Forests Department Conservator of Forests Charles Lane-Poole dispatched forester Geoffrey Drake-Brockman to study and report on the industry.	Forests Department, Talbot 1983
1920	WA Conservator of Forests Charles Lane-Poole reported that sandalwood had been largely extirpated from the Western Australian agricultural zone.	Forests Department, Lane-Poole 1920
1920s	Forests Department research revealed sandalwood's slow growth rate, low germination rates, low survival (of seedlings), and susceptibility to grazing.	WA Forests Department report, Robertson 1958; Conservation and Land Management (CALM), Kealley 1991
1921	WA botanist reported on the decimation of sandalwood populations in the agricultural zone.	WA Government, Herbert and Gardner 1921
1921	Forests Department official Geoffrey Drake-Brockman recommended that the WA government should better control the industry, and that the Forests Department should establish sandalwood plantations.	Forests Department, Talbot 1983
1923	New regulations implemented that placed control of the sandalwood industry almost entirely under the WA Government.	Statham-Drew 2007
1929	The *Sandalwood Control Act* was passed by the WA Government, which closed a number of loopholes in the earlier legislation; restricted private property proportion of exports to 10 per cent of total.	Statham-Drew 2007
1950s	Harvesting restrictions introduced, aimed at better conservation of the species.	CALM, Kealley 1991
1958	Forests Department warned of future exhaustion of supplies of sandalwood, that it was facing extinction, and had little hope of conservation.	WA Forests Department report, Robertson 1958
1980-84	Concerned about the uncertainty regarding the extent of the resource, an inventory of sandalwood stocks was conducted by WA Forests Department and Australian Sandalwood Company.	CALM, Kealley 1991
1987	Poor recruitment/regeneration highlighted in a WA Government agency paper on the WA Sandalwood Industry.	CALM, Kealley 1987
1987	WA Government agency expressed a need for sandalwood plantations to come onstream as soon as possible, and for more to be established.	CALM, Kealley 1987
1990	Reiteration that sandalwood is exhausted in the agricultural zone due to overexploitation and clearing for agriculture.	CALM, Loneragan 1990
1991	Sandalwood Management Plan introduced—recommended that the harvesting quota be reduced to 2000 tonnes per annum – 1000 greenwood; 1000 deadwood. (This recommendation was not adopted).	CALM, Kealley 1991
1993	*Sandalwood Regulations 1993* introduced, outlined more stringent licensing requirements and restricted the harvest size of sandalwood trees.	Government of Western Australia 1993
1995	A CALM-supervised research report stated that sandalwood supplies will eventually run-out in pastoral areas, and that future supply will need to come from plantations in the agricultural zone.	Johnston 1995
1996	*Sandalwood* (*Limitation of Removal of Sandalwood*) *Order 1996* introduced, established an annual quota/limit of 3000 tonnes per annum (1500 tonnes 'green').	Government of Western Australia 1996
1999	WA Government forester and sandalwood authority Jon Brand reported that there has been 'very little (sandalwood) recruitment for 50 years' at study sites in the WA rangelands (mainly due to grazing, drought and low annual rainfall), and that 'the lack of natural recruitment of *S. spicatum* is a concern for the conservation of this species.'	CALM, Brand 2000
2000	Replanting of sandalwood seeds during harvest operations introduced.	Government of Western Australia, SCEPA 2012*b*

(*Continued*)

Table 1. (Continued)

Year	Issues/action	Source
2002	CALM paper acknowledged impact of commercial harvesting, poor recruitment, and slow growth rate on the extent of sandalwood.	CALM, Byrne *et al.* 2003
2004	FPC reported that sandalwood has not been regenerating in WA's rangelands at a level capable of sustaining the species.	FPC 2004
2007	FPC aware that replanting using the '12 seeds' policy introduced in 2000 was not working to replace the number of trees being harvested.	Government of Western Australia, SCEPA 2012*b*
2012	2000-signature petition presented to the WA Government calling for a Royal Commission into the sandalwood industry and a cessation of operations, expressing particular concern about unsustainability, overharvesting, and illegal harvesting.	*The Kalgoorlie Miner* 2012; Government of Western Australia, SCEPA 2012*a*
2012	Parliamentary Inquiry into the Sandalwood Industry in Western Australia convened, undertaken by the Legislative Council Standing Committee on Environment and Public Affairs (SCEPA), to investigate deficiencies in the regulation and management of the industry; the status of the species; and the sustainability of the harvest of wild sandalwood.	Government of Western Australia, SCEPA 2012*a*
2012	Multiple submissions made to the Parliamentary Inquiry expressed concerns about unsustainability of exploitation; poor industry management; damage to the environment; lack of a management plan; lack of Aboriginal participation; illegal harvesting; and poor practices by contract harvesters.	Gillam 2012; Jones 2012; Mader 2012; North 2012; Tucker 2012
2012	Department of Environment and Conservation Director General Keiran McNamara and Goldfields Regional Manager Ian Kealley highlighted the lack of sandalwood regeneration, population decline, potential for extinction in the wild, and unsustainable levels of harvest.	SCEPA 2012*d*
2012	WA Government advised by DEC that a more accurate sustainable level of harvest for sandalwood is 200 tonnes per annum.	Government of Western Australia, SCEPA 2012*d*
2014	WA Government acknowledges that 'there will come a time when the State is left with no wild sources of sandalwood' (for 100 years) after 'the current resource of living trees finishes', FPC forester Ben Sawyer.	Government of Western Australia, SCEPA 2014*a*
2014	WA Government sandalwood industry inquiry report finds that 'the rate of harvest is not sustainable and could lead to the resource ultimately being wiped out.'	Government of Western Australia, SCEPA 2014*b*
2015	WA Government undertakes *Review of the Sandalwood* (*Limitation of Removal of Sandalwood*) *Order 1996.*	DPAW 2015
2016	*Sandalwood* (*Limitation of Removal of Sandalwood*) *Order 2015*, and *Biodiversity Conservation Act 2016* introduced (replacing the *Sandalwood Act* of 1929, and *Wildlife Conservation Act* 1950)–contained new harvesting regulations and lowered the harvest quota from 3000 tonnes per annum to 2500 tonnes per annum.	Government of Western Australia 2016
2016	Appeals lodged by civil society organisations in objection to the decision by the WA Environmental Protection Authority (EPA) not to assess the proposal by the FPC to undertake wild sandalwood harvesting on Crown lands (due to the absence of a management plan for sandalwood and concerns about the sustainability of the wild sandalwood industry).	Appeals Convenor, Government of Western Australia 2016
2016	FPC/DPAW acknowledged decline of sandalwood, lack of recruitment and regeneration, and concerns about the level of harvest.	Appeals Convenor, Government of Western Australia 2016
2016	FPC General Manager Gavin Butcher acknowledged sandalwood's lack of replacement regeneration resulting in ongoing and future sandalwood population decline.	Butcher 2016, FPC2016; Appeals Convenor, Government of Western Australia 2016
2016	FPC monitoring indicated insufficient regeneration in the wild to replace natural mortality.	Appeals Convenor, Government of Western Australia 2016
2018	An assessment of the regulatory framework of the WA sandalwood industry established that it is not clear what level of harvest is sustainable, and that by 2118 'there could be no wild sandalwood for harvesting'.	Lingard and Perry 2018
2021	Multiple submissions made to the WA Government's WA Sandalwood Taskforce highlighted decline of the species in the wild, ongoing overexploitation, and potential for extinction in the wild.	WA Sandalwood Taskforce, 2021 (unpublished)

actions, recommended a maximum harvest level of 2000 tonnes per annum (1000 tonnes greenwood, 1000 tonnes deadwood) (Kealley 1991). Despite this recommendation, in 1996 the Government set the annual quota/limit at 3000 tonnes under the *Sandalwood* (*Limitation of Removal of Sandalwood*) *Order 1996* (Government of Western Australia 1996).

The WA Government has acknowledged the impact of harvesting on natural populations and resource supply, noting that 'sandalwood is declining throughout its range' (and) 'in the long term, harvesting will impact if failure of regeneration is not reversed, or alternative sources of supply not developed' (Kealley 1991). The decline of the sandalwood population, partly due to ongoing exploitation in the FPC Sandalwood Supply Areas, was documented in the *WA Sandalwood Harvesting Proposal 2016–2026*, which showed that the combined impact of natural mortality and harvesting will result in ongoing

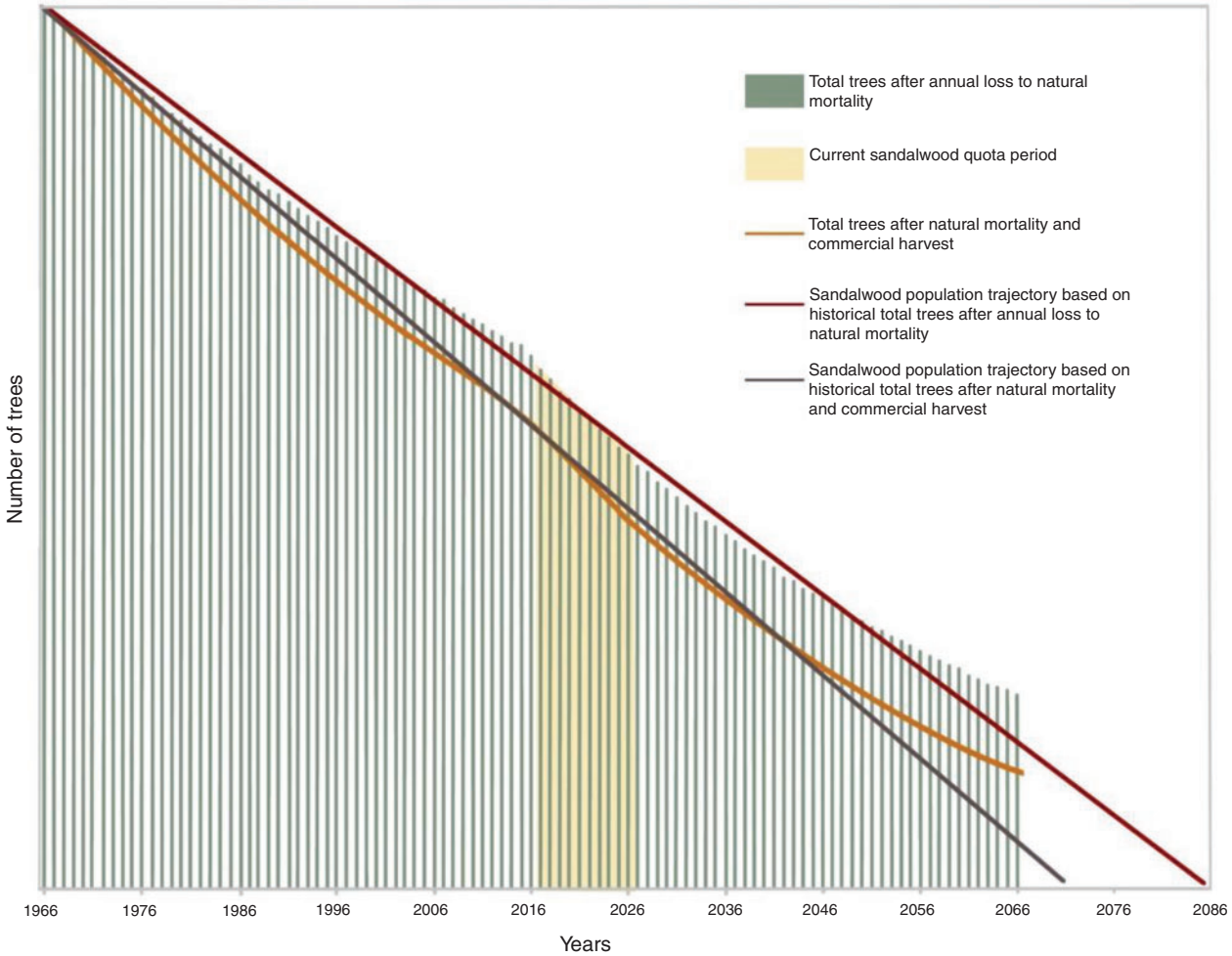

Fig. 4. Sandalwood population decline from mortality and harvest, 1966–2066. Total wild sandalwood population is projected to continue to decline as a result of natural mortality and harvesting. Note: this graph does not reflect the cumulative impact from the total historical harvest (the graph starts in 1966, not 1844), and is therefore not an entire representation of the total population decline since harvesting commenced. The source graph also did not have a scale on the *y*-axis. Trajectory lines to 2070 and 2086 added by the authors. Source: FPC 2016–2026 Sandalwood Harvesting Proposal (FPC 2016).

decline of sandalwood in the wild, and the likelihood of no sandalwood trees remaining across a large part of its natural range (major sections of the FPC harvesting area) before the end of the century (FPC 2016) (Fig. 4).

Illegal harvesting adds unknown quantities of sandalwood to decades of legal overharvesting (SCEPA 2012*d*, 2014*a*; Lingard and Perry 2018). Estimates of illegally-harvested sandalwood range from 500–700 tonnes (FPC 2016) to almost 3000 tonnes per annum (SCEPA 2012*c*). Although apparently curtailed after infringement penalties were substantially increased under the *2016 Biodiversity Conservation Act*, illegal harvesting continues (Lingard and Perry 2018).

Estimates of sustainable yield are uncertain because of insufficient accurate quantitative data on standing crop, recruitment and growth rates (Kealley 1991; Anderson 2005; SCEPA 2012*b*). Kealley (1991) recommended a sustainable harvest quota of 2000 tonnes per annum, but in 2012, suggested that 'a sustainable level (of harvesting) based on current level of regeneration … would probably (require) reducing the greenwood harvest to something like 200 tonnes a year' (SCEPA 2012*d*).

With this recommended 7-fold reduction in harvesting (200 tonnes compared with the 1500 tonnes greenwood quota at the time) (SCEPA 2012*d*), the Parliamentary Inquiry acknowledged the unsustainability of the then legal quotas and the likelihood of 'the resource ultimately being wiped out across the state', with the prospect of there being '100 years with no wild sandalwood being available for harvest' without tightening of the quota limits (SCEPA 2012*b*, 2014*a*). Similarly, Lingard and Perry (2018) concluded that the regulatory framework of the sandalwood industry in WA would result in no harvestable wild sandalwood being available by early next century. This projection, and other documented estimates for when the sandalwood 'resource', might be exhausted in the wild are in Table 2.

In its review of the 1996 Sandalwood Order, and on the basis of advice from its Department of Parks and Wildlife (DPAW), the WA Government reduced the sandalwood harvest quota

Table 2. Estimates of when Australian sandalwood may become extinct in the wild in WA
Although impossible to put an exact date when a species may disappear in the wild, a number of reports have suggested this may occur within the next 80–100 years without major intervention by regulatory authorities

Year	Scenario	Annual allowable harvest (tonnes)	Source
2038	Estimate by Forests Department in 1985 when current sandalwood harvesting resource stocks would run out	2000	Richmond (1983); Statham-Drew (2007)
2045	Projection of when the natural resource will disappear	2000	Kealley (1987)
2061	Projection when natural stock will disappear without 'ingrowth'	2000	Kealley (1991)
2064	Estimate of when sandalwood population at Ninghan Station (western rangelands) may become locally extinct (Range: 2064–2074)	3000	Brand *et al.* (2014)
2076– 2086	Estimate based on the current trajectory of harvesting and mortality trend depicted in FPC Sandalwood Harvesting Proposal 2016–2026	2500	FPC (2016)
2114	Estimate of when there could be no wild sandalwood available for harvest	2500	Lingard and Perry (2018)

level in 2015, from 3000 tonnes to 2500 tonnes per annum (DPAW 2015), still well above the recommended 200 tonnes per annum (SCEPA 2012*d*).

Trends in the population

Official harvest and export records indicate that 541116 tonnes of sandalwood, amounting to 16.6 million trees (based on the average of 30 kg of commercial timber per tree; FPC 2016), have been harvested from the wild in WA between 1845 and 2020 (Fig. 3). The actual number of trees may be either considerably lower due to the known greater weight of many of the first-harvested trees or higher due to the large quantity of illegally harvested wood, the diminishing size of trees being harvested, and the lack of size limits on all early-harvested trees. This estimate of sandalwood trees harvested in WA suggests current sandalwood harvest plans may therefore be based on a standing population as low as 10 per cent of the original population based on harvest figures alone (i.e. not counting the unknown quantity of trees cleared for agriculture, or illegally harvested).

When asked in the 2012–2014 Parliamentary Inquiry if the WA government would continue to have access to wild sandalwood in the future, FPC Director of Forest Operations John Tredinnick responded: 'Probably not, certainly not live or green wood' (SCEPA 2012*b*).

Farm forestry an alternative for Australian sandalwood

Despite its lack of recruitment in the wild, sandalwood is being successfully cultivated in plantations in WA's agricultural zone (Clarke 2006), with currently more than 20000 hectares under cultivation. A viable alternative is therefore available to meet demand for sandalwood exports. However, the lower cost of wild collection, where land and management costs are not incurred by the harvester means that commercial plantations will succeed only if wild collection is curtailed.

Importantly, the rangelands and production landscapes where sandalwood once occurred need new approaches to conservation and management, and application of more regenerative production principles as climates dry and traditional production systems fail. Sandalwood has the potential to provide a high-value product as part of regenerative agricultural practices while supporting livelihoods for farmers and disadvantaged rural communities, particularly Indigenous communities.

Conclusion

Australian sandalwood has experienced a precipitous decline in the wild in Australia's southern and western semiarid and arid rangelands, with estimated losses of 90 per cent of the original pre-European abundance. It has been extirpated throughout much of its range, particularly in southwest Australia and in SA, where only small populations persist. Although no longer legally exploited in SA, populations there are declining as a result of cascading threatening processes other than harvesting, and are dying out through continuing natural mortality, lack of recruitment (including due to grazing) and by changing climatic conditions.

In WA, the commercial sandalwood harvest quota has been reduced during the last decade, and although a regeneration program implemented by Government (SCEPA 2012*b*; FPC 2016), little evidence exists of its wide scale success. Neither measure is likely to alter the continued decline in wild sandalwood populations.

Sandalwood is a species under threat, being detrimentally affected by multiple inter-connected key threatening processes. It is not sustainably regenerating in the wild, with commercial harvesting contributing to its further decline. Without proactive interventions and adequate controls, wild sandalwood is facing extinction. Urgent consideration should be given to the impact of ongoing exploitation of the species in WA and consideration of IUCN listing of the species as under threat. Farm forestry of the species provides a ready solution to develop the industry on more sustainable principles, but the success of farmed sandalwood to arrest the decline in wild harvesting of population will depend upon substantial reduction and phasing-out of wild harvesting to protect remaining populations.

Conflicts of interest

The authors declare no conflicts of interest.

Data Availability Statement

The historic data used in this paper are available through the references provided below.

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