Department of **Biodiversity, Conservation and Attractions**

GOVERNMENT OF
WESTERN AUSTRALIA

Review of the Sandalwood (Limitation of Removal of Sandalwood) Order (No. 2) 2015

2026 Draft Technical Report

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Front cover Sandalwood survey team in the field. *Photo – DBCA.*

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Acronyms and abbreviations

(BC Act) *Biodiversity Conservation Act 2016*

(BC regulations) Biodiversity Conservation Regulations 2018

(CALM) Department of Conservation and Land Management

(CALM Act) *Conservation and Land Management Act 1984*

(cf.) An abbreviation of the Latin word ‘confer’ meaning ‘compare’, and is generally used to refer the reader to other material to make a comparison with the topic being discussed.

(DBCA) Department of Biodiversity, Conservation and Attractions

(DEA) Digital Earth Australia

(EP Act) *Environmental Protection Act 1986*

(ESD) Ecologically Sustainable Development

(ESU) Ecologically Sustainable Use

(FPC) Forest Products Commission

(GPS) Global Positioning System

(IBRA) Interim Biogeographic Regionalisation for Australia

(ICIP) Indigenous Cultural and Intellectual Property

(RGB) Red, Green and Blue – this is an additive colour model used for electronic displays like computer monitors, TVs, and smartphones. By combining these three primary colours of light in various intensities, digital screens can create a wide spectrum of colours.

(SE) standard error

(SEP) Sandalwood Enrichment Program

(sph) stems per hectare

(SPP) Sandalwood Population Projection

1. Acknowledgements

The Department of Biodiversity, Conservation and Attractions (DBCA) acknowledges the Aboriginal peoples who are the first custodians of sandalwood (*Santalum spicatum*) and the Traditional Owners of the lands where sandalwood originated and thrived. We respect the connection and knowledge of their Elders past, present and emerging.

This Draft Technical Report for the review of the Sandalwood Order incorporates Cultural Knowledge and traditional cultural expressions that embodies the Indigenous Cultural and Intellectual Property (ICIP) of the Yilka Heritage and Land Care Pty. Ltd., the K. Farmer Dutjahn Foundation, Dutjahn Sandalwood Oil Pty. Ltd., Kutkabubba Aboriginal Corporation, Windidda Aboriginal Corporation, and Bindulbu Aboriginal Corporation, and has been created with the consent of these groups. Use of any data or any part of this report that includes ICIP for any purpose that has not been authorised by the Traditional Owners may be a serious breach of their customary law. For enquires about permitted reproduction, please contact sandalwood@dbca.wa.gov.au or phone (08) 9219 9000.

We also thank the Forest Products Commission (FPC), Ian Kealley, Dr Hugh Chevis and Grant Pronk for providing information on sandalwood ecology, conservation and population demography. We would also like to thank DBCA and FPC staff for their extensive efforts in collecting field data and for their contributions for the preparation of this report. We thank Dr Martin Rayner and Paul Roberts for their contribution to this review. We also thank Jack Bradshaw who carried out the sandalwood population modelling. Lastly, we thank all those who have not been specifically mentioned here who have provided various contributions—either indirectly or more directly via their work or engagement with DBCA—which has helped to provide input into the Sandalwood Order review process.

2. Executive summary

This *Draft Technical Report* presents the methods and results of sandalwood population analyses and modelling of various potential management scenarios, undertaken to inform the review of the *Sandalwood (Limitation of Removal of Sandalwood) Order (No. 2) 2015* in accordance with Section 3(1) of the *Biodiversity Conservation Act 2016* (BC Act) and Strategy 2(a) of Western Australia's *Santalum spicatum* (Sandalwood) Biodiversity Management Programme (Sandalwood BMP) (DBCA, 2023). The purpose of this report is to provide evidence-based insights into the current condition of wild sandalwood populations and to evaluate the ecological implications of future management options across key regions of the species' distribution.

The assessment followed four main stages:

(1) collation of available demographic data;

(2) stratification of sandalwood habitat at a regional level;

(3) analysis of population demographics; and

(4) development of a population projection model to simulate future population structure under different harvest[1] and seeding scenarios.

Comprehensive strategic-level surveys of sandalwood occurrence and condition are either incomplete or unavailable across the full range of the species distribution. However, historic sandalwood inventory datasets, complemented by targeted survey in 2022–2024, together with refinements in mapping the extent of potential sandalwood habitat and vegetation associations were used to examine population demographics in key regions. For the remote desert regions, assessment of condition was informed by inventory datasets provided in confidence by licence applicants.

Consistent with previous assessments of sandalwood condition, this study suggests that while some natural regeneration of sandalwood has established and persisted at local scales, at broader landscape scales there are insufficient trees in younger age classes to provide for natural recruitment processes to replace older trees as they senesce. This pattern was evident to varying degrees in each region, suggesting that long-term population decline across most regions and tenures is likely due to insufficient natural recruitment. Active seeding of areas—whether with or without harvest—has potential to mitigate this decline at a local scale, provided establishment is successful and regeneration persists over time.

A Sandalwood Population Projection model was developed to simulate future population structure across decades for up to 100 years, based on the initial size-class of trees and growth, mortality and recruitment rates. Modelling was undertaken for a range of seeding scenarios, either independent of harvesting (such as on conservation tenures) or variously associated with different levels of harvest of living and dead sandalwood for 10 years. Simulations suggest restoring a balanced size-class distribution at landscape scale would require very large, long-term annual seeding programs requiring sustained logistical and funding support. However, smaller, short-term seeding programs targeting specific areas could enhance the future stability and resilience of size-class structure at the local scale (as outlined in Strategy 10 of the *Sandalwood BMP*).

On tenures where harvesting is permitted, modelling explored the impact of varying levels of annual harvest for a 10-year period, spanning a range from the current *2015 Sandalwood Order* level of 2,500 tonnes per annum to a reduced level of 1,000 tonnes per annum. Restrictions on the minimum size of trees that can be harvested, combined with requirements to sow a minimum quantity of seed for each tree harvested, mean that several decades after harvest the modelled impact on future size-class distributions is a reduction in the frequency of trees larger than 127 mm diameter accompanied by an increase in the frequency of trees in smaller size classes (less than 50 mm diameter). This increase was substantial where additional, concurrent seeding initiatives (such as the current ‘Operation Woylie’) were included. While these improvements in regrowth size-class distributions were marked at the scale of the annual areas harvested over a 10-year period, effects were minor when considered at the whole-of-region level. This is because the range of annual harvest levels—from 1,000 tonnes to 2,500 tonnes—constitute only a small proportion (less than one per cent) of the estimated available commercial-sized resource of living sandalwood. The net

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[1] Throughout this report, ‘harvest’ is used interchangeably with ‘take’ or ‘removal’.

area harvested to supply these quantities each year would also constitute a small proportion (around 0.6 per cent) of the total potentially available area of sandalwood habitat mapped in the present work.

Importantly, all the management scenarios involving harvesting assumed annual seeding programs successfully create a regeneration cohort that is subject only to natural mortality over time. While the area stratification process sought to refine the available area for harvest to those correlated with higher sandalwood regeneration potential, in the rangelands and desert environments, establishment and persistence of regeneration can be episodic, often aligned with favourable rainfall patterns. In an extreme scenario where all regeneration failed to establish or persist over the 10-year period of harvest the modelling indicated a substantial depletion of tree numbers in all size classes by year 40, highlighting the relative risks and importance of achieving and monitoring regeneration success associated with harvest operations.

Across the various harvesting scenarios, ecological outcomes differ only modestly and the overall risk to sandalwood species conservation of a modest level of take over 10 years is considered to be low. Higher harvest levels may increase risks to seed tree density, regeneration potential, and genetic connectivity, while moderate reductions in current harvest levels offer limited mitigation of these impacts. Dispersing the annual harvest across geographic regions will potentially reduce ecological pressures and promote restoration activities across a representation of landscapes. The most precautionary harvesting scenarios, involving substantial reductions in total harvest, are expected to have minimal negative ecological impacts and align more closely with the principles of Ecologically Sustainable Use (ESU).

The report concludes that while active seeding can support localised population recovery, its effectiveness is constrained by scale and environmental conditions. All harvesting scenarios require active seeding and sustainable management (including retention of sufficient seed-bearing trees, protection of soil and hydrological values, and control of introduced pests and weeds) by the harvesting entities to mitigate ecological impacts, and these operations show better outcomes than scenarios involving no harvest and no seeding. These findings provide a foundation for informed decision-making in the review process and highlight the importance of balancing harvest levels with regeneration capacity, long-term population viability, and appropriate resourcing for seeding efforts. However, any decisions must also account for the full suite of Ecologically Sustainable Development (ESD) considerations. This is discussed in more detail in the *Review of the Sandalwood (Limitation of Removal of Sandalwood) Order (No. 2) 2015, 2026 Draft Review Report (Draft Review Report)*. This report should be read in conjunction with the *Draft Review Report*, and the Sandalwood BMP, which also provides further background information on sandalwood management.

3. Introduction

The maximum quantities of wild sandalwood (*Santalum spicatum*) that may be taken from Crown and private (freehold) land in Western Australia (WA) are currently set in the *Sandalwood (Limitation of Removal of Sandalwood) Order (No. 2) 2015* (2015 Sandalwood Order). The *2015 Sandalwood Order* was originally set under the now repealed *Sandalwood*

Act 1929 and is in effect until 31 December 2026 under transitional arrangements of regulation 173 of the Biodiversity Conservation Regulations 2018 (BC regulations).

Under Section 187 of the *Biodiversity Conservation Act 2016* (BC Act), the Minister for the Environment (Minister) will issue a new Sandalwood Order, which is intended to take effect in 2027, which will repeal and replace the *2015 Sandalwood Order*. DBCA will recommend to the Minister the content of the new Sandalwood Order, based on a review of the best available information to ensure future management of the species will be in accordance with Section 3(1) of the BC Act and Strategy 2(a) of the *Sandalwood BMP*. For more information on this process, please refer to the *Draft Review Report* at dbca.wa.gov.au/review-sandalwood-order.

Recommendations in the *Draft Review Report* will have due consideration for the conservation and ecologically sustainable use of the species and will account for:

- strategic inventory and population modelling in relation to a range of management scenarios;
- risk assessment of the species' potential for persistence across its distribution;
- scale, nature and requirements of effective sandalwood recruitment strategies[2];
- differences in sustainability and management requirements of removing living or dead sandalwood;
- regional licensing protocols for harvesting of sandalwood to ensure conservation, protection and management of the species across its distribution; and
- principles of Ecologically Sustainable Development (ESD) as defined in Section 4 of the BC Act[3].

The *Review of the Sandalwood (Limitation of Removal of Sandalwood) Order 1996* (Review of the 1996 Sandalwood Order) (Department of Parks and Wildlife, 2015) assessed the Forest Product Commission's (FPC) strategic inventory (FPC Inventory) and found it an acceptable basis for determining an appropriate harvest limit for the *2015 Sandalwood Order*. The FPC Inventory included a consolidation of several earlier inventories—completed by the then Forests Department of WA (Forests Department) and Department of Conservation and Land Management (CALM)—to define the occurrence and size class profiles of the sandalwood populations within the FPC supply areas (Figure 1).

This review of the *2015 Sandalwood Order* includes analysis of data from the FPC Inventory (the historical dataset) and a more recent DBCA survey (the contemporary dataset) to inform recommendations for the future management of wild sandalwood. While the FPC Inventory covered a broader area of sandalwood distribution, the DBCA survey remeasured a subset of the historical plots from the FPC Inventory to assess the current population condition and demographic changes over time. Various management scenarios were then modelled, including different levels of harvesting and seeding programs.

Inventory and population data from surveys located outside the FPC supply areas, including those associated with sandalwood licence applications, were examined to inform potential

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[2] Including manual or machine supplemental seeding during harvest activity and targeted seeding within conservation reserves.

[3] The discussion of current population condition and modelling projections in this document does not consider all aspects of principles of ESD. This document focuses more on ESU.

differences between regions but were not used for general population condition assessment and modelling because they were localised and not considered representative of their broader environments.

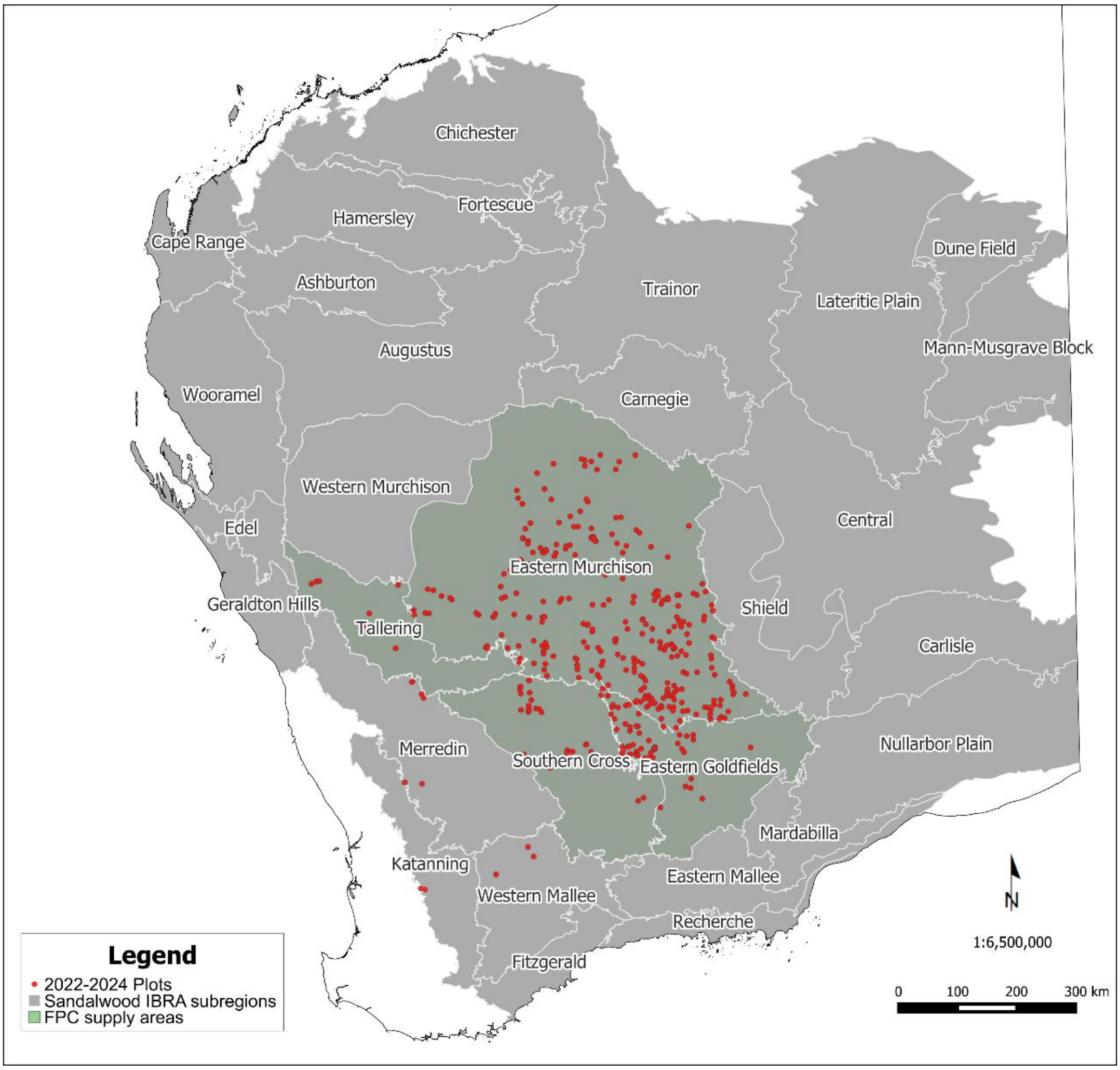

Figure 1. The natural distribution of wild sandalwood in WA highlighting FPC's supply areas in relation to IBRA subregions, and the location of the contemporary sandalwood inventory plots measured in 2022–2024.

While factors such as sandalwood plantation supply, market dynamics for sandalwood products, and relevant socio-economic priorities were not explicitly modelled, they provided important contextual background that informed the development of management scenarios. In addition, an extensive literature review relevant to sandalwood biodiversity conservation also provided relevant context (Northover et al., in press). Further information about socio-economic considerations is provided within the *Draft Review Report*.

This document presents the methods and results of the population analysis and modelling used to assess the current condition of wild sandalwood populations and future management scenarios, to inform recommendations in the *Draft Review Report*.

4. Methods

This section is structured into four key sub-sections describing the data and methods used to assess the current status of wild sandalwood populations and the modelling of different management scenarios. Following each stage illustrated in Figure 2, the process to collate available inventory datasets is described, followed by detailed derivation of spatial strata defining the extent of wild sandalwood habitat in each region. Analysis of the inventory data and allied information to quantify the current demographics and changes over time is then described and results presented. Development of a population projection model to explore the impact of varied management strategies on tree size-class distributions is then described, together with the basic model inputs and assumptions.

Consistent with the *Sandalwood BMP* (DBCA, 2023), the Interim Biogeographic Regionalisation for Australia[4] (IBRA) subregions were adopted as the primary unit for stratifying and interpreting sandalwood distribution and demographic data. The estimated areas of sandalwood habitat and the relative recruitment, growth and mortality rates (and other variables) were then used to model the future condition of sandalwood populations under different management scenarios.

The distribution of sandalwood in WA is estimated to be approximately 173 million hectares, which has been derived from the extrapolation of WA Herbarium[5] records to the IBRA boundaries. Sandalwood has been recorded in 30 IBRA subregions (Figure 1) but also occurs irregularly and sparsely within each of these subregions. Landscape-scale sandalwood population surveys have been almost entirely limited to the Eastern Goldfields, Southern Cross, Eastern Murchison and Tallering IBRA subregions. There have been a limited number of small-scale surveys in other subregions, but for many subregions the data are restricted to herbarium records. Generalised descriptions of sandalwood habitat suggest that the species is generally absent, or occurs at low densities in homogenous vegetation, including pure woodland, spinifex, sand plain and halophytic shrublands, while more likely to occur in mixed *Acacia* shrublands (Kealley, 1991; Loneragan, 1990; Williamson, 1982).

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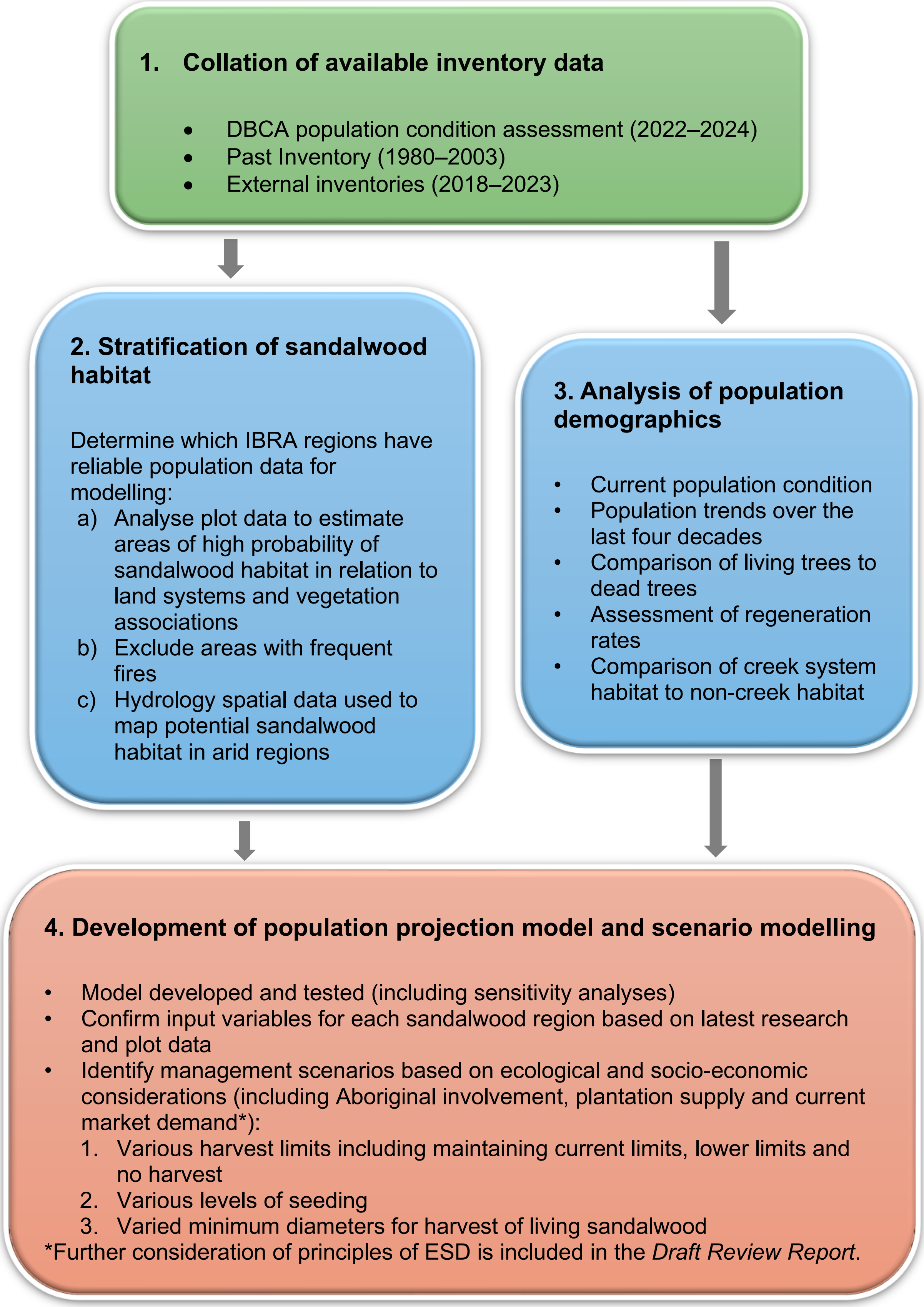
[4] More information about the Interim Biogeographic Regionalisation for Australia can be found at dcceew.gov.au/environment/land/nrs/science/ibra.

[5] More information about DBCA's WA Herbarium can be found at dbca.wa.gov.au/science/research-tools-and-repositories/western-australian-herbarium.



1. Collation of available inventory data

- DBCA population condition assessment (2022–2024)
- Past Inventory (1980–2003)
- External inventories (2018–2023)

2. Stratification of sandalwood habitat

Determine which IBRA regions have reliable population data for modelling:

a) Analyse plot data to estimate areas of high probability of sandalwood habitat in relation to land systems and vegetation associations
b) Exclude areas with frequent fires
c) Hydrology spatial data used to map potential sandalwood habitat in arid regions

3. Analysis of population demographics

- Current population condition
- Population trends over the last four decades
- Comparison of living trees to dead trees
- Assessment of regeneration rates
- Comparison of creek system habitat to non-creek habitat

4. Development of population projection model and scenario modelling

- Model developed and tested (including sensitivity analyses)
- Confirm input variables for each sandalwood region based on latest research and plot data
- Identify management scenarios based on ecological and socio-economic considerations (including Aboriginal involvement, plantation supply and current market demand*):
  1. Various harvest limits including maintaining current limits, lower limits and no harvest
  2. Various levels of seeding
  3. Varied minimum diameters for harvest of living sandalwood

*Further consideration of principles of ESD is included in the *Draft Review Report*.

Figure 2. The four stages of the methods used to inform the modelling.

4.1 Collation of available inventory data

The sandalwood population condition assessment and modelling of select management scenarios were informed by data from three main sources: the historic FPC strategic and operational inventories; a contemporary DBCA-led survey; and various sandalwood harvest licence inventories (in desert regions[6]). Figure 1 shows the locations of plots measured in 2022 to 2024.

4.1.1 Past strategic and operational inventories (1980–2003)

Between 1980 and 2003, FPC (and predecessor agencies)[7] established 1,511 four-hectare sandalwood plots (or occasionally six-hectare plots) and conducted 1,605 km of track-based surveys across sandalwood supply areas. These supply areas included the Southern Cross, Eastern Goldfields, Eastern Murchison and Tallering IBRA subregions. The dataset comprises 1,286 plots established under CALM, and 200 Sandalwood Inventory and FPC's Sandalwood Enrichment Program (SEP), which were generally selected using a 'partially random' approach. In this method, randomly chosen plots were positioned within 30 to 500 metres of existing roads and tracks (Bradshaw, 2004). An additional 60 plots were randomly selected from areas classified as High and Medium probability of sandalwood occurrence to assess potential bias in the original plot selection. These supplementary plots were not constrained by geographic location or accessibility. Statistical analysis of the number of trees exceeding 126 mm in diameter confirmed that the additional random plots were representative of the same population as the original inventory and SEP plots, thereby demonstrating no systematic bias in plot location and hence representativeness.

4.1.2 DBCA survey (2022–2024)

A DBCA-led survey undertaken between 2022 and 2024 measured 317 plots (each six hectares in size) distributed within the Southern Cross (n = 25), Eastern Goldfields (n = 57), Eastern Murchison (n = 222) and Tallering (n = 5) IBRA subregions, plus eight plots in the broader Wheatbelt region (Figure 1). The Wheatbelt plots were located in the Merredin (n = 3), Katanning (n = 1), Western Mallee (n = 3) and Northern Jarrah Forest (n = 1) IBRA subregions, and were grouped together for analyses based on their similar landscape context (Figure 1). Only a subset of the 317 contemporary plots were suitable for particular demographic analyses (see Section 4.3 Analysis of sandalwood population demographics).

To assess changes in sandalwood population distributions within the FPC supply areas since the *Review of the 1996 Sandalwood Order* in 2015, 268 of DBCA's 317 contemporary plots were placed in the same location as the past inventory plots. The selection of historical plots for resurveying during the 2022–2024 period was guided by the presence of a minimum of six stems per plot in earlier assessments conducted between the 1990s and early 2000s. This criterion was adopted to support the primary objective of the DBCA survey, which was to quantify stand dynamics rather than to generate an unbiased strategic inventory estimate of the total standing resource. This approach also facilitated efficient data collection during fieldwork, given the remote and difficult-to-access locations of many plots. While these data may not be representative of plots that historically had the lowest stem densities, potential

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[6] Reference to 'Desert regions' refers to the combined IBRA subregions of Shield, Central, Carnegie, Trainor and Lateritic Plain.

[7] 1980–1984: Forests Department, 1990–2000: Department of Conservation and Land Management, 2001–2003: FPC.

bias was addressed in the modelling by restricting the area basis of projections to strata with higher stem densities.

Unfortunately, the precise location of many historical plots could not be guaranteed due to the imprecision of earlier Global Positioning System (GPS) technology and because they had not been permanently demarcated in the field. A proportion of the new plots were also a different size and shape, and measurement of tree size classes also varied during the historical inventories (see Section 4.3 Analysis of sandalwood population demographics). These factors confounded comparisons between contemporary and historical plot datasets. The intent of the recent DBCA-led survey was to collect data to identify changes in population demographics over the last 20–35 years (the oldest plots remeasured were from the mid-90s), including recruitment, growth and mortality rates and size class distributions. It should be noted that most contemporary plots were located in areas potentially available for harvesting.

All contemporary plots were approximately one kilometre long and 60 metres wide (six hectares). Three different plot shapes—horseshoe (Figure 3), stream (Figure 4) and track-based (Figure 5) plots—were used depending on the local environmental variables. Horseshoe plots were typically adopted in relatively homogenous vegetation communities to inform patterns of sandalwood distribution and population demographics within individual land systems and vegetation associations. Stream plots provided insight into patterns of seed dispersal (in the absence of small marsupial dispersal vectors) through water runoff, while measurement across the hydrological gradient provided a comparison of sandalwood distribution between mesic and drier habitats. Track-based plots were used where the transition between vegetation types allowed measurement of sandalwood habitat heterogeneity along other environmental gradients. This provided insight into the probability of sandalwood occurrence and demographic variability across land systems and vegetation associations.

The location of sandalwood trees in each plot was recorded with GPS technology, and their over-bark diameters measured at 150 mm above ground level. Other measurements included crown health, bark condition, mortality status (living, dead), proximity to creek line, and likely host plants.

Twenty-seven DBCA plots overlapped the past inventory plots in sandalwood stands established in the 1920s at Karramindie State Forest, Scahill Timber Reserves and Yallari Timber Reserve, near Kalgoorlie. This contemporary and historical data provided further insight into sandalwood recruitment, growth and mortality rates, which were used to inform the relevant variables when modelling the implications of different management scenarios on wild sandalwood populations. This sub-set of plots were not, however, included in the general demographic analyses because they reflect a history of extensive seeding and associated silviculture, and were therefore unrepresentative of the broader sandalwood populations.

Twenty of the 317 DBCA plots were established along drainage systems to examine the relationship between sandalwood distribution and hydrological gradients, particularly patterns of seed dispersal and recruitment in the absence of native seed-caching marsupials (that disperse and bury seed) and the implications of a drying climate.

Drone RGB imagery was captured for most contemporary plots, to assist visual interpretation of sandalwood habitat in different land systems and vegetation associations during the biogeographic stratification of sandalwood distribution. The drone imagery is likely to be useful in future condition monitoring and assist other remote sensing projects. FPC have previously investigated the utility of data from drone-based hyperspectral sensors for locating individual sandalwood trees and hence replace or enhance conventional, time consuming, on-ground surveys. The technology is, however, currently unable to reliably detect individual sandalwood trees, and further development is required.

4.1.3 Other sandalwood inventories

Recent sandalwood inventories undertaken to support licence applications (Kealley, 2018, 2022; Kealley and Chevis, 2022; Pronk 2023a, 2023b) provided valuable supplementary data for IBRA subregions not covered by past inventory and DBCA inventories, particularly within the Shield, Central, Carnegie, Trainor, and Lateritic Plain subregions. Although these inventories employed broadly comparable methodologies—including vegetation stratification, track-based transects and plot-based sampling—their localised nature within subregions lacking comprehensive vegetation or land systems mapping likely introduced an unknown level of sampling bias. The limited sample sizes also precluded broader extrapolation to entire subregions. Consequently, the data were not directly used for modelling population trends in these subregions but provided valuable examples of sandalwood population demographics within specific areas which were used to support qualitative assessments and generate illustrative resource estimates in these Desert IBRA subregions.

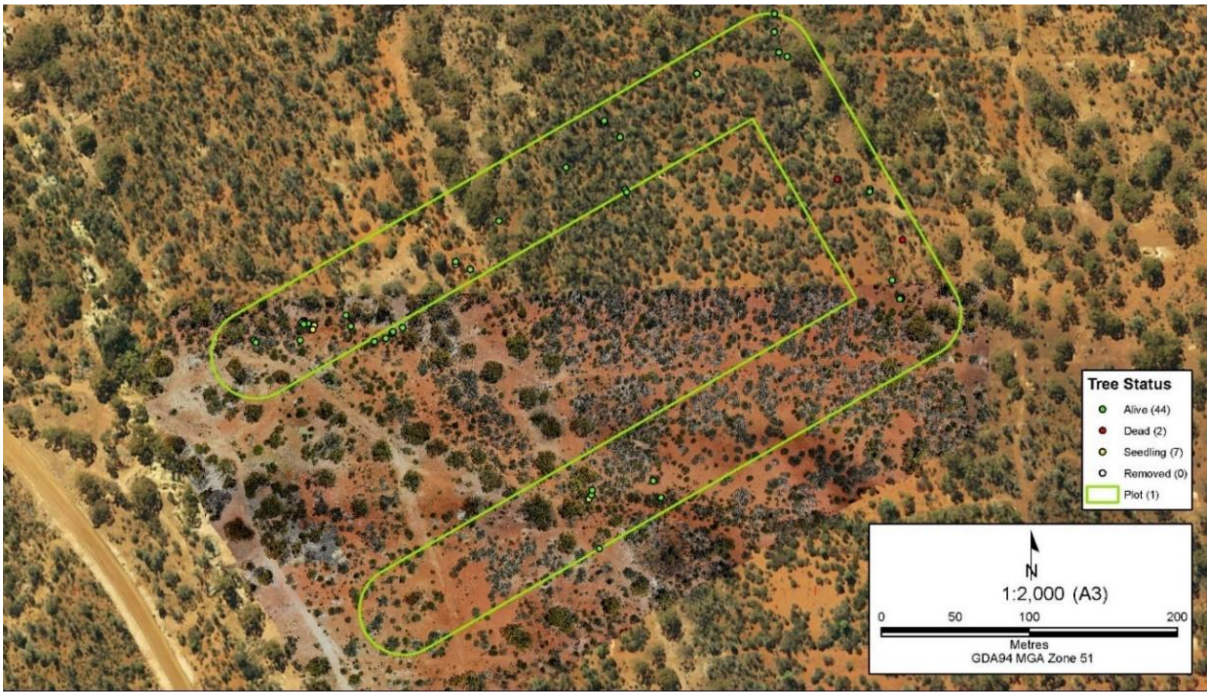

Figure 1. An example of a horseshoe plot layout and measured sandalwood trees.

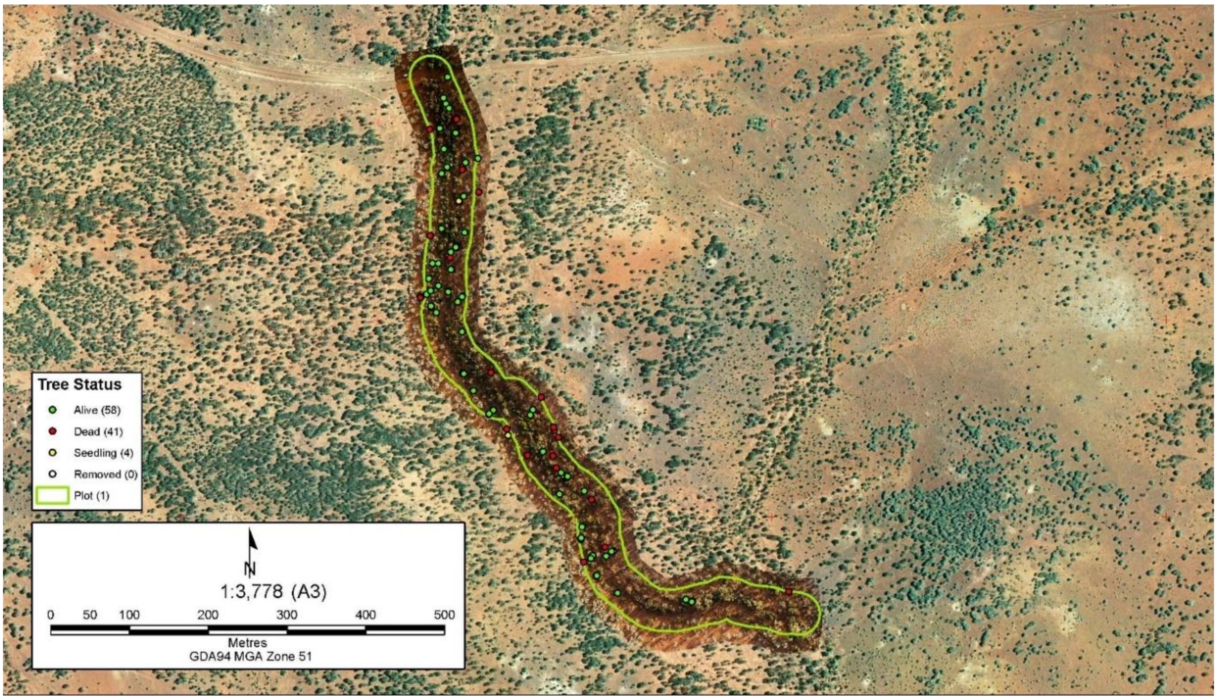

Figure 4. An example of a stream plot layout.

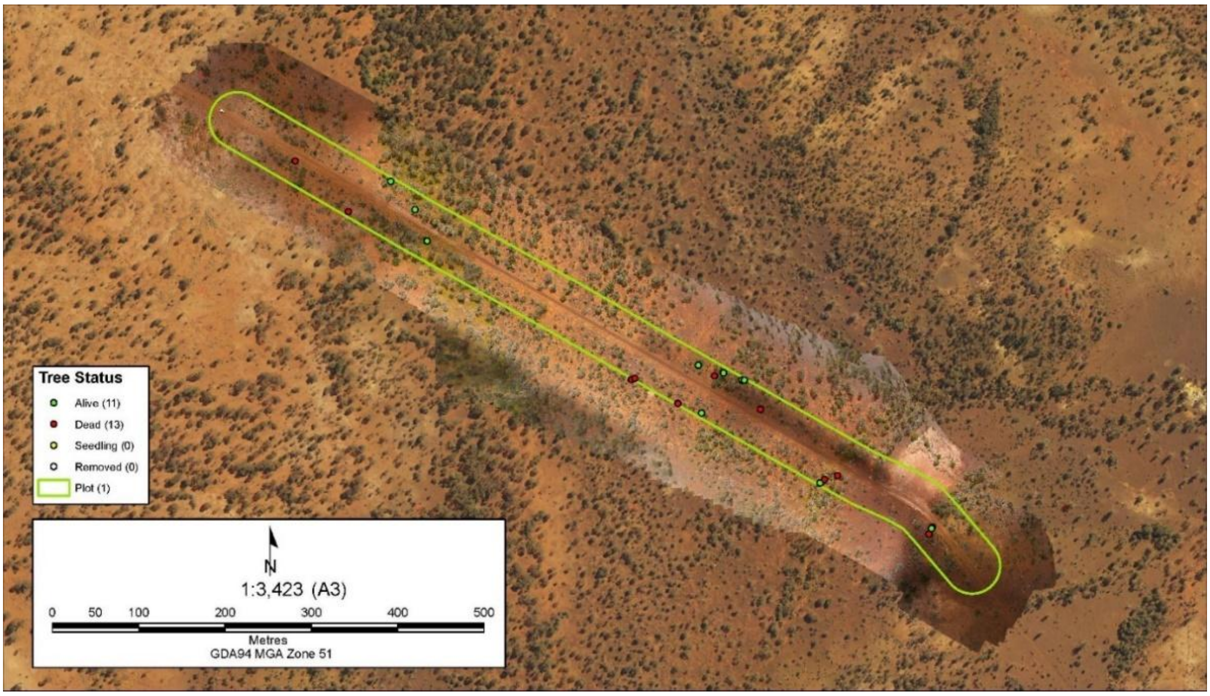

Figure 5. An example of a track plot layout.

4.2 Stratification of sandalwood habitat

In each IBRA subregion an understanding of the extent of sandalwood habitat[8] and the associated demographic profile is necessary to assess present population condition, and to

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[8] ‘Sandalwood habitat’ is defined here as a subset of the total extant distribution of wild sandalwood that is considered to have sufficient stems per hectare to be a candidate area for modelling resource scenarios, as opposed to areas without sandalwood, or with only sparse densities.

project (through modelling) the implications of different management scenarios on the long-term viability of sandalwood populations. The area estimates of sandalwood habitat are key variables in the model developed to project future population structure, with the demographic data then extrapolated to the broader IBRA subregions.

Unfortunately, sandalwood occurrence cannot be mapped directly from aerial imagery because current remote sensing technology cannot reliably and consistently detect sandalwood trees. Due to its broad, scattered distribution extensive ground-based surveys for mapping were not feasible, particularly in such remote areas. Consequently, the probability of sandalwood occurrence was inferred primarily from its association with vegetation types. In this approach areas of low or marginal[9] habitat suitability for sandalwood as well as those with the lowest recorded tree densities, were excluded from estimated areas incorporated into the resource estimation and population modelling. This conservative approach seeks to minimise the risks of overestimation of suitable sandalwood habitat and propagating such errors through subsequent analyses.

The data collation work (Section 4.1 Collation of available inventory data) confirmed that comprehensive biogeographic and demographic datasets were not available for many IBRA subregions. The subregions were therefore grouped (based on similar biogeographic ecosystems) into those with sufficient information for estimation of sandalwood habitat (candidates for subsequent analysis and modelling), and those to be excluded.

Table 1 lists the status of each subregion, while Figure 6 depicts their geographic distribution. For mapping sandalwood habitat, subregions were grouped based on: (1) availability of spatial data; (2) similarity in environment and habitat; and (3) availability of plot data for modelling (Table 1). Only two of the groupings were identified for analysis and modelling of population demographics, namely the Semi-Arid Rangelands and the Eastern Murchison because of the availability of sandalwood demographic data from the inventories discussed under Section 4.1. The limited inventory data available for the Great Victoria Desert and Western Deserts groups precluded detailed modelling, but given ongoing interest in sandalwood management in these regions an indirect approach to mapping potential habitat was developed and available inventory used to provide a first approximation of extent and illustrate provisional sandalwood resource.

The areas of sandalwood habitat were informed by an analysis of the sandalwood plot data (both historical and contemporary) and calculated by a hierarchical stratification of spatially explicit, biogeographic datasets, including vegetation, fire history and (in the case of the Desert groupings) hydrology (Figure 7).

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[9] For the purposes of the stratification method used in this assessment, ‘low or marginal habitat suitability’ follows sandalwood habitat differentiation as defined by Loneragan (1990) and Kealley (1991), or as ‘low probability of occurrence’ as defined in the FPC Inventory (see Appendix 1 and 2). Generally, all habitats with less than one stem per hectare, were considered ‘low or marginal’.

Table 1. The IBRA subregions (and groupings) either included or excluded for subsequent stratification, demographic analyses or population modelling based on data availability.

Groupings[1]	**IBRA subregions**	**Justification for grouping**
INCLUDED – for stratification, demographic analyses and modelling		
Semi-Arid Rangelands	Eastern Goldfields, Southern Cross	Similarities in sandalwood occurrence and population demographics.
Eastern Murchison	Eastern Murchison	Comprehensive distribution of plots across its diverse land systems.
INCLUDED – for provisional stratification and demographic analyses		
Great Victoria Desert	Shield, Central	Similar vegetation associations, and several resource level inventories.
Western Deserts	Carnegie, Trainor, Lateritic Plain	Similar vegetation types and the availability of some sandalwood population data.

EXCLUDED		
Central Ranges	Mann-Musgrave-Block, Dune Field	Similarity in vegetation types and only herbarium records for sandalwood within the individual subregions.
Nullarbor	Carlisle, Nullarbor Plain, Mardabilla	Similarity in vegetation types and only herbarium records for sandalwood within the individual subregions.
Esperance Plains	Fitzgerald, Recherche	Similarity in vegetation types and only herbarium records for sandalwood within the individual subregions.
Wheatbelt	Merredin, Katanning, Western Mallee, Eastern Mallee, Geraldton Hills	Most sandalwood habitat has been cleared for agriculture and the remnant populations are highly fragmented.
Mid-West	Tallering, Edel, Western Murchison, Wooramel	Very limited data available for the Mid-West subregions and most sandalwood habitat has been significantly impacted by small stock grazing.
Pilbara	Ashburton, Cape Range, Hamersley, Fortescue, Chichester, Augustus	Similarity in vegetation types and only herbarium records for sandalwood within the individual subregions.

[1] The groupings are based on generally similar biogeographic ecosystems.

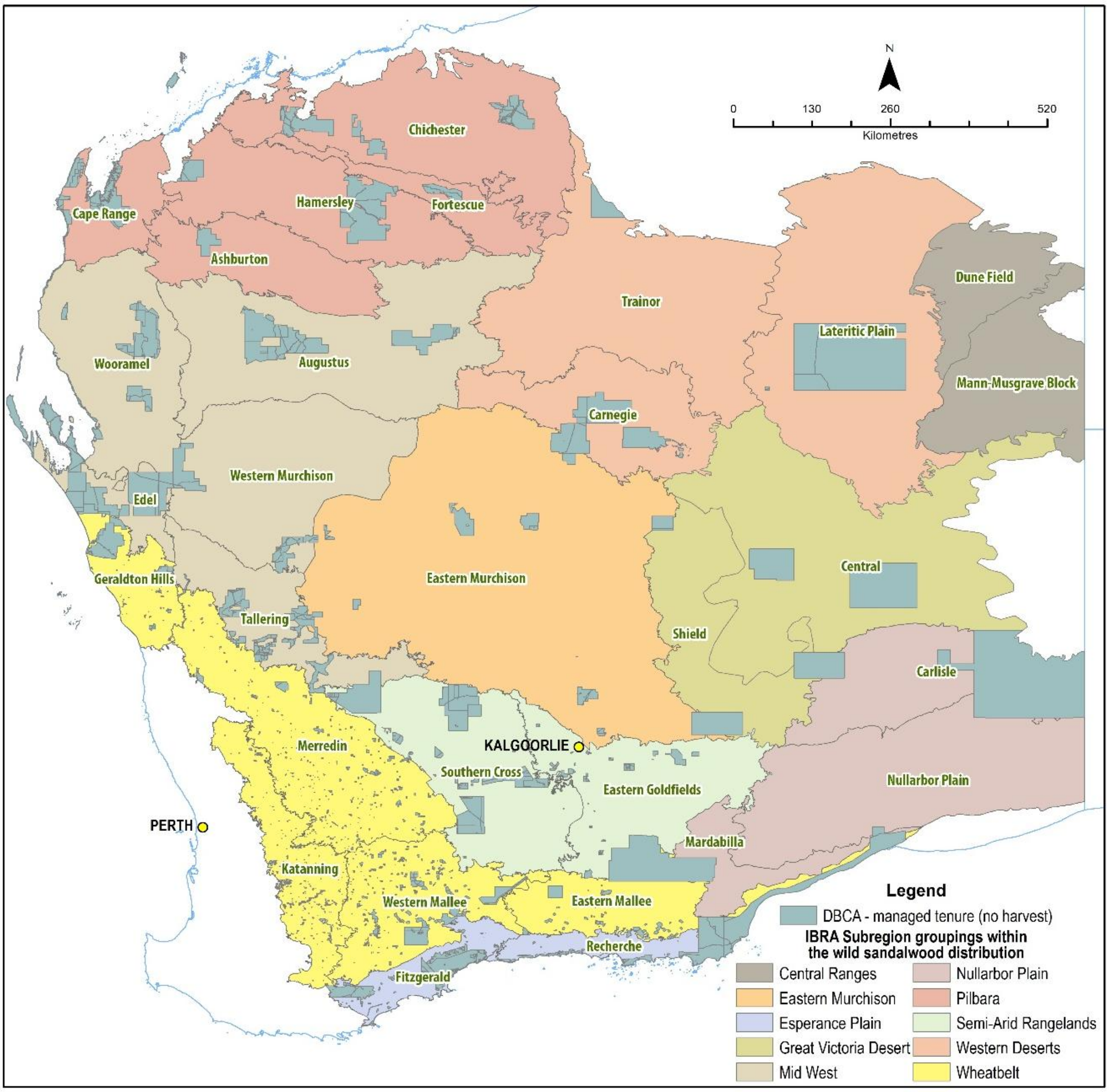

Figure 6. The stratification of groups of IBRA subregions across the broad distribution of wild sandalwood within WA, based on biogeographic similarities.

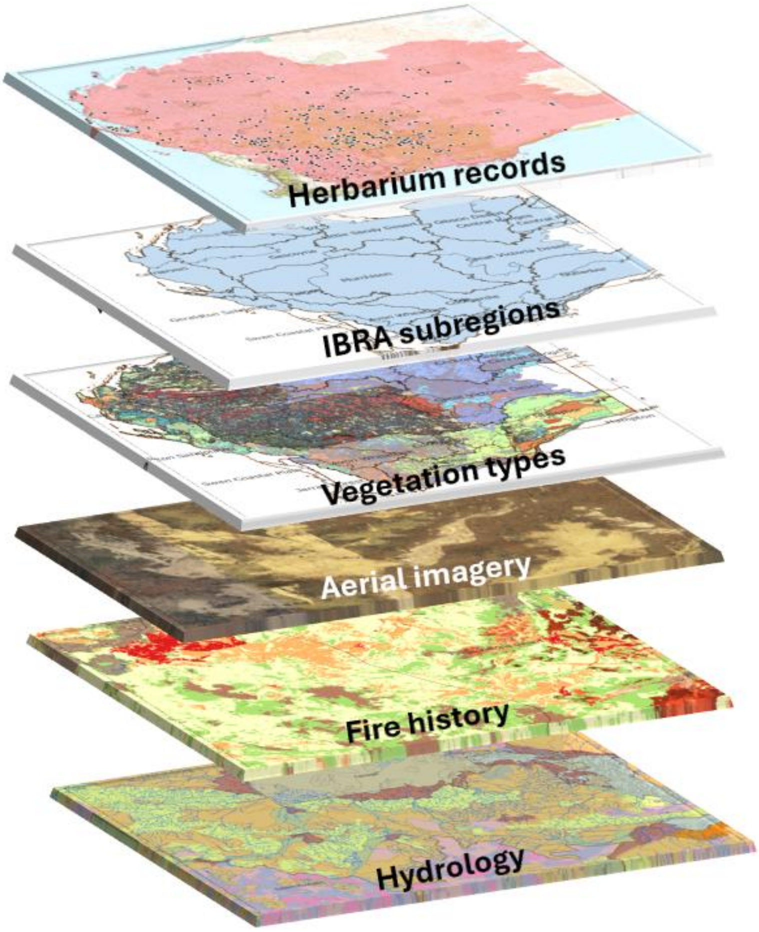

Figure 7. The hierarchy of geospatial datasets used to identify sandalwood habitat extent.

4.2.1 Vegetation strata

Land systems (Tille, 2006) and vegetation associations (Beard et al., 2013) were used as the primary proxies for estimating the probability of sandalwood occurrence in the Southern Cross, Eastern Goldfields and Eastern Murchison IBRA subregions. Land systems were preferred where available, because of the finer scale at which they were mapped and their detailed descriptions of vegetation communities, geomorphology, soils, and other environmental variables that were useful for identifying likely sandalwood habitat. Land systems have been mapped for most of the sandalwood distribution, except for those IBRA subregions outside the pastoral lease areas.

Only land systems or vegetation associations that were considered to have a medium to high probability of supporting relatively suitable[10] sandalwood habitat, were used to derive the preliminary estimate of the area of sandalwood habitat in each IBRA subregion. This ensured a conservative approach to estimating sandalwood densities and population profiles across the broader distribution. Homogenous vegetation types (Loneragan, 1990; Kealley, 1991; Williams, 1982), such as sand plains, pure mulga, pure eucalypts, eucalypts with hummock grassland (spinifex) and eucalypts with blue bush, were considered to have a low probability of supporting sandalwood habitat and were therefore excluded from the dataset. Mixed shrublands and woodlands with an *Acacia* component were generally considered to

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[10] Despite overall low abundance, spatial variation in habitat suitability enables differentiation between higher and lower quality sandalwood habitats.

have a higher probability of sandalwood occurrence. Aerial and drone imagery were inspected where available to support interpretation.

The probability of occurrence of sandalwood habitat within land systems was estimated from the original 1,511 past inventory plots and 1,605 km of track surveys (Sawyer and Jones, 2000), together with the contemporary plot data (Appendix 1 and Appendix 2). For the historical data, the probability of occurrence was based on the proportion of plots and track-based transects within a land system or vegetation association which contained sandalwood populations, and which were consequently ranked as high (>50%), medium (25–49%), or low (0–24%) probability. The contemporary data were used to refine these estimations using the mean and median number of sandalwood stems per hectare derived for each land system and vegetation association.

Fire history and hydrological geospatial datasets were also used to refine the likely extent of sandalwood habitat (Figure 8).

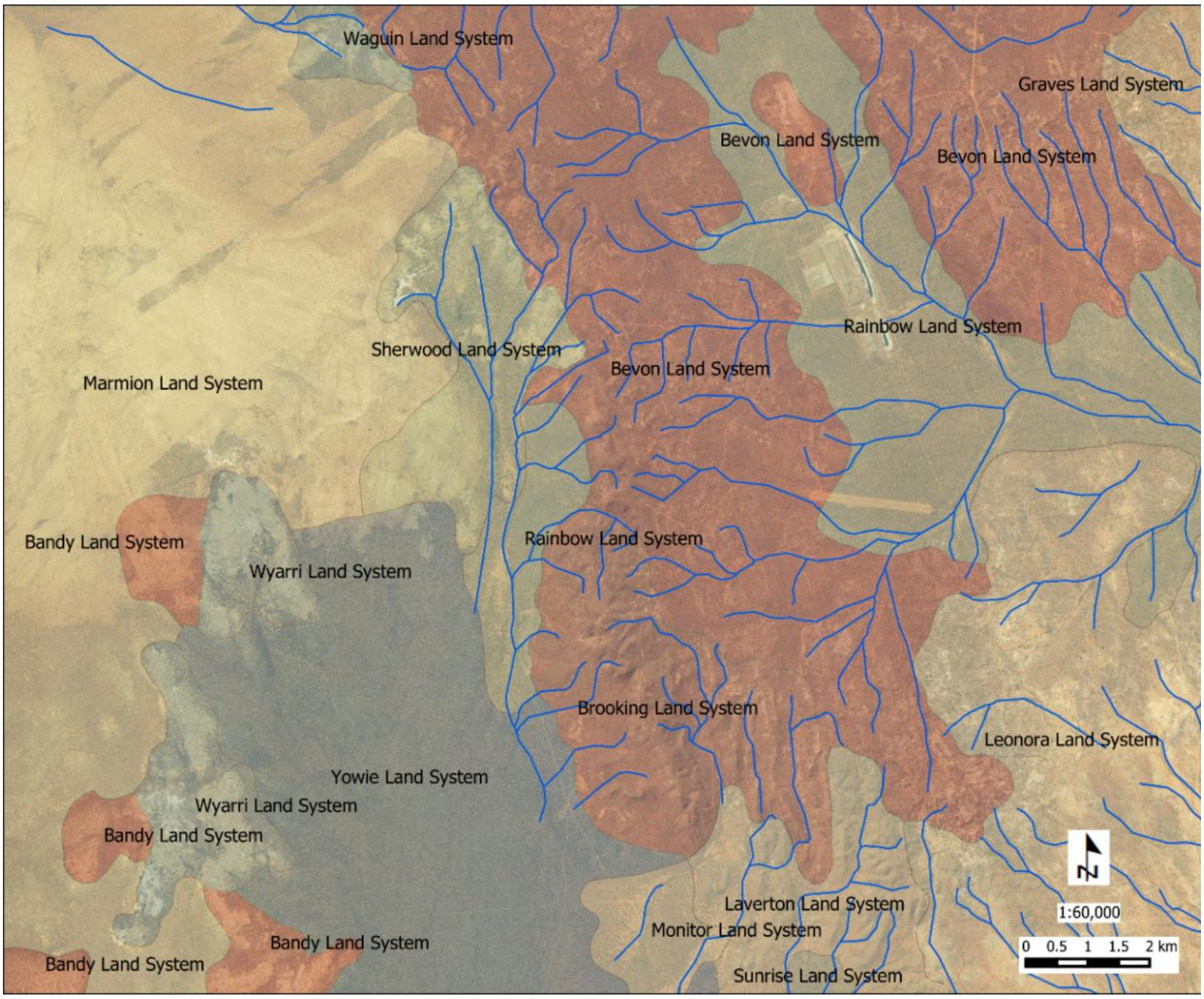

Figure 8. An example of aerial imagery relative to a suite of land systems. Note that land systems such as Bevon, Rainbow, Laverton, Graves and Leonora, which were assigned a high or medium probability of sandalwood occurrence, are generally associated with drainage systems and less impacted by fire. Land systems which were assigned a lower probability of sandalwood occurrence are generally impacted by recurring fires, for example, Marmion (top left where repetitive fire scarring is apparent) or absence of drainage lines (for example, the Yowie Land System).

4.2.2 Fire history

Fire history geospatial data were considered in relation to land systems and vegetation associations (Figures 9 and 10). The source data was Landsat imagery, downloaded from Digital Earth Australia (DEA) Sandbox, then re-projected from Universal Transverse Mercator (UTN) to Australia Albers (GDA94).

Vegetation that is more prone to relatively frequent fires, for example, spinifex grasslands (approximately 6–25-year intervals between fires) or sand plain shrubland vegetation (approximately 8–50-year intervals), generally does not support stands of sandalwood, except infrequently in areas that have escaped fire for long enough to allow establishment and maturation of sandalwood. These temporary fire refugia are generally found along the interface of fire-prone and less fire-prone vegetation, or in isolated pockets of the former, where the main pathways of frequent fires, which generally align with prevailing summer winds, are interrupted by topographical features such as salt lakes or less fire-prone vegetation (for example, Salmon gum [*Eucalyptus salmonophloia*] over bluebush). The Bullimore Land System and its equivalent Beard's vegetation association, 'hummock grasslands', are examples of vegetation units that generally burn too frequently to support representative populations of sandalwood (Figure 9).

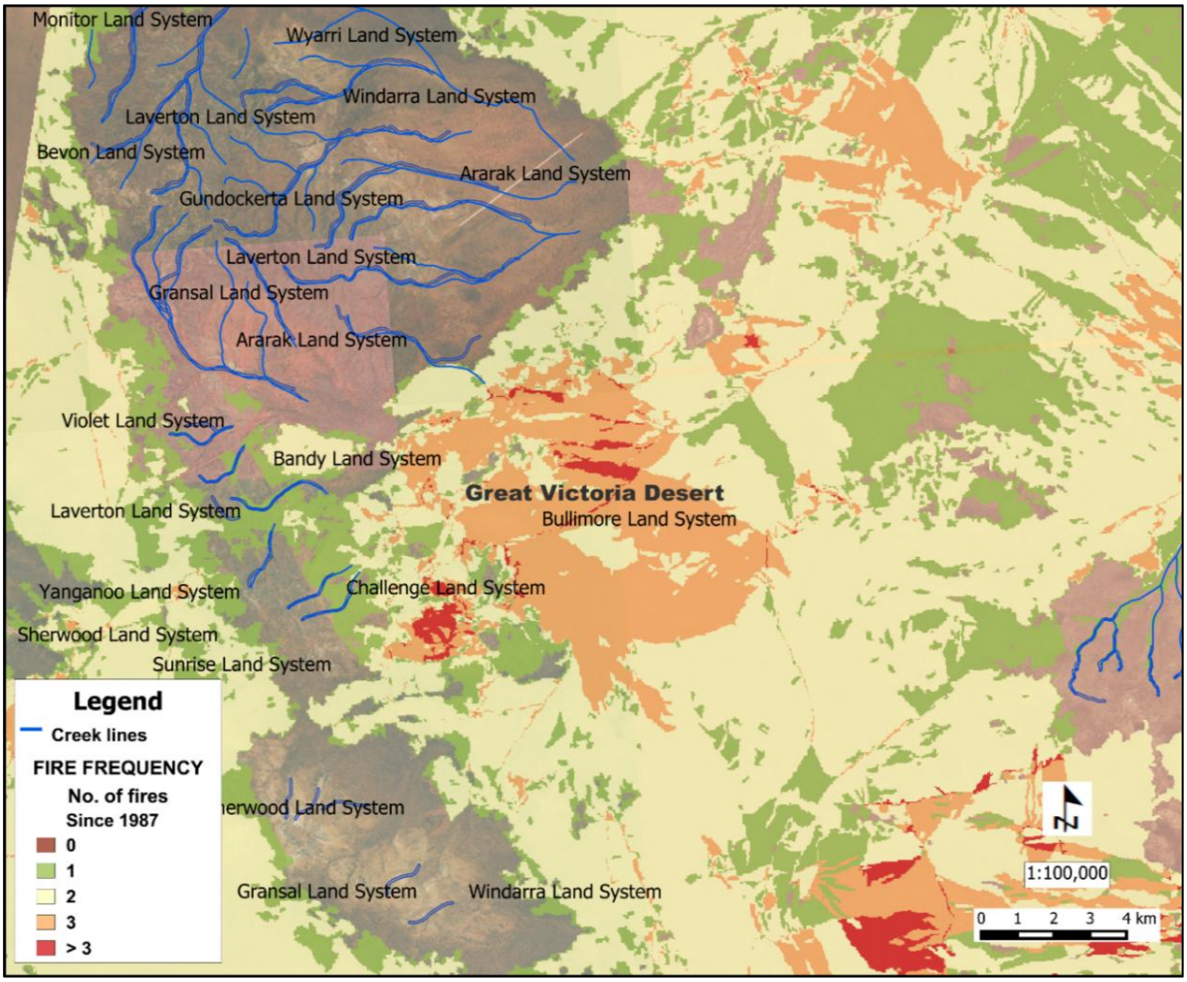

Figure 9: Fire history in relation to land systems dominated by spinifex in the Shield IBRA subregion.

Areas intersected by any fire scars were excluded from the dataset. This approach reduced the risk of overestimating the spatial extent of sandalwood habitat potentially suitable for sandalwood harvesting. An example of potential over-estimation would be to ubiquitously assign a high probability of sandalwood occurrence to sand plain vegetation which covers extensive areas of the Southern Cross and Eastern Goldfields IBRA subregions. Although sandalwood can occur in long unburnt sand plain vegetation, these areas are generally along the ecotone between woodland and sand plain or as isolated patches within the latter, which escape too frequent fire. Without excluding those areas with mapped fire history, too large an area of sandalwood habitat would be estimated for this vegetation association (Figure 10).

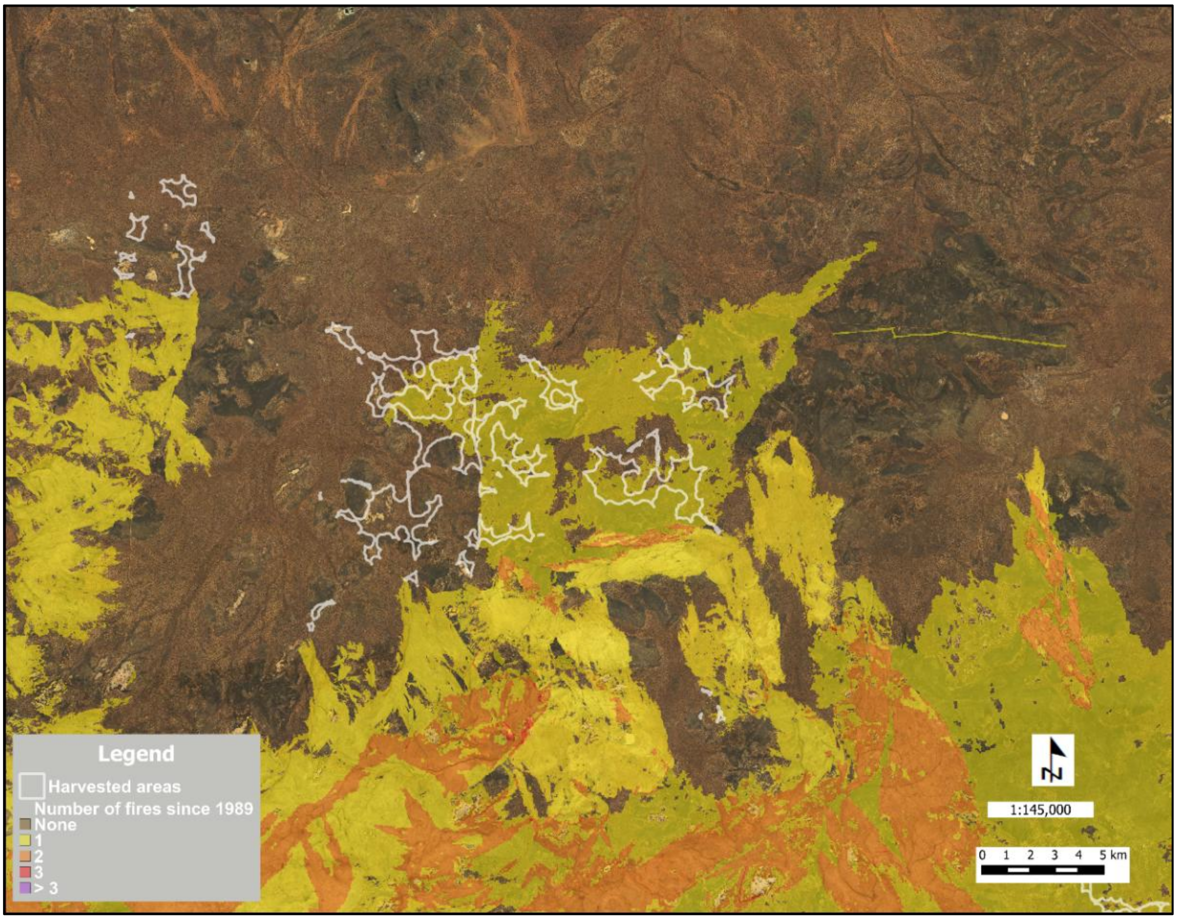

Figure 10. Aerial imagery of an area in the Southern Cross IBRA subregion illustrating the relationship between sandalwood habitat occurring along the ecotone of homogenous woodland (light brown areas) and sand plain (dark brown/grey patches) and fire history. The white polygons represent areas in which sandalwood has previously been harvested and which are generally isolated patches within woodland or along the ecotone with senescent sand plain vegetation. The contiguous expanse of sand plain to the south, burns too regularly to support significant stands of sandalwood.

4.2.3 Estimation of potential sandalwood habitat

4.2.3.1 Semi-Arid Rangelands and Eastern Murchison

Estimates of potential sandalwood habitat extent, as determined through stratification, are presented in Table 2 and depicted in Figure 11. Areas identified as available for harvesting exclude land under formal conservation tenure (managed by DBCA) and areas harvested since 2012.

In the Semi-Arid Rangelands (Southern Cross and Eastern Goldfields IBRA subregions), habitat classification included both ‘Medium’ and ‘High’ probability categories due to the species' broad distribution across the landscape. Unlike regions where sandalwood is typically confined to mesic environments such as creek systems, its occurrence in these subregions is more widespread. Notably, the total area of potential habitat was significantly reduced after excluding fire-prone vegetation types, particularly sand plain vegetation and spinifex, which are highly susceptible to bushfires.

In contrast, the Eastern Murchison subregion was assessed using only the 'High' probability category, reflecting sandalwood's stronger association with mesic creek systems in this subregion. The reduction in potential habitat due to fire risk was less pronounced due to the dominance of mulga shrublands, which are less fire-prone than sand plain and spinifex vegetation.

The stratified habitat estimates in columns 'B', 'D' and 'E' of Table 2 provide the spatial basis for extrapolating demographic variables within the population modelling approach.

Table 2. Area (hectares) of potential sandalwood habitat derived for the Semi-Arid Rangelands and Eastern Murchison regions.

Subregion grouping	Area (hectares)				
	A Areas of high/medium probability sandalwood habitat in land systems/vegetation associations	**B** Area remaining after habitats with short return fire intervals subtracted	**C** Conservation estate	**D** Sandalwood habitat on conservation estate	**E (B – D)** Net area potentially available for harvesting
Semi-Arid Rangelands	5,392,087	4,149,266	1,300,410	519,139	3,630,127
Eastern Murchison	2,949,363	2,628,168	632,942	106,717	2,521,451

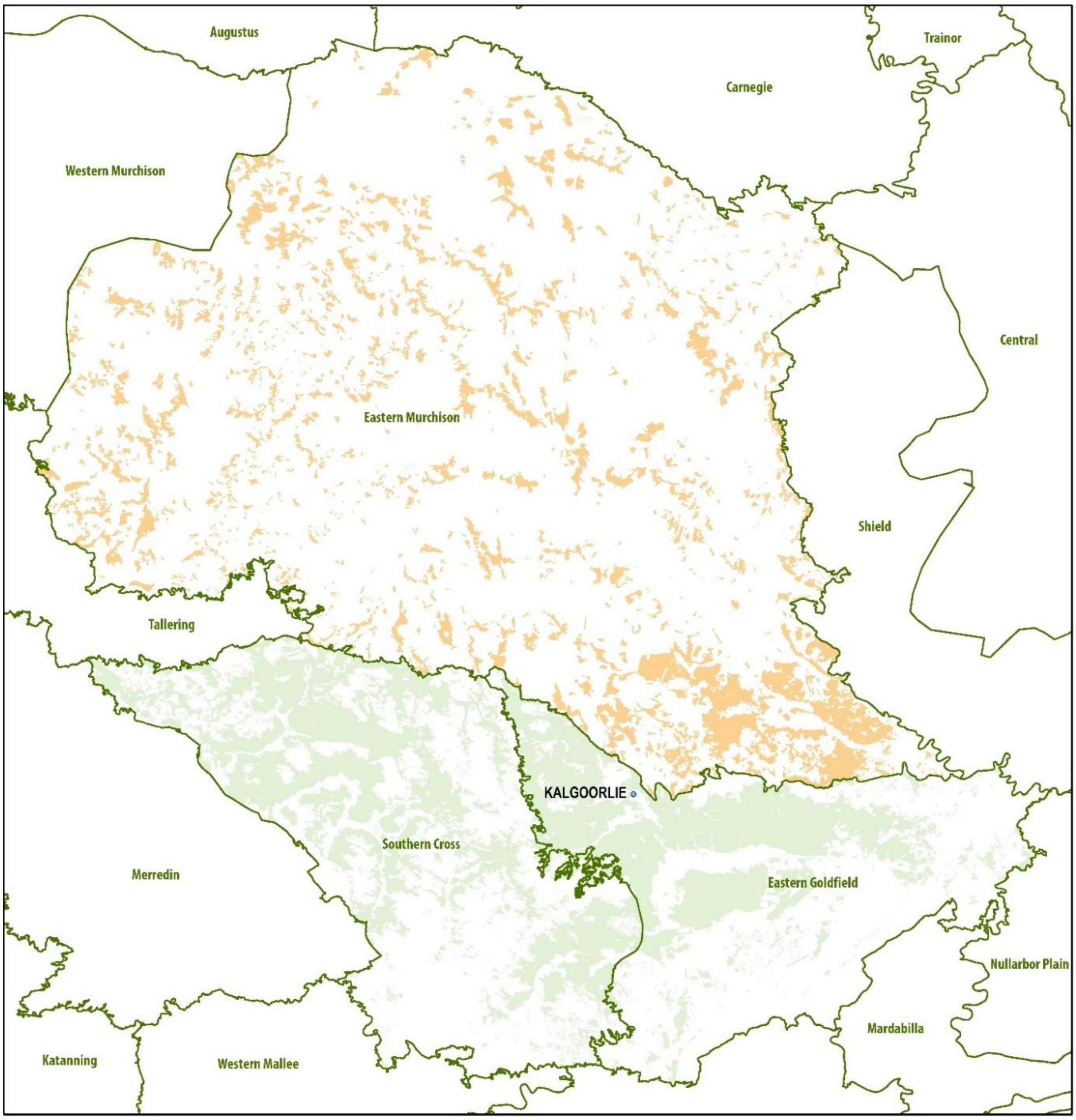

Figure 11. The extent of sandalwood habitat in the Semi-Arid Rangelands and Eastern Murchison as estimated through the stratification process.

4.2.3.2 Great Victoria Desert and Western Deserts

The area of potential sandalwood habitat was not estimated in the same manner for the Great Victoria Desert (Shield and Central subregions) and the Western Deserts groupings (Carnegie, Trainor and Lateritic Plain subregions). In these areas the coverage of land system and vegetation datasets are absent or incomplete, but independent sandalwood surveys have been undertaken (for example, Kealley, 2018, 2022; Pronk 2023a, 2023b). However, it could be expected that because these landscapes are dominated by spinifex, the short fire intervals associated with these vegetation associations play an important role in restricting the establishment and persistence of sandalwood (Figure 9). This would also likely be the case for all spinifex-dominated IBRA subregions.

Hydrology is also highly likely to influence the distribution and quality of sandalwood habitat in the arid subregions[11]. Further south within the semi-arid Great Western Woodlands[12], a Topographic Wetness Index derived from high density LiDAR datasets was a strong predictor of occurrence, size and decadal growth of eucalypt species (Battison et al., 2024). Data from the contemporary plot survey and recent sandalwood licence inventories suggest that sandalwood is more frequently found in mesic habitats such as creek lines than on the intervening xeric plains (Kealley, 2022; Kealley, 2024; Kealley and Chevis, 2022; Pronk, 2023a and 2023b). With the projected impacts of climate change (refer *Sandalwood BMP* Strategy 7), it is reasonable to expect that sandalwood populations may further contract to more mesic habitats. Accordingly, stratification of drainage systems along which water will flow or accumulate and sandalwood is more likely to persist, disperse and establish, was investigated to identify sandalwood habitat in these arid subregions. This approach was a precautionary measure to mitigate the potential risk of overestimating the area of sandalwood habitat in generally xeric landscapes.

To investigate the potential to use of creek systems as proxy indicators of sandalwood habitat within arid subregions, a Digital Elevation Model (Kovács et al., 2026) was employed to delineate hydrological features across the Great Victoria Desert and Western Deserts IBRA subregion groupings (hereafter referred to interchangeably as the ‘Desert’ regions). Creek systems were then classified using the Strahler stream order method (Strahler, 1952), resulting in 10 distinct stream orders. First-order creeks, which have the highest elevation and steepest gradients within catchments and may function as sandalwood seed banks (seeds are likely to be dispersed downstream during flooding events), were delineated with a 10-metre buffer to define their spatial extent. Given their ecological sensitivity, areas within the 10-metre buffer were excluded from subsequent calculations of suitable habitat potentially available for harvesting, and this will be considered as a condition in any potential future licences.

Creeks of second to eighth order were spatially defined using progressively wider buffers—20, 40, 60, 80, 150, and 200 metres respectively—reflecting their increasing size and lower elevation within the catchment. Stream orders greater than eighth-order creeks were excluded when calculating sandalwood habitat as they represent large river systems along which sandalwood is generally not associated.

The resulting area estimates delineate provisional zones of potential ‘Medium or High’ probability sandalwood habitat occurrence and harvestability within these Desert regions. These second to eighth order zones, sometimes referred to as buffered areas for spatial analysis purposes, are not excluded from harvesting; rather, they represent the areas most likely to be targeted for potential harvesting and seeding efforts. The buffer widths were based on limited field observations and remote sensed vegetation extent, but will be validated and refined through further field measurement.

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[11] The transition from the semi-arid to arid subregions (and rangelands) is thought to closely approximate the long-term average rainfall of 250 mm per year (Sawyer, 2013; dcceew.gov.au/environment/land/rangelands).

[12] The Great Western Woodlands, covering almost 16 million hectares in the southern Goldfields, contain the largest remaining area of intact temperate (Mediterranean-climate) woodland on Earth. This eucalypt-dominated woodland region largely overlaps with the Semi-Arid Rangelands and stretches from the edge of the Wheatbelt to the pastoral lands of the mulga country in the north, the inland deserts to the northeast, and the treeless Nullarbor Plain to the east.

The licence inventory data were used to estimate the number of sandalwood stems exceeding 127 mm in diameter—the minimum legal harvest size—within the delineated zones. This approach enables a more informed evaluation of the potential impacts of harvesting on population structure and condition, ensuring that any inferences regarding harvest limits were not made in the absence of empirical evidence. A summary of the stratified area estimates is presented in Table 3, while Figures 12 and 13 depict the spatial distribution of creek systems and associated buffer zones.

When considered alongside the licence inventory data, the area estimates offer a first approximation of potential habitat extent and illustrative example of current sandalwood population condition in a portion of these subregions. Similarly, while extrapolation of the inventory data across the broader subregional scale has been attempted (see Section 5.2 Desert regions) to inform preliminary assessments of the order of magnitude of standing resource, such extrapolation to broader subregional scales is regarded as illustrative only.

Table 3. Area (hectares) of 'Medium or High probability' sandalwood habitat for the Great Victoria Desert and Western Deserts IBRA subregions as derived from buffering the creek line stratification.

IBRA subregion	**A** Total area of IBRA subregion	**B** Total area of creek systems ('Medium or High probability' of sandalwood habitat)	**C** Area remaining after habitats with short return fire intervals subtracted	**D** Sandalwood habitat on conservation estate	**E (B-C-D)** Net area available for harvesting
Shield	6,225,854	445,673	251,273	14,570	236,703
Central[1]	16,151,181	823,278	434,897	50,459	384,438
Carnegie	5,841,111	452,739	227,855	46,572	181,283
Trainor[1]	12,178,046	337,594	131,487	0	131,487
Lateritic Plain[1]	15,432,240	450,184	326,248	52,222	274,026

[1] Note: In the Central, Trainor and Lateritic Plain subregions (within Figure 12), East-West and North-South axes were used to demarcate the potential geographic extent of 'Medium or High probability' sandalwood habitat. The areas North and East of the axes respectively, are considered too fire prone and too arid to support 'Medium/High probability' sandalwood habitat.

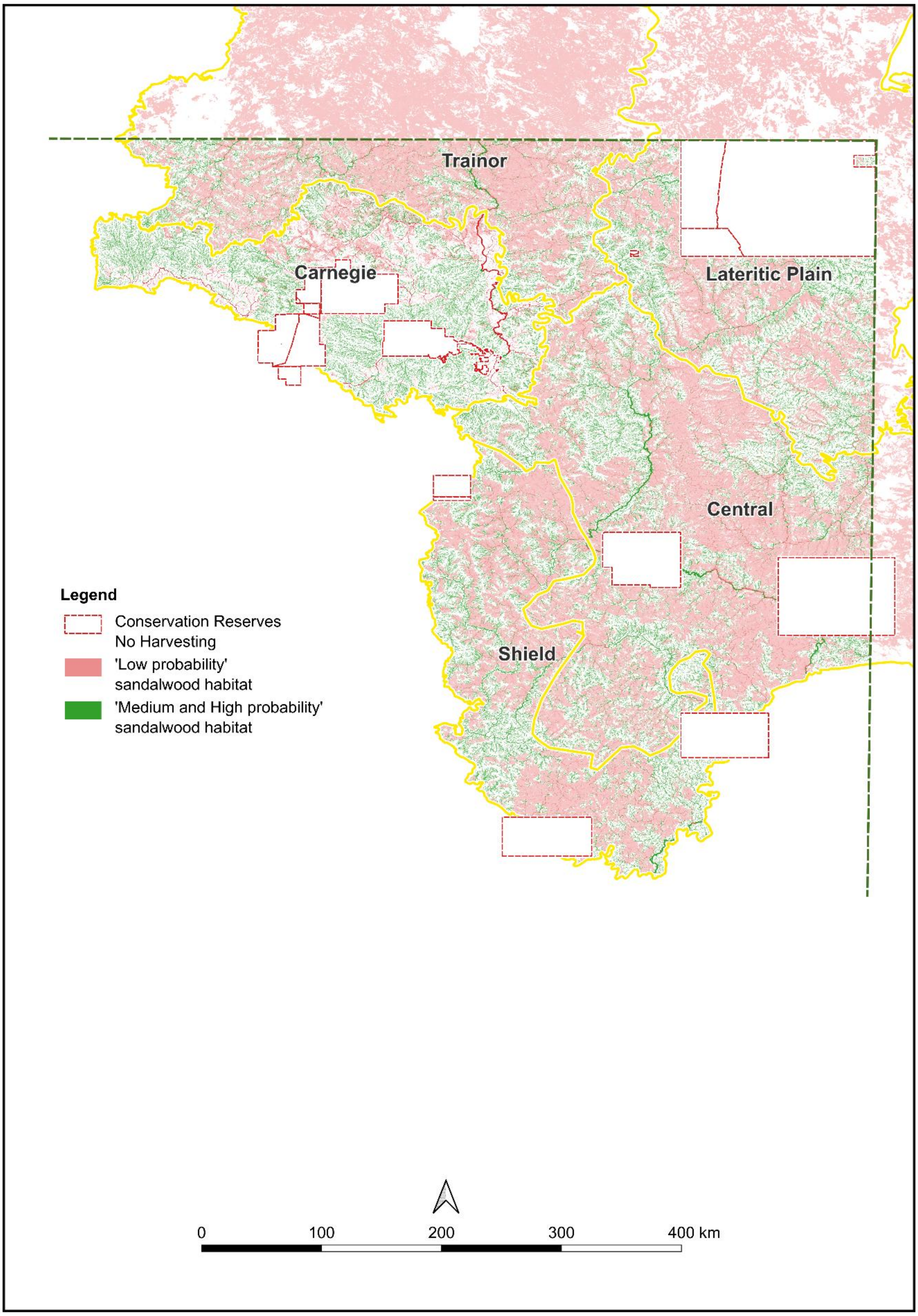

Figure 12. Stratification of the Great Victoria Desert and Western Deserts IBRA subregion groupings using the Strahler stream classification system (Strahler, 1952).

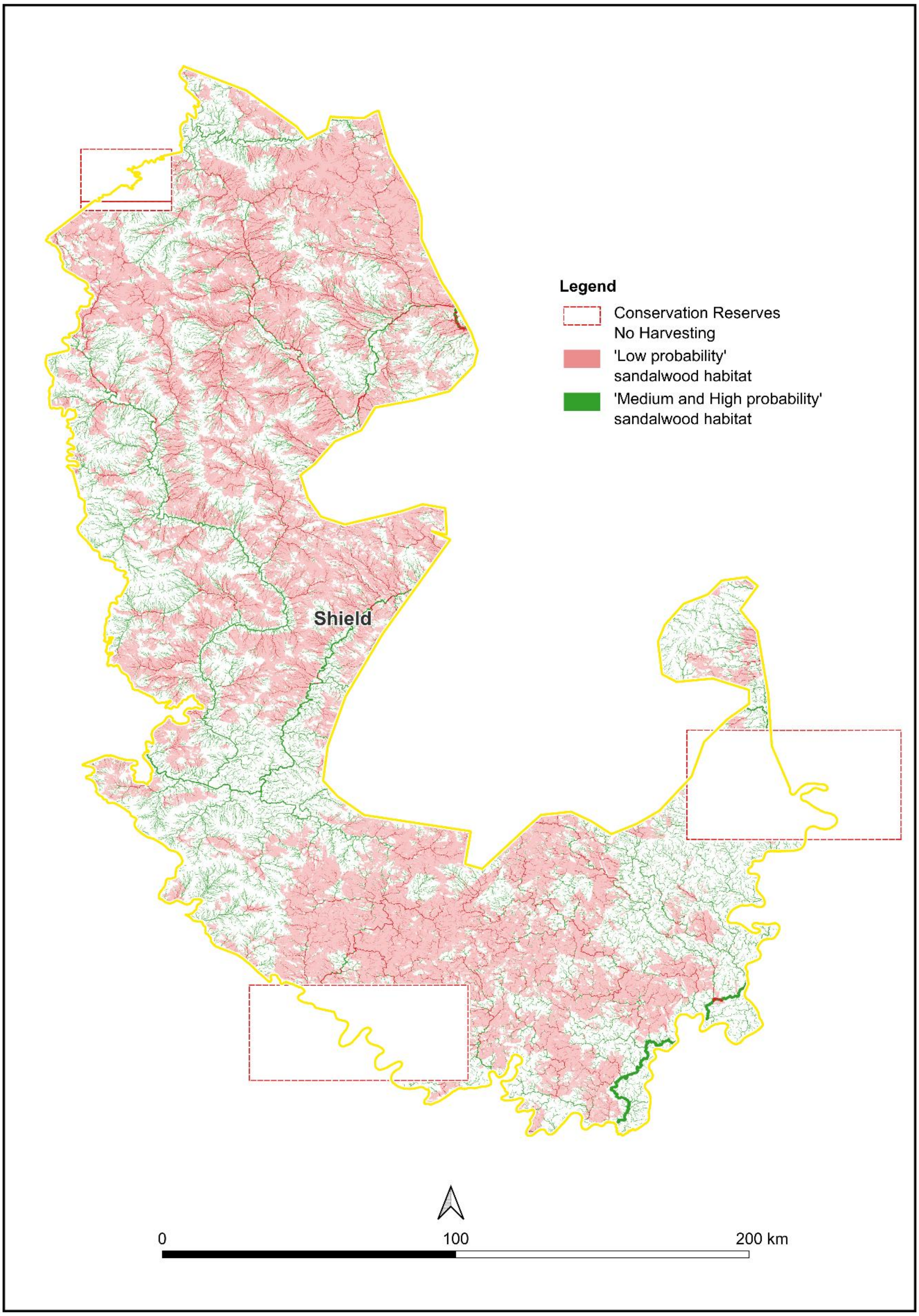

Figure 13. Illustrating the net area of 'Medium/High probability' sandalwood habitat in the Shield IBRA subregion after fire-prone areas ('Low' probability) and conservation estate are excluded.

4.3 Analysis of sandalwood population demographics

The key data collected during past inventory and the contemporary DBCA field survey were stem diameters (measured at 150 mm above ground level) of individual living and dead sandalwood trees. Stem diameters have been found to be a workable proxy for estimating tree age and growth and therefore in understanding population demography for long-lived tree species (Boland and Sinclair, 2014; Lange and Sparrow, 1992).

4.3.1 Expected natural population structure

Viable populations of wild sandalwood (in the absence of introduced grazing pressures and presence of native mammal dispersal vectors) would generally be expected, at a landscape scale, to have tree diameter size class distributions where there is a sufficient density of younger trees to replace the current older cohort. In natural forest and woodland populations with continuous recruitment by natural regeneration this pattern is characterised by a negative exponential distribution (or inverted-J shape distribution) for the frequency of trees within diameter classes (Philip, 1994). This pattern is considered an indicator of long-term structural viability of tree populations (Rubin et al., 2006).

Size class distributions expected to be compatible with the maintenance of structural viability of sandalwood populations, as compared with the contemporary plot data are shown at Figure 14. The 'expected values' depicted in each histogram in Figure 14 were derived by extrapolating the 100–126 mm classes in the contemporary plot data both forward and backward in time, using default mortality rates (see Section 4.4.2.9 Mortality rates), on the basis that this cohort is representative of the natural population distribution prior to the historic impacts of harvesting, introduced grazing, and loss of seed-caching fauna in these landscapes.

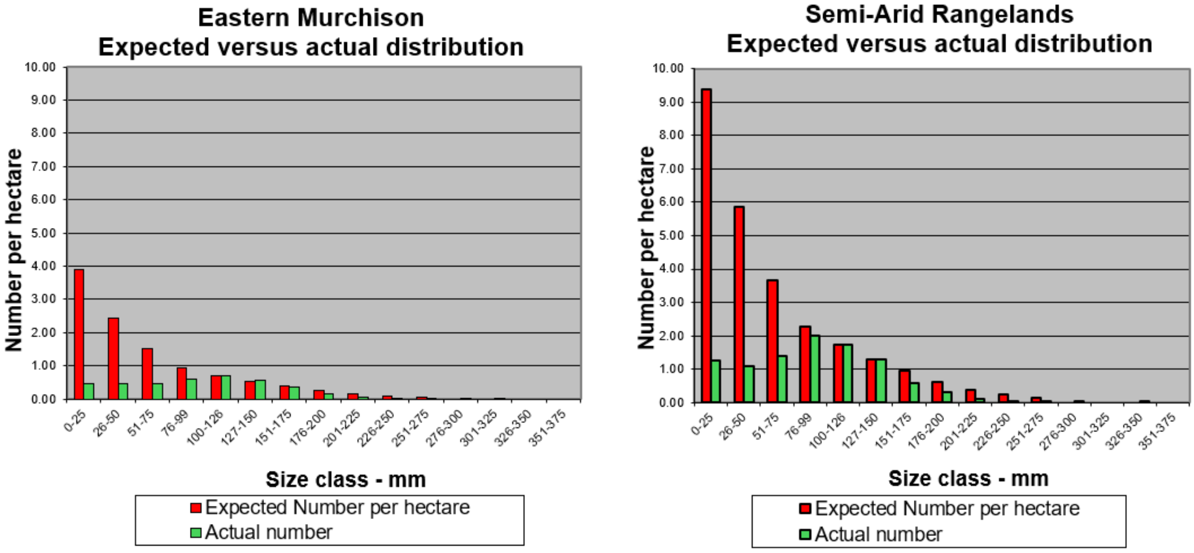

Figure 14. Population structures expected to be compatible with the maintenance of structurally viable populations (if only natural mortality rates are considered), in comparison to actual size-class data in two IBRA region groupings.

The current size class distributions highlight a deficit of young (small) trees, approximately an order of magnitude lower in the Semi-Arid Rangelands and fourfold lower in the Eastern Murchison, than the thresholds required to eventually replace the older cohorts as they senesce. These patterns imply that in the absence of enhanced recruitment, the long-term structural viability of these populations is at risk. The paucity of natural recruitment in sandalwood populations has previously been documented by various authors (Anderson, 2005; Brand, 1999; Kealley, 1991; Loneragan,1990; McLellan and Watson, 2022; Williamson, 1982).

4.3.2 Assessment of current population condition

The current condition of sandalwood populations was assessed through a series of analyses involving:

- comparison of the current population structure to the expected natural structure (without anthropogenic disturbances);
- population structure within and between the IBRA subregion groupings;
- comparison of the proportion of living stems to dead stems;
- assessment of regeneration cohorts;
- analysis of population demographic trends over the past three decades; and
- interpretation of the relevance of stream zone habitat to sandalwood distribution.

While a total of 317 contemporary plots were measured, different subsets of the plot dataset were used for some of the statistical comparisons. For example, only 267 plots were used to statistically compare the diameter size class structures in subregions, with the 13 plots in Tallering and Wheatbelt subregions excluded because of the low level of replication (n = 5–8 plots). The 28 plots from the enrichment seeding stands at Karramindie, Scahill and Yallari were also excluded from the analyses described below because although they provide valuable information on regeneration potential in these sites, their historic seeding treatments were not considered representative of the broader population. Importantly, the contemporary plots did not sample areas mechanically seeded through the Operation Woylie program (see Section 4.3.5 Enhancing and restoring regeneration through seeding) so the following analyses of population demographics will underestimate the total pool of regeneration present in the regions.

4.3.2.1 Eastern Murchison and Semi-Arid Rangelands population structures

The current sandalwood population structure in each subregion provides the basis for projecting future changes arising from natural processes and management actions. Comparison of the contemporary structures between the Eastern Murchison and Semi-Arid Rangelands regions is also important to better understand the biogeography of sandalwood and the potential impacts of a drying climate across the distribution of the species.

Given the low level of replication, the statistical analyses only compared total stem densities between groupings, without considering an interaction with diameter class. A generalised linear mixed effects model was fitted where the response variable was total stems per hectare, the predictor variable was region, there was a random effect of property, and the Tweedie error distribution was used, which is appropriate for zero-inflated continuous data (Jorgensen, 1997; Tweedie, 1984).

Mean total living stems per hectare was almost three-fold higher in the Semi-Arid Rangelands (mean±SE [54 plots] = 10.25±1.17) compared to Eastern Murchison (3.84±0.53 [213 plots]) and this difference was statistically significant ($P < 0.001$).

The highest living stem densities for both the Eastern Murchison and Semi-Arid Rangelands occurred in the 26–126 mm size class, followed by 127–195 mm, 0–25 mm and >195 mm (Figure 15). These patterns were also evident when 25 mm diameter classes were used for plotting (Figure 16). These distributions suggest there are sufficient sandalwood trees in the 26–126 mm cohort to progressively replace the trees in the 127–195 mm cohort should there be removals through natural mortality or an appropriately managed harvest. However, the low representation in the 0–25 mm class raises concerns about long-term population viability. Without sufficient recruitment into this smallest size class, the 26–126 mm cohort will eventually decline as individuals transition into larger classes, leading to structural collapse over time. This bottleneck in early recruitment limits the capacity for sustained regeneration and replacement.

The current structure suggests that approximately one tree per hectare in the Eastern Murchison and four trees per hectare in the Semi-Arid Rangelands could transition from the 26–126 mm to the 127–195 mm class. Thus, while the mid-size cohort appears adequate for short to medium-term replacement, the lack of juvenile stems poses a significant risk to long-term structural and demographic stability.

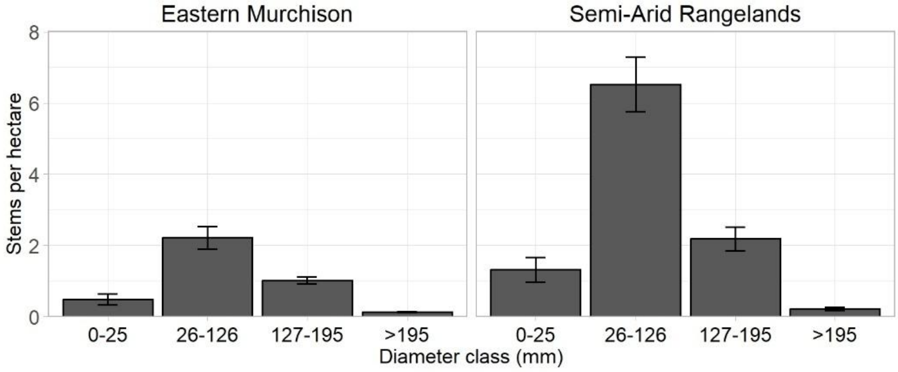

Figure 15. Mean density of living sandalwood stems in four diameter classes in the contemporary monitoring period (2022–2024), stratified by region. Error bars represent standard errors.

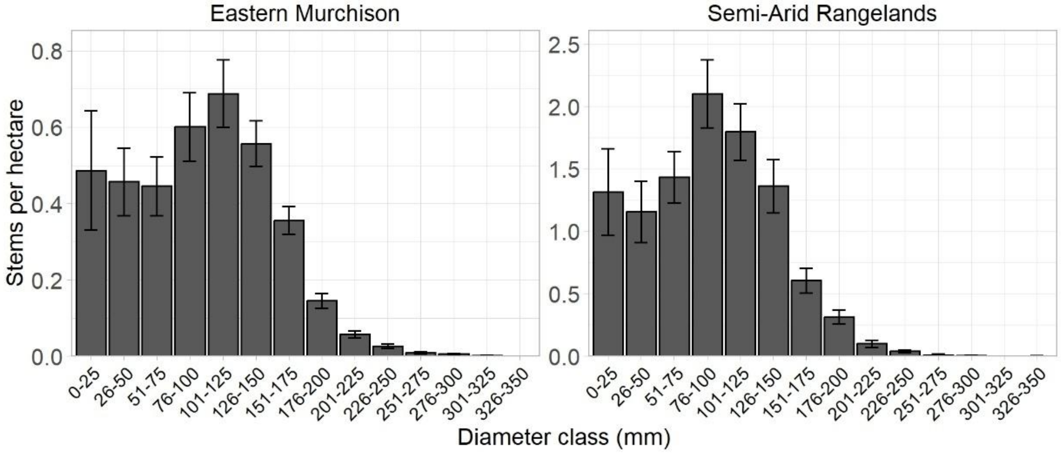

Figure 16. Mean density of living sandalwood stems in 25 mm diameter classes in the contemporary monitoring period (2022–2024), stratified by region. Error bars represent standard errors. Note that the y-axis scales differ between panels.

4.3.2.1.1 Comparison of the proportion of living stems to dead stems

The condition of sandalwood populations was also assessed using the ratio of living to dead trees as a key ecological indicator (FAO, 2020; Hill et al., 2019; McLellan and Watson, 2022). The living-to-dead stem ratio may serve as a practical and scalable indicator of sandalwood population condition and can be used in the long-term monitoring program to track changes in population dynamics and resilience. The living-to-dead tree ratio will also provide insights to inform sustainable harvesting limits and regeneration practices and is essential for predicting future population dynamics under various scenarios.

Dead stems, using data collected during the contemporary survey, were classified into three categories based on their physical characteristics, which serve as proxies for the time since mortality: (1) 'dead with bark'—recently deceased trees, likely within the past two decades; (2) 'dead grey'—intermediate-aged dead stems, characterised by bark loss and greying; and (3) 'dead withered'—the oldest class, exhibiting advanced decay and structural collapse of a tree. This stratification was intended to infer temporal patterns of mortality and to facilitate interpretation of potential causal factors. A predominance of stems in the 'dead with bark' category may indicate recent mortality events such as the millennial drought of the early 2000s and potentially be linked to emerging environmental pressures such as increased aridity associated with climate change.

To explore these patterns, histograms were constructed depicting stem counts across 25 mm diameter classes for each of four categories (living, dead with bark, dead grey, dead withered) using the contemporary monitoring data. In the Eastern Murchison, dead withered stems (n = 2,126) were more common than dead with bark (n = 975) and dead grey (n = 556) stems (Figure 17). Dead with bark stems tended to be larger (median diameter = 112 mm [range = 9–319]) than dead grey (80 mm [19–230]) and dead withered (64 mm [6–284]) stems. There were 5,566 living stems in the Eastern Murchison, with a median diameter of 100 mm (range = 1–307). In the Semi-Arid Rangelands, the numbers of stems that were dead with bark (n = 286), dead grey (n = 301) and dead withered (n = 383) were broadly similar (Figure 17). Dead with bark stems again tended to be larger (85 mm [5–206]) than dead grey (55 mm [1–211]) and dead withered (55 mm [10–155]) stems. There were 4,047 living stems in the Semi-Arid Rangelands, with a median diameter of 82 mm (1–350).

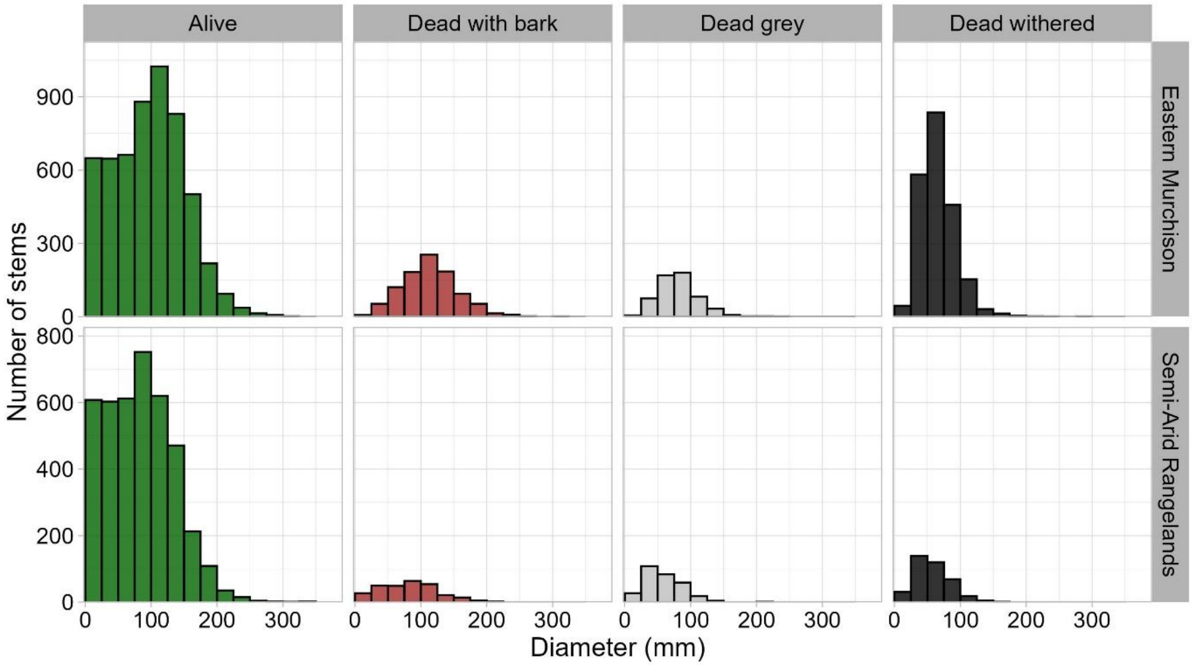

Figure 17. Histograms of stem counts in 25 mm diameter increments for four categories of living/dead. Separate panels are provided for the Eastern Murchison (top) and Semi-Arid Rangelands (bottom). Note that the y-axis scales differ.

The mean proportion of all stems that were living per plot was lower in the Eastern Murchison (0.49) compared to the Semi-Arid Rangelands (0.79), whereas the mean proportion ‘dead with bark’ was higher (0.12 cf. 0.05), as was the mean proportion ‘dead withered’ (0.29 cf. 0.09; Figure 18). The mean proportion ‘dead grey’ was ~0.07 in both regions.

The results are relevant when considering the potential impacts of a drying climate. There have been anecdotal reports of recent mass mortalities in sandalwood populations in the Eastern Murchison, apparently caused by prolonged drought conditions (B. Sawyer, personal communication, 5 August 2024). This may provide context to the observations of the decline in mean living stem density in the Eastern Murchison shown in Figure 19.

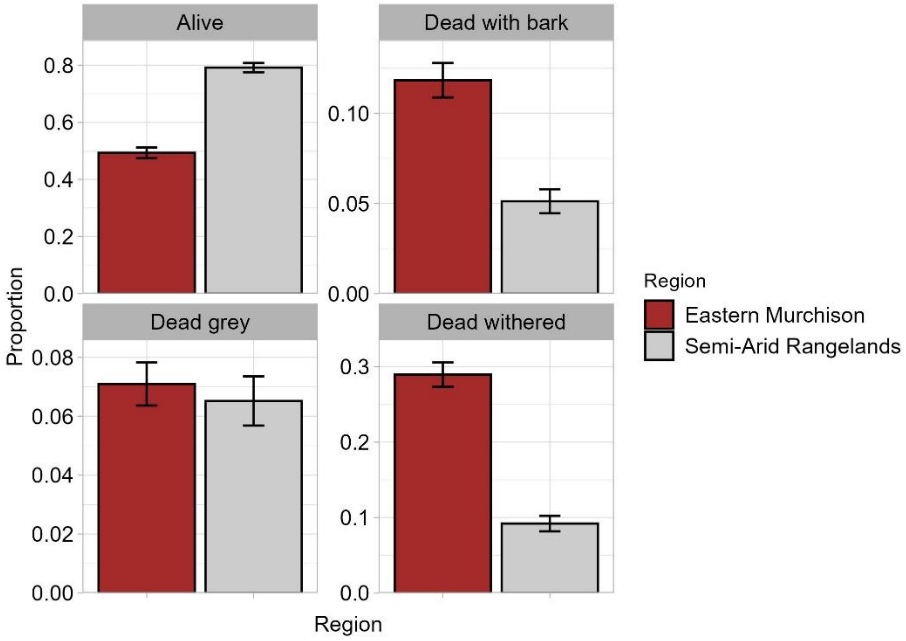

Figure 18. Mean proportion of all stems per plot in different living and dead categories, stratified by region. Error bars are standard errors. Note that y-axis scales vary between panels.

4.3.2.1.2 Assessment of regeneration cohorts

A key additional indicator of sandalwood population condition is the presence and size distribution of young and juvenile trees (collectively comprising the regeneration cohort) across plots within each region. The percentage of plots per region with stems present in the regeneration class (0–25 mm) was 69 per cent for the Semi-Arid Rangelands and 27 per cent for the Eastern Murchison. On average, five per cent of all living stems per plot were regeneration size in Eastern Murchison plots, whereas the figure was nine per cent for the Semi-Arid Rangelands.

These statistics should be interpreted with caution given the original plot selection for the 2022–2024 assessment was biased toward plots with higher stem densities in 1990–2003, but they do indicate that regeneration and natural recruitment has occurred in these landscapes over the measurement period. In general, landscape seeding programs are likely to be more successful in the Semi-Arid Rangelands, but if recruitment to promote structural viability of local populations in the Arid Rangelands (including Eastern Murchison) is to be undertaken, efforts should be targeted to more mesic habitats, such as creek lines and mulga groves (Kealley and Chevis, 2022; Kealley, 2024).

4.3.2.2 Great Victoria Desert and Western Deserts population structures

The population data from the sandalwood licence applications in the Great Victoria Desert and Western Deserts subregion groupings were analysed, recognising that any interpretation of the results should consider that the inventory areas (Kealley, 2018, 2022; Kealley and Chevis, 2022; Pronk, 2023a, 2023b) were spatially clustered and may not be representative of the broader subregions. Data comprised counts of living stems in 28 survey areas/zones in the Great Victoria Desert region and 18 in the Western Deserts, which were standardised as stems per hectare. Due to the nature of the available data, the diameter classes used here differ slightly to those used earlier in this document. To facilitate comparisons with the past inventory and DBCA data sets, the relevant data were pooled at 25–125 mm and then plotted as mean stems per hectare across four diameter classes.

Mean living stem densities (±SE) per survey area/zone were 2.16 (±0.49) per hectare (range = 0–13.60) for the Great Victoria Desert and 1.80 (±0.38) per hectare (range = 0.41–5.31) for the Western Deserts. Similar to elsewhere, mean stem densities were highest in the 25–125 mm diameter interval and lowest in the 0–24mm and >174 mm intervals for both the Great Victoria Desert and Western Deserts (Figure 19).

The results indicate that natural recruitment in these drier environments is markedly insufficient to offset senescence-related losses in the older cohorts, with an inevitable precipitous decline in population structural viability. Without enhanced recruitment, which may be achieved through targeted seeding operations in creek systems, sandalwood populations could become locally extinct in these areas in the long-term (see Section 4.3.5 Enhancing and restoring regeneration through seeding).

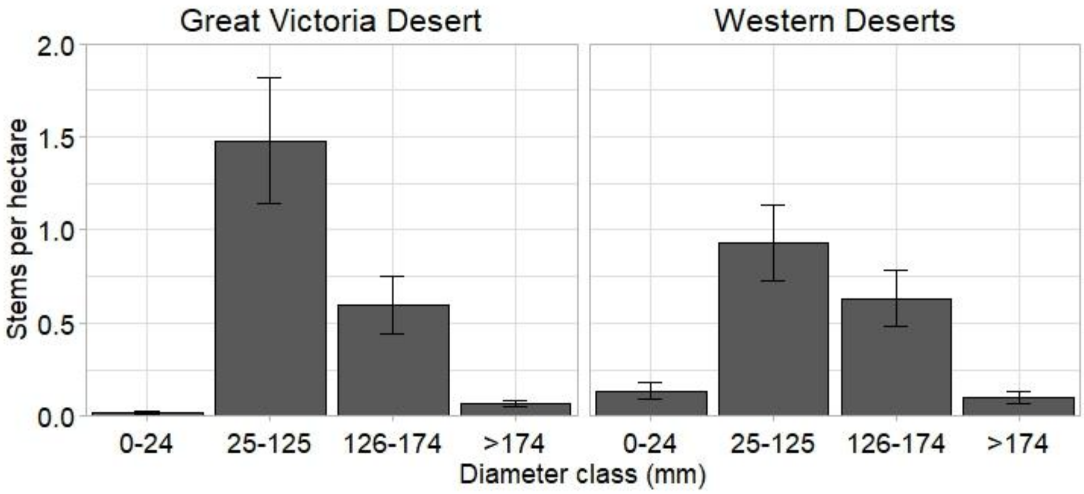

Figure 19. Mean density of living sandalwood stems in the two desert regions based on inventory data from 2018–2023. Error bars represent standard errors.

4.3.3 Analysis of population demographic trends over the past three decades

The contemporary DBCA field data were compared to the past inventory survey data to assess demographic trends over the last three decades, including changes in size class distributions, and natural regeneration. Such analyses are important for understanding the impacts of both natural and anthropogenic disturbances during this period, as well as quantifying input variables for subsequent population modelling discussed later.

The different survey techniques for the historical and contemporary plots also made direct comparisons of the data challenging. The trees in the historical surveys were tallied in different size class intervals dependent on monitoring year, while the diameter of every stem in the contemporary plots was measured. Most historical plots were four hectares (some were six hectares), while most contemporary plots were six hectares.

Analysis of any changes in stem densities over time used 229 plots for which measurements in both the historic (1990s–2003) and contemporary (2022–2024) periods were available. Both historical and contemporary data were summarised into the following stem diameter intervals for living stems: 0–25 mm, 26–126 mm, 127–195 mm and >195 mm. Dead stems were excluded. These intervals align with those used in 2001–2002 and were chosen because they enabled all relevant historical plot data to be included. This process involved aggregating the existing size classes or individual stems into the aforementioned standard intervals[13]. Due to variation in plot sizes, the data were standardised into stems per hectare for each diameter class by dividing stem counts by plot areas. Mean stem densities across the whole survey area were graphically examined to identify differences between periods, and separate graphs were also created for each region to identify any geographic differences.

Comparison of historical and contemporary data combined across the Semi-Arid Rangelands and Eastern Murchison indicates that mean living stem densities have decreased by 40 per cent on average in the 127–195 mm size class and by 50 per cent in the >195 mm size class (Table 4, Figures 20 and 21). Average declines in the two smallest size classes (0–25 and 26–126 mm) were 4–11 per cent, but with high overlap in standard errors between periods (Figure 20). A generalised linear mixed effects model provided support for this pattern through a statistically influential interaction between period and diameter class ($P < 0.001$).

Table 4. Summary statistics relating to living sandalwood stem densities in the historical (1990s–early 2000s) and contemporary (2022–2024) monitoring periods. The main values represent means ± standard errors of stems per hectare. Values in parentheses are the ranges of observed data.

Period	0–25 mm	26–126 mm	127–195 mm	>195 mm
Historical	0.75 ± 0.13 (0–14.25)	2.91 ± 0.33 (0–51.75)	1.87 ± 0.14 (0–14.25)	0.24 ± 0.03 (0–2.75)
Contemporary	0.67 ± 0.16 (0–26.25)	2.79 ± 0.32 (0–44.82)	1.13 ± 0.11 (0–15.38)	0.12 ± 0.02 (0–1.44)

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[13] One limitation of this approach is that the 10 mm increments from the 1990s included an interval of 126–135 mm, which means that stems of exactly 126 mm diameter were included in the new 127–195 mm increment rather than the 26–126 mm increment.

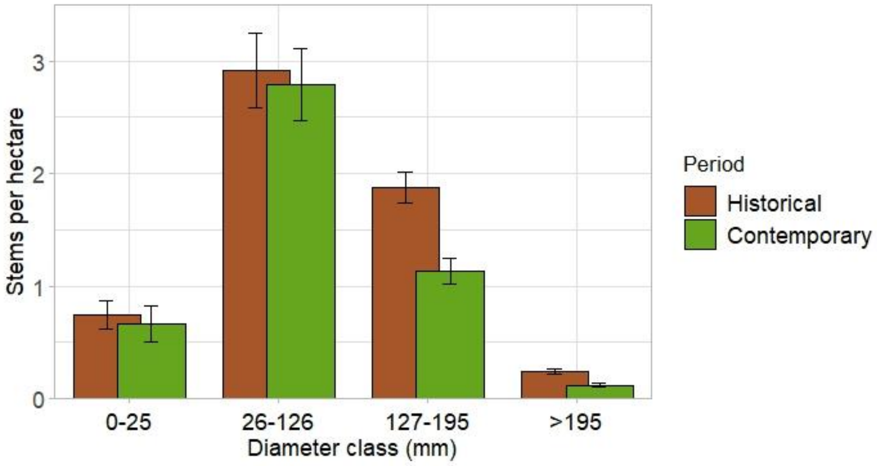


Figure 20. Mean density of living sandalwood stems in four diameter classes and two monitoring periods (past: 1990s–early 2000s; contemporary: 2022–2024). Error bars represent standard errors.

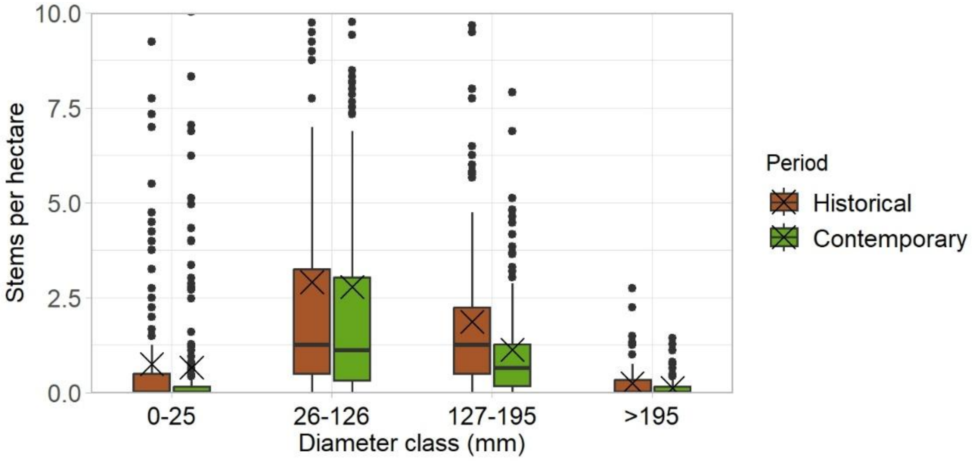


Figure 21. Box and whisker plot of living sandalwood stem densities in four diameter classes and two monitoring periods (past: 1990s–early 2000s; contemporary: 2022–2024). Black horizontal bars are medians, 'Xs' are means and black circles are outliers. Note that there are many outliers beyond the range of the plot (>10 sph), but the y-axis has been truncated to facilitate interpretation. All data were included in calculations of medians, means and interquartile ranges.

Examining the data by region shows that declines in mean living stem densities have been more pronounced in the Eastern Murchison compared to the Semi-Arid Rangelands (Table 5, Figure 22). For example, declines in mean stem density in the 127–195 and >195 mm intervals were 50 per cent and 59 per cent, respectively, for Eastern Murchison, and 14 per cent and 28 per cent, respectively, for the Semi-Arid Rangelands (Table 5). These figures likely represent the combined effects of growth, natural mortality, harvest removal and regeneration events across plots over this period. While harvesting likely occurred on many plots, distinguishing its impact from other pressures—such as grazing, historical overharvesting, and the loss of seed dispersers—is challenging with the available data. Moreover, these declines cannot be attributed solely to climate change, as multiple interacting factors are at play. Incomplete harvest records and limited unharvested control plots further constrain attribution. Therefore, observed declines should be interpreted as the result of combined ecological and anthropogenic influences, rather than any single cause.

Table 5. Average changes in living stem densities for each diameter class and region between the historical (1990s–early 2000s) and contemporary (2022–2024) monitoring periods.

Region	0–25 mm	26–126 mm	127–195 mm	>195 mm
Eastern Murchison	-8%	-16%	-50%	-59%
Semi-Arid rangelands	-14%	+10%	-14%	-28%

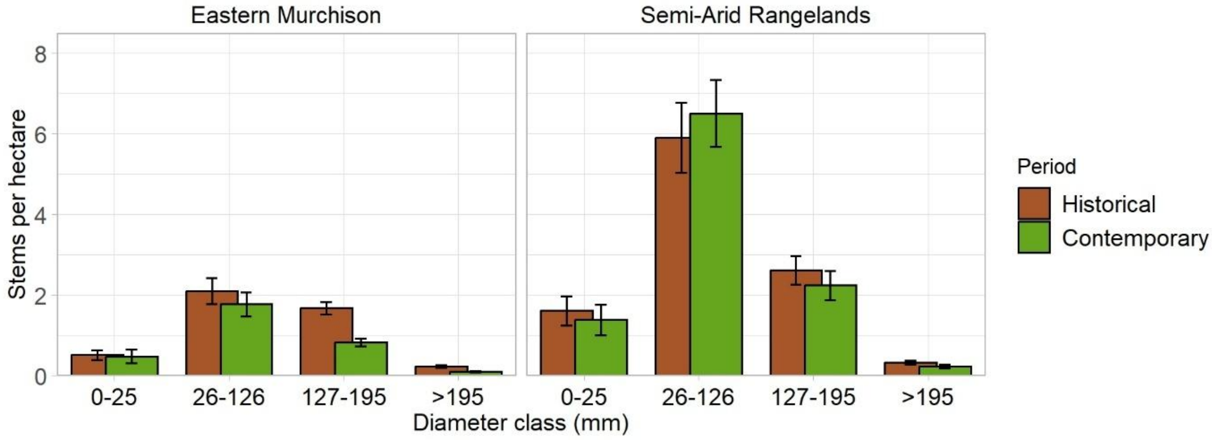


Figure 22. Mean density of living sandalwood stems in four diameter classes and two monitoring periods (historical: 1990s–early 2000s; contemporary: 2022–2024), stratified by region. Error bars represent standard errors.

4.3.4 Potential importance of stream zone habitat to sandalwood distribution

The stream plot data from the contemporary survey were analysed to test the hypothesis, based on anecdotal observations and recent survey results, that regeneration and persistence of sandalwood is higher in stream zones. The inference is that projected climate changes might cause sandalwood populations, particularly in the arid regions, to contract to creek systems over time. This analysis will enhance the understanding of how sandalwood distribution and ecology are influenced by hydrological gradients, especially concerning seed dispersal and recruitment without native seed-caching marsupials such as the woylie (*Bettongia penicillata ogilbyi*) and boodie (*Bettongia lesueur*) and the effects of a drying climate. Corroborative results would support the use of the buffered creek systems in stratifying sandalwood occurrence, and subsequent recommendations (outside the scope of this report) for conditions attached at the licencing phase for retention of seed trees in creeks, the location of seed placement and seeding programs.

Histograms of living stem counts classified by tree location (inside or outside a stream zone) were generated to visually assess the possible role of stream zones in facilitating sandalwood regeneration (Figure 23). A proportionally higher number of smaller stems in stream zones would suggest that recruitment or seedling survival is higher in these areas compared to outside stream zones. A statistical test was applied to assess whether stems in the stream zone are generally smaller than those outside of the stream zone and whether this differs between regions. The response variable was the diameter of each stem, and the predictor variables were stream zone (yes/no), region and their interaction. The model included random effects of plot nested within property and used a Tweedie error distribution.

Histograms of stem counts stratified by stream zone position indicate some differences between regions (Figure 23). In the Semi-Arid Rangelands, the smallest stems (0–50 mm) were more common in the stream zone compared to outside of it. This effect was not evident in the Eastern Murchison, although it is noteworthy that the size distribution was more uniform inside compared to outside the stream zone there (Figure 23).

A generalised linear mixed effects model showed that living stem diameters across both regions were smaller on average (P < 0.001) for stream zone trees (model estimated mean diameter [95% confidence intervals] = 97.87 mm [91.91–104.22]) compared to non-stream zone trees (108.24 mm [102.08–114.78]).

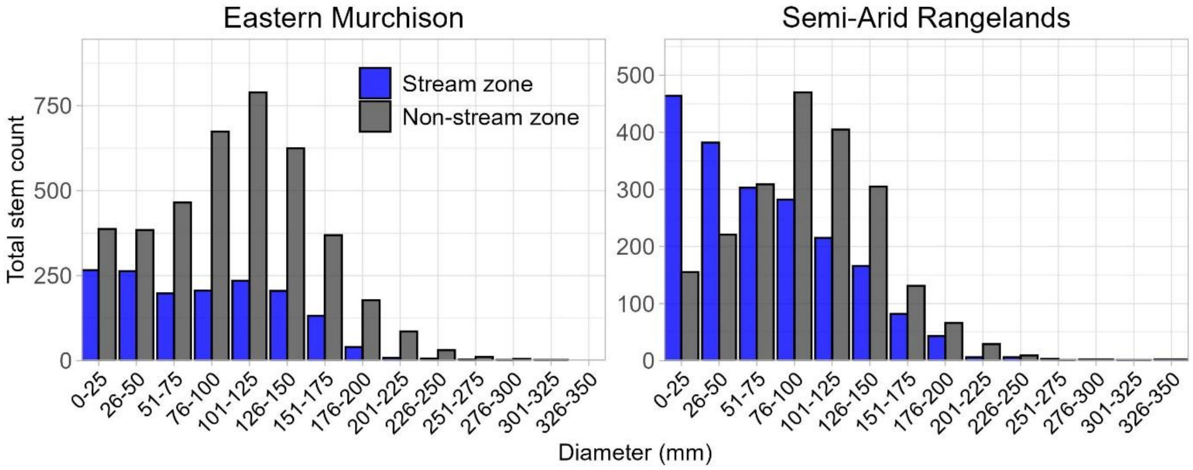


Figure 23. Histograms of living stem counts stratified whether stems occur inside (blue) or outside (grey) of stream zones using the contemporary monitoring data (2022–2024). Bin size is 25 mm. Note that the y-axis scales differ between panels.

For the contemporary monitoring program, a limited number of targeted stream plots were established along creek lines, whereas the other plots (primarily the historical plots) were positioned more broadly across the landscape. In the Eastern Murchison, the mean total living stem density (±SE) was significantly higher (P < 0.001) in stream plots (8.13 ± 2.50; *n* = 15) compared to regular plots (1.82 ± 0.29; *n* = 85). This suggests that creek line environments in this region may support higher sandalwood densities, potentially due to more favourable habitat conditions. In the Semi-Arid Rangelands, the stream plots (6.52 ±2.18; *n* = 4) had lower mean stem densities than the regular plots (9.89 ±1.63; *n* = 18), but this difference was not statistically significant (P = 0.285). This implies that sandalwood distribution in this region is more variable and not strongly influenced by proximity to creek lines.

To ensure comparisons were appropriate, the regular plots used here were in the same monitoring areas/pastoral properties as the stream plots. Plotting the data in 25 mm diameter classes shows that stream plots in the Eastern Murchison had higher mean stem densities than regular plots for all diameter classes, whereas the opposite was true in the Semi-Arid Rangelands for most diameter classes, but with high variability (Figure 24), suggesting site-specific influences beyond stream proximity influence occurrence in the higher rainfall Semi-Arid Rangelands.

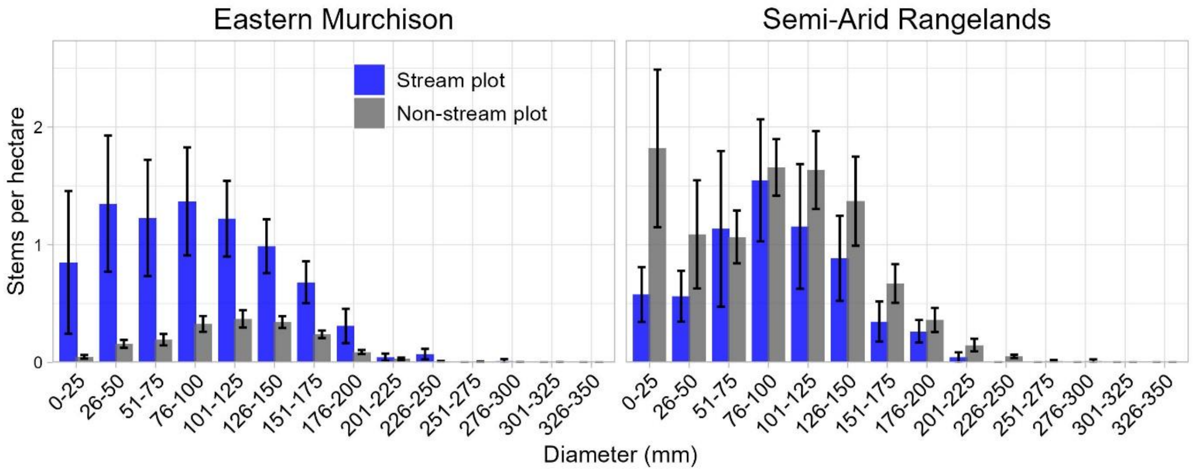


Figure 24. Mean density of living sandalwood stems in 25-mm diameter classes for stream plots and regular plots in two regions. Error bars are standard errors.

4.3.5 Enhancing and restoring regeneration through seeding

The foregoing analyses of population demographics underscore the necessity for seeding operations to augment natural regeneration to improve long-term population viability. Modelling of the scale and frequency of seeding needed (accompanied by protection from other threatening processes) to restore large landscapes to a pre-1750 condition (see Section 8 Glossary) is discussed in Section 5.1.9 (Seeding regimes required to attain pre-1750 population structures). Operational experience has demonstrated that annual seeding programs (conducted using mechanical seeding over large areas or hand seeding at localised scales) can successfully increase the proportion of younger trees in stands and improve structural viability.

Section 4.3.5.1 outlines FPC's large-scale 'Operation Woylie' program that has been underway since 2011, while Section 4.3.5.2 summarises results from hand seeding by Aboriginal people and long-term outcomes from trials of multiple seeding initiated in the 1920s by the Forests Department.

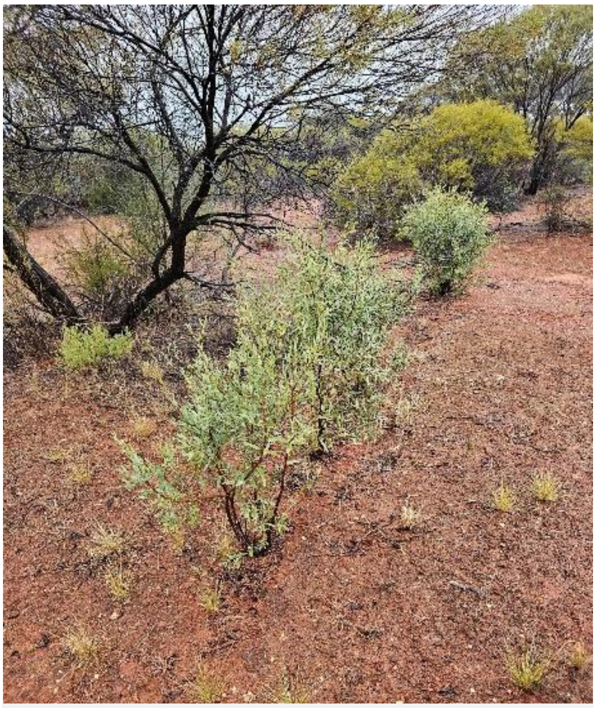
4.3.5.1 Operation Woylie

'Operation Woylie' is a mechanised sandalwood seeding program that has been implemented by FPC since 2011 (Figure 25). Each year, FPC plants over five million sandalwood seeds along approximately 1,500 kilometres of mechanical rip-lines (equivalent to around 25,000 hectares per year). Table 6 summarises the results of Operation Woylie for 2011–2023. Approximately five per cent of the distance of the total 13,000 kilometres of seeding establishment lines has been randomly sampled to measure rates of seedling establishment.

Table 6. Summary of Operation Woylie results for the period 2011–2023 inclusive.

Region groups	Seeds sown	Hectares sown	Seedlings (sown 2011–2023)	Seedlings per hectare	Seedlings per seeds (survival)
Eastern Murchison / Tallering	40,256,235	169,232	393,203	2.32	0.98%
Southern Cross / Eastern Goldfields	20,515,561	87,105	310,900	3.57	1.52%
Total	**60,771,796**	**256,337**	**704,103**	**2.71**	**1.16%**

Results of sandalwood seeding from 2001–2007 suggest that seedling survival rates exceed 2.5 per cent when exposed to average winter rainfall conditions (Sawyer, 2013). Based on these findings, Operation Woylie adopted a conservative seed-to-seedling survival estimate of 1.5 per cent to account for the anticipated benefits and limitations of mechanised seeding.



Sandalwood regeneration (approximately nine years old) from Operation Woylie mechanised seeding. *Photo – DBCA*

Machine seeding was considered more effective than hand seeding due to its capacity to sow substantially larger volumes of seed, improved cost efficiency, and significantly higher germination rates in rip-lines (Sawyer, 2013). However, it was expected that machine seeding would have less precision than hand seeding and would thus sow some seed in suboptimal microhabitats, limiting establishment success. Also considered was the likelihood that winters in the rangelands were increasingly not meeting rainfall thresholds to enable sandalwood germination and establishment.

The program was initially designed with the aim of replacing the annual harvest of trees that at the time of its inception was estimated to be approximately 50,000 trees. Therefore, with an anticipated 1.5 per cent survival level, an annual program to seed 3.5 million seeds equating to about 10 tonnes was implemented. The program subsequently increased to 20 tonnes per year.

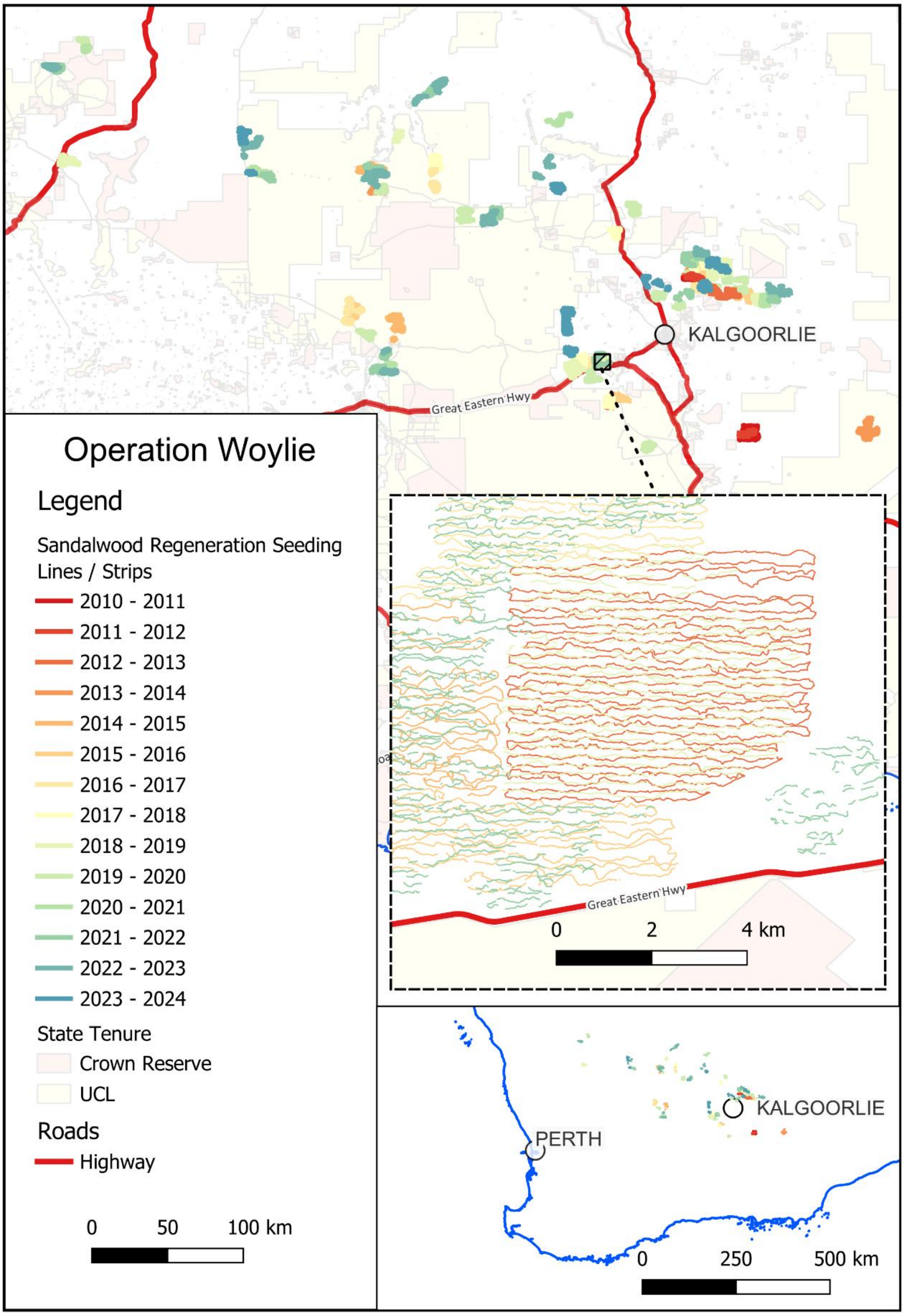


Figure 25. Map of Operation Woylie areas. This map illustrates the extent of the mechanised seeding program across a total of approximately 325,000 hectares within the Goldfields, Midwest and Wheatbelt regions, and shows an example of the intensity of seeding operations within a local area close to Kalgoorlie.

The overall survival result of 1.16 per cent reported in Table 6 coupled with increases in annual seeding programs since its inception, indicates that Operation Woylie has achieved its target of a rolling average of establishing 50,000 seedlings per year. Based on current sampling, the average annual establishment of seedlings from 2011–2023 is approximately 55,000 seedlings per year.

4.3.5.2 Seedling survival achieved through hand planting

In the 1920s, the Forests Department implemented sandalwood enrichment seeding at densities of up to 1,000 seeds per hectare across reserves in the Goldfields and Wheatbelt regions. Recent surveys (Chevis et al., 2026; Sawyer, 2024) indicate that these efforts produced 75–125 mm cohorts with stem densities exceeding those typical of natural pre-1750 populations in the Semi-Arid Rangelands (Figure 26). These findings underscore the long-term benefits of enrichment seeding and its potential applicability across the species' broader distribution.

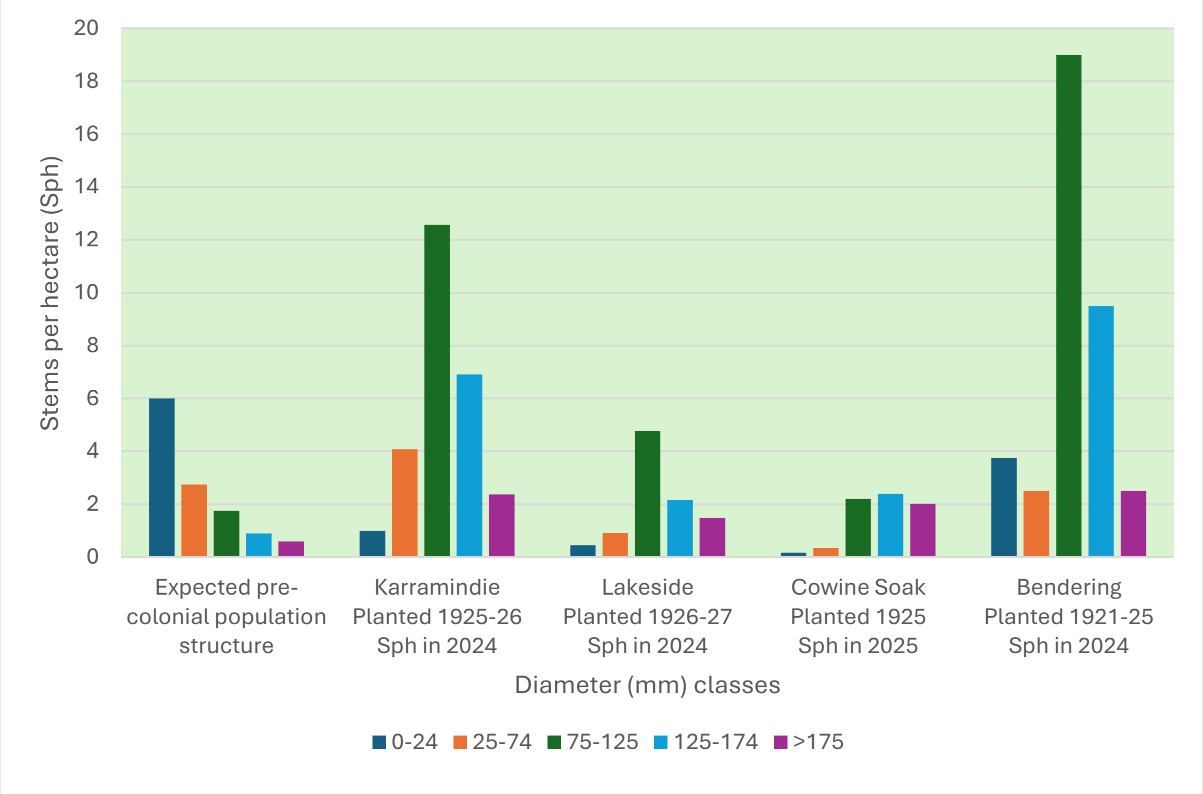


Figure 26. Comparison of four sandalwood seeding enriched populations with the expected natural population in the Semi-Arid Rangelands (after Chevis and Kealley, 2024).

Hand planting of sandalwood seed by Aboriginal people at Mungilli and Cosmo Newberry has demonstrated promising sandalwood recruitment outcomes, particularly when integrated with conservative harvesting practices (see Figures 27 and 28). These efforts, guided by Cultural Knowledge and careful site selection, have yielded encouraging results (Kealley and Chevis, 2022; Kealley, 2024). This highlights the potential for broader application of Aboriginal-led sandalwood restoration initiatives across the species' distribution while reinforcing cultural connections to Country and sustainable land stewardship.

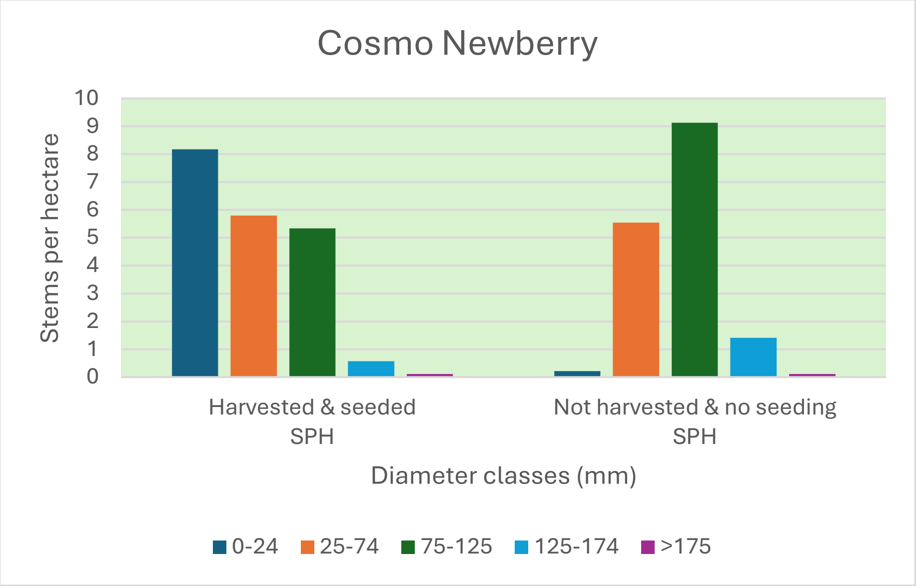


Figure 27. Results of seeding by Aboriginal people within conservatively harvested sites, compared to sites with no harvesting and no seeding (Kealley, 2024).

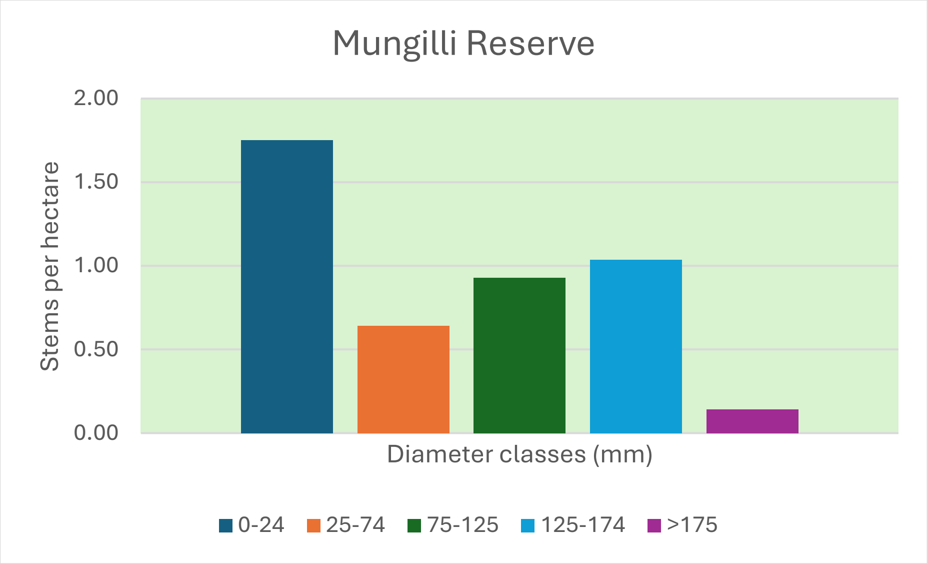


Figure 28. Encouraging recruitment results at Mungilli have been attributed to careful site selection and Cultural Knowledge (Kealley and Chevis, 2022).

4.4 Development of population projection model and scenario modelling

To illustrate the implications of different management strategies on wild sandalwood demographics, a simulation model was developed to project future size class distributions arising from various management scenarios. The Sandalwood Population Projection (SPP) model was developed in Microsoft Excel (Microsoft Corporation, 2018) and is structured to simulate changes in diameter size class distributions for a projection period of 100 years, recognising the inherent cumulative uncertainty of projections over time.

4.4.1 Model structure and operation

The SPP model is a stand table projection model (Vanclay, 1994) which predicts the future number of trees in diameter size classes based on the initial size-class distribution. Rates of factors influencing stand dynamics—such as regeneration, growth, mortality, harvest removals—as well as management options such as supplementary seeding can be applied to generate summaries of diameter size class distributions for living, dead and retained tree counts over time. SPP is a deterministic aspatial model designed to illustrate changes in population demographics at the regional to landscape-scale for this slow growing species.

Model input variables include:

- area (hectares) of sandalwood habitat;
- area (hectares) potentially available for commercial harvest;
- initial tree diameter size-class distribution (in 25 mm intervals), measured at 150 mm above ground;
- natural recruitment rate relative to past treatments or operations;
- supplemental seeding rates (manual or mechanical);
- survival rate of sown seed;
- tree diameter growth rates;
- number of trees 'growing' into the minimum size class (termed 'Ingrowth');
- tree mortality rates within tree diameter size classes;
- effective harvesting rate[14];
- quantity of dead wood present at commencement of projection period;
- attrition rate of dead wood;
- average stem weight (kg) by tree size-class;
- minimum tree size thresholds for harvesting living sandalwood; and
- harvesting rate of living and dead sandalwood per decade, specified as default tonnes removed per year.

4.4.2 Source of default values for model input variables

4.4.2.1 Area of sandalwood habitat

The area of sandalwood habitat was derived from stratification of the IBRA subregions. Demographic data were extrapolated to two subregion groupings, the Semi-Arid Rangelands and the Eastern Murchison, based on vegetation type similarities and dataset availability (Table 2 and Figure 29). This comprehensive data enabled different management strategies to be modelled in detail for the sandalwood populations in the Semi-Arid Rangelands and the Eastern Murchison, while modelling of other subregion groupings (Western Deserts and Great Victoria Desert) was precluded by the limited demographic and stand dynamics data available for these regions.

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[14] The assumed rate of access to harvestable-sized sandalwood reflects the logistical constraints associated with locating individual trees in remote regions and within structurally homogenous vegetation, which can obscure detectability and reduce search efficiency.

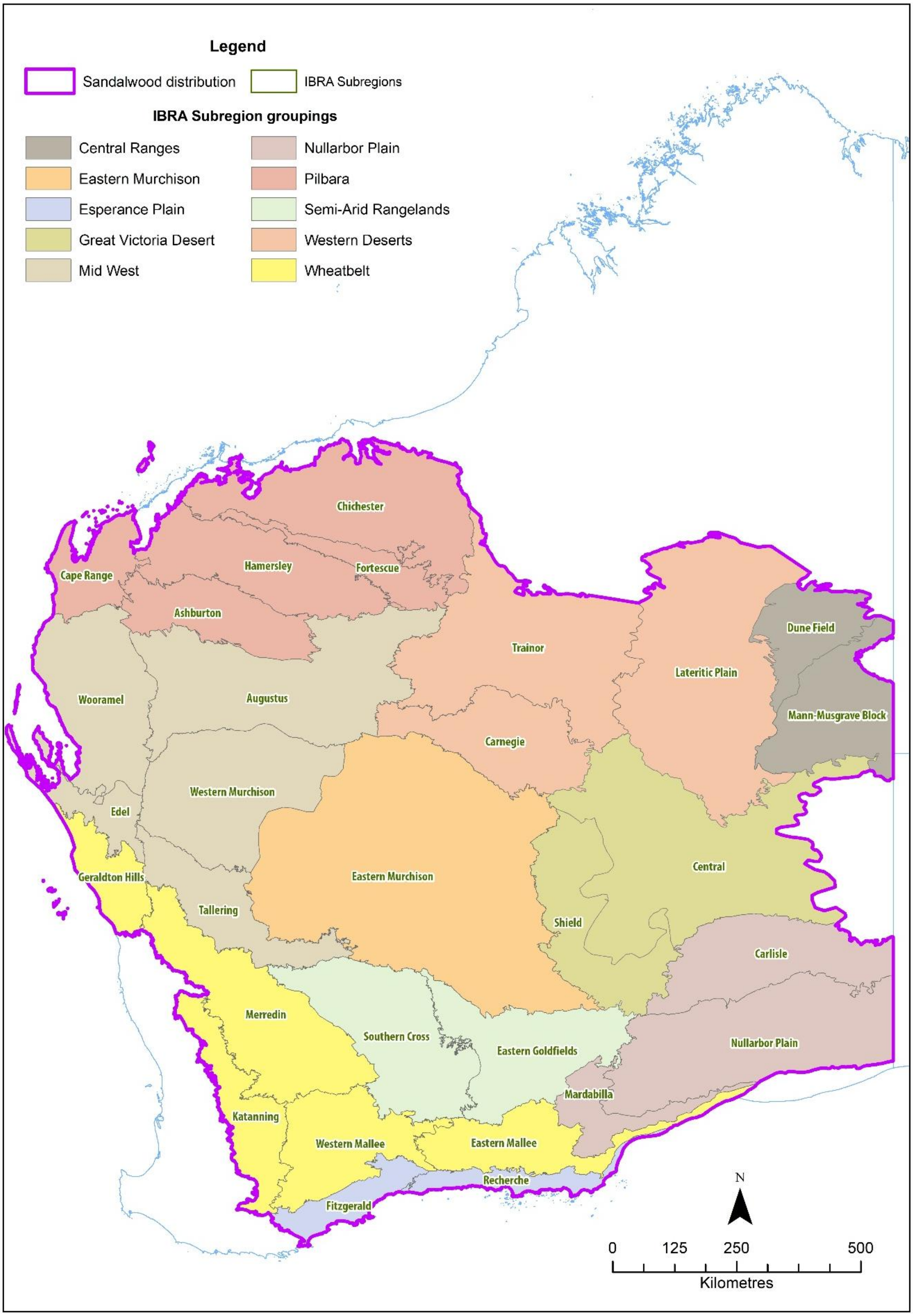

Figure 29. Sandalwood modelling and analysis regions based on IBRA subregions.

4.4.2.2 Area potentially available for removal of sandalwood

Calculation of the net area potentially available for commercial harvest of sandalwood, excluded all *Conservation and Land Management Act 1984* (CALM Act) conservation tenures (such as national parks and nature reserves). Former pastoral leases that were purchased by DBCA, but for which there are currently no formal joint management arrangements under the *Native Title Act 1993,* were considered as potentially available for harvesting of sandalwood.

While detailed historical records of previously harvested locations are not available, it was assumed a large proportion of the rangelands has been subjected to some degree of harvest in the past. Because of the scattered occurrence of sandalwood and low intensity of access, a relatively high proportion of harvestable-size trees are likely to have been retained in previously harvested areas. However, improvements over the last decade in locating harvestable-size trees during commercial operations has meant that fewer trees have been left. Consequently, areas recorded as harvested since 2012 were excluded in the calculation of potentially available area.

4.4.2.3 Initial tree diameter size-class distributions

The initial size-class distributions for Eastern Murchison and Semi-Arid Rangelands were derived from the population demographic analyses.

4.4.2.4 Natural recruitment rate relative to historic conditions

The current natural recruitment, represented by the number of trees in the 1–10 mm diameter class, is influenced by the number of seed trees in the existing population. However, because this level is related to recent environmental conditions, the SPP model provides for varying the success of natural recruitment rates should future conditions vary from historic trends. A default recruitment factor of 100 per cent was used to represent recent conditions, which can be scaled to reflect anticipated changes in recruitment success if future conditions become less or more favourable for regeneration establishment and persistence.

4.4.2.5 Supplemental seeding rates

Successful supplemental seeding, via either manual or mechanical methods, can result in establishment and subsequent recruitment of trees into the 1–10 mm diameter size-class. SPP provides for the quantity of seed to be varied to model the effect of different rates on future size-class distributions. Default values applied in different scenarios modelled included:

1. no supplemental seeding;
2. seeding rates associated with current sandalwood licence conditions for most IBRA subregions[15], which require hand sowing five kilograms of sandalwood seed for each tonne (both living and dead) harvested. This equates to approximately 40 seeds for each tree harvested;
3. a combination of 2 (above) and Operation Woylie-scale recruitment programs, where a default value of 200 seeds per harvested stem, was applied; and

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[15] An exception is the Wheatbelt Region, which will require two kilograms to be planted for every tonne harvested, as germination rates in these areas are comparatively higher.

4. additional landscape-scale supplemental seeding programs (independent of harvest sowing and Operation Woylie) using increasing quantities of seed up to 20 tonnes per annum overall, split between IBRA subregion groupings.

4.4.2.6 Survival rate of sown seed

Seedling survival rates over a 10-year period vary considerably (Brand et al., 2014). Default survival values applied for each region (Table 7) were derived from empirical monitoring data associated with the mechanised seeding conducted under the Operation Woylie program, as well as hand-seeding results reported by Brand et al. (2014), Kealley and Chevis (2022) and Kealley (2024).

Table 7. Default survival rates (per cent) of sown seed for each regional grouping and seeding application method.

Regional grouping	Application method	
	Hand seeding	Mechanical (Operation Woylie equivalent)
Eastern Murchison	2.1	0.98
Semi-Arid Rangelands	5.2	1.52

4.4.2.7 Tree diameter growth rates

Multiple factors will influence the annual diameter growth rate of individual wild sandalwood trees, including their age, site characteristics (such as moisture availability through seasons), stand characteristics (including species, competition and relative vigour of hosts), as well as episodic events such as fire or grazing impacts (Brand, 2002; Brand et al., 2014; Kealley, 1991; Loneragan, 1990). However, the species is slow growing and long-lived, and studies have demonstrated a strong relationship between tree age and stem sizes measured at 150 mm above the ground. In natural populations, diameter increments are generally highest during the seedling and juvenile growth stages and decline with increasing tree age (Anderson, 2005; Brand et al., 2014; Kealley, 1991; Loneragan, 1990; Williamson, 1982).

Brand et al. (2014) reported seedlings established in three separate semi-arid areas averaged over bark growth rates of 1.2 to 2.3 mm per year over a 17-year period, while mature trees (around 123 to 158 mm diameter) over the same period averaged 0.5 to 0.9 mm per year in the same areas. Sandalwood measured near Kalgoorlie had diameter growth rates (measured at 75 mm above ground) of 0.7 to 2.44 mm per year for the first 34 to 50 years (Sawyer, 2024; Loneragan, 1990). Limited measurements of older sandalwood trees suggest growth rates of about 0.25 to 0.5 mm per year are maintained into old age (B. Sawyer, personal communication, 5 August 2024). Local environmental conditions may also affect growth rates with trees situated closer to creeks typically growing faster than those located further away (B. Sawyer, personal communication, 5 August 2024). For the purposes of scenario modelling, a set of default growth rates for each diameter class were applied (Table 8), following the general functional form of tree growth and mortality varying non-linearly with tree size (Weiskittel et al., 2011).

Table 8. Default values of average annual diameter growth rate (mm) for wild sandalwood in regional groupings.

Regional grouping	Tree diameter size class (mm)												
	0-25	26-50	51-75	76-99	100-126	127-150	151-175	176-200	201-225	226-250	251-275	276-300	301-325
Semi-Arid Rangelands	1.5	1.5	1	0.75	0.75	0.75	0.75	0.75	0.5	0.5	0.5	0.5	0.5
Eastern Murchison	1	1	0.75	0.5	0.5	0.5	0.5	0.5	0.25	0.25	0.25	0.25	0.25

4.4.2.8 Ingrowth

In SPP, natural ingrowth of trees into the 1–25 mm diameter class was assumed to vary with the available number of living trees potentially capable of producing seed. In the model, trees larger than 25 mm diameter are assumed to be seed trees. Natural ingrowth was calculated as a percentage of the seed trees that would have been required to produce the initial (derived) number of stems in the 1–10 mm size class. This value was carried through to each decade and responds to the changing number of stems larger than 25 mm.

4.4.2.9 Mortality rates

Default values for mortality rates in the model were based on a mean of one per cent mortality rate per year for large trees reported by Brand et al. (2014). The value used in the 1–25 mm class was based on a mortality rate of seedlings from 10–25 years (Table 9).

Table 9. Default mortality rates (per decade) applied within tree diameter classes.

Regional grouping	Tree diameter size class (mm)												
	0-25	26-50	51-75	76-99	100-126	127-150	151-175	176-200	201-225	226-250	251-275	276-300	301-325
Semi-Arid Rangelands	15%	15%	10%	10%	10%	10%	10%	10%	15%	15%	15%	100%	100%
Eastern Murchison	15%	15%	10%	10%	10%	10%	10%	15%	15%	15%	15%	15%	100%

4.4.2.10 Effective harvesting rate

Past FPC monitoring has estimated that only around 80 per cent of harvestable-sized sandalwood (≥127 mm) within an area is accessed during harvesting operations, because of difficulties locating the sparsely scattered trees. A default value of 80 per cent was assumed in SPP as the percentage of the total available harvest quantity that would be removed under current practices. While based on historic practices, this default value is a generic reduction which can also provide for recent licence conditions and silvicultural practices requiring the retention of some larger harvestable-sized trees at the local scale.

4.4.2.11 Initial quantity of dead wood

The default values for quantities of dead wood were based on inventory data. The number of tonnes of dead wood available for harvesting was modelled to include the accumulation rate as a product of the mortality rates above, and a concomitant reduction through harvesting and natural attrition.

4.4.2.12 Attrition rate of dead wood

Dead wood is lost through decomposition, bushfires and harvesting. There are no comprehensive data for these rates of attrition and a default value of 20 per cent per decade was applied based on expert field judgement.

4.4.2.13 Stem weight by tree size class

The weight of a tree varies with stem size, and based on measurements of 69 trees the following regression model was developed to compute the weight of the tree of mean diameter in each diameter class (Sawyer and Jones, 2000):

$$\text{Log}\,[\text{tree weight (kg)}] = 2.805 \times \text{Log}\,[\text{diameter (mm)}] - 4.331$$

where ‘Log’ denotes common logarithm (base 10); ‘diameter’ denotes tree diameter measured at 150 mm above ground level.

The largest tree in the dataset used to develop this regression model had a diameter of 201 mm. The weight of larger stems was extrapolated according to the increasing sectional area of larger stems.

The weight of the tree of mean diameter in each diameter class >126 mm was multiplied by the number of stems per hectare in that class to give weight per diameter class and total tonnage >126 mm.

4.4.2.14 Minimum tree size threshold for harvesting living sandalwood

The SPP model provides for varying the minimum tree diameter permissible for harvest of living sandalwood trees. The default value applied was the current minimum legal size of 127 mm (>126 mm). A separate analysis was conducted to examine the effect of increasing the threshold to >150 mm (≥151 mm).

4.4.2.15 Harvesting rate of living and dead sandalwood per decade

The model computes the total sandalwood tonnes per hectare potentially available above the minimum tree size threshold and adjusts this by the effective harvesting rate. The area required to be harvested to attain a specified annual target level of living and dead sandalwood is then computed.

Annual target levels for the 10-year period are specified at commencement of the model simulation.

4.4.2.16 Variables excluded from direct modelling: sandalwood quantities removed through illegal harvesting or other sources

Historically, a quantity of sandalwood that might ordinarily be available for harvesting is removed through illegal harvesting or approved infrastructure developments (including exploration, mining and roading).

Illegal harvesting activities preferentially target large, mature sandalwood trees due to their higher visibility and greater economic return per unit of effort locating and removing trees. In contrast, trees within younger regeneration cohorts are less likely to be targeted, as their lower commercial value renders them less attractive for illegal harvest. The collection of dead sandalwood is likely to occur opportunistically and inconsistently, given the difficulty distinguishing it from other similar woody species in a degraded state.

Forecasting future levels of illegal harvest is highly problematic, as even recorded quantities of historic seizures during compliance operations are believed to underestimate likely activity levels. Accordingly, the SPP modelling did not directly incorporate provision for estimating removals from future illegal harvesting: rather, separate projections can be added to model outputs as appropriate.

As the *Sandalwood BMP* explains, sandalwood (living and dead) can also be lawfully removed under approvals for mining and other infrastructure development issued under the *Environmental Protection Act 1986* (EP Act). Annual quantities removed vary considerably and are often highly localised, making forecasting future trends difficult. Based on the typical development envelope of mining operations, the affected area is likely to be less than 1,000 hectares per annum. The SPP modelling did not include specific provision for EP Act removals, but allowance can be made beyond the model outputs to reflect anticipated levels of activity.

4.4.3 Operation of the SPP model and standard outputs

The model is initialised with the living tree diameter size-class distribution considered representative of the area stratum—in this study derived from contemporary sample plot data for each regional grouping. The initial total tonnes of dead wood is also derived from inventory, and the natural ingrowth percentage is calculated from the number of seed trees. Initial values are also input for the variables: area potentially available for licensed removal of sandalwood; seeding rate; seedling survival rate; diameter increment in each size class; mortality per decade for each size class; and attrition rate of dead wood.

The initial stem distribution was ‘grown through’ to the next decade based on ingrowth, growth rate and mortality. ‘Mortality’ became ‘dead wood’ which was also reduced by the nominated attrition rate. The harvested tonnes of living (green) and dead sandalwood, entered as a variable for each decade, was removed from the projected tonnes. The proposed harvest tonnage was rejected if it exceeded the net available tonnage. The number of stems in each size class remaining at the end of the decade were calculated and become the basis for the next decade’s projection. The projections were carried forward for a nominal 100 years.

The SPP model produces tabular and graphical outputs for each simulation depicting at 20-year intervals for 100 years:

- retained living stem numbers per hectare by 25 mm diameter size classes;
- available tonnes of living (green) sandalwood at the end of each period;
- tonnes of dead sandalwood at the end of each period; and
- total number of trees (stems per hectare) larger than 25 mm diameter, representing the number of potential seed trees standing at the end of each period.

4.4.4 Model testing and interpretation of outputs

Model testing and validation included comparison of the measured versus projected diameter size-class distributions for the subset of plots with measurements in both 1994–2003 and 2022–2024. Over the nominal 30-year projection period the model reproduced the pattern of observed stem stocking densities, suggesting the model formulation adequately represented the biological form and processes of regeneration and development, and that the default values for growth rates, survival and mortality were realistic at the generalised landscape scale.

Although the SPP model generates outputs for a 100-year period, as with all forecasting models there will be compounding uncertainty in simulation projections as the length of the projection period increases. While the simulated size-class distributions by 100 years provide useful comparisons of scenario outcomes, for practical purposes projections beyond 40 years are considered illustrative only because the varied imprecision of input data and cumulative interacting impacts arising from grazing, harvesting, fire or episodic regeneration and establishment programs, will provide for many possible population structure trajectories over time. For example, annual and seasonal rainfall patterns are key drivers of sandalwood regeneration, survival and growth, and climate change projections to 2070 (CSIRO and Bureau of Meteorology, 2015) suggest increases in temperature and variability of rainfall events across large swathes of the natural distribution of sandalwood.

4.4.5 Management scenarios

The model was used to investigate impacts of different management strategies on future population structures. The suite of scenarios modelled in this work are listed in Table 10 and Figure 30. These were selected to illustrate the potential consequences on future sandalwood population structure of a range of management options from no active management (a ‘do nothing’ approach, including no harvesting or supplemental seeding) through to varying levels of annual harvest of living and dead sandalwood within regions for a 10-year period, with the harvest operations accompanied by supplemental seeding either at harvest only or combined with a broader regeneration program (labelled ‘Additional landscape-scale supplemental seeding’).

The ‘do nothing’ (no harvest or seeding) scenario would involve the cessation of lawful take (commercial harvest) of wild sandalwood under a Sandalwood Order at the end of 2026. It provides a scenario of no future harvesting on any tenure and no continuation of supplemental seeding activities for comparison to all other scenarios. An alternative scenario was also modelled whereby the harvesting of living sandalwood ceases at the end of 2026 but the take of dead sandalwood continues at the level of total harvest (2,500 tonnes per annum) defined in the current Sandalwood Order.

Within the area potentially available for harvest, scenarios representing different levels of total annual sandalwood harvest (including both living and dead wood) were developed and allocated across regions. Stepped reductions in the total level of living sandalwood harvest were selected to evaluate the relative impact on future population structure. The total annual harvest was broadly distributed in approximate proportions of 40 per cent to the Semi-Arid Rangelands, 40 per cent to the Eastern Murchison, and 20 per cent to an aggregated allocation for the Great Victoria Desert and Western Deserts regions (the ‘Desert’ regions) (Figure 30). This preliminary allocation reflects differences in total potentially available habitat area between the regions, historic operational experience of resource viability, and accommodates emerging operations in the Desert regions, much of which is subject to Native Title determinations.

In summary, the management scenarios included:

1. no future harvesting and no supplemental seeding (regeneration) program (‘do nothing’ approach);
2. no future harvesting but with a modest landscape-scale regeneration program (20 tonnes of seed per year);
3. harvesting of only dead wood[16];
4. maintenance of the current maximum harvest level for the last 10 years, with the current levels of regeneration achieved by FPC’s Operation Woylie (Table 10); and
5. a suite of nominal harvesting quantities being removed (Table 10 and Figure 30), with a continuation of the level of seeding achieved through landscape-scale regeneration, together with hand sowing by sandalwood licence holders.

Harvesting scenarios for the Semi-Arid Rangelands and Eastern Murchison considered allocations of living and dead sandalwood to the ‘Desert’ regions (see Table 10 and Figure 30). This approach resulted in reduced harvest quantity targets for the Eastern Murchison and Semi-Arid Rangelands. The allocations for the Desert subregions were informed by stratified creek system mapping and available licence inventory data, as detailed in Sections 4.2.3.2 and 4.3.2.2. It is important to reiterate that the assessments for the Desert allocations were qualitative and based on the best available data. However, the stratification method and the statistical representativeness of local inventories at the IBRA subregion level have not been formally validated, so results presented for the Desert regions are therefore considered illustrative rather than definitive.

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[16] Dead sandalwood trees retain significant commercial value, primarily due to the fragrant heartwood, which remains aromatic and oil-rich even after the tree has died. This makes dead wood a viable and often preferred source for various high-value products. Dead sandalwood holds deep cultural, spiritual and practical value for Aboriginal peoples of Western Australia (Martin, 2023). The aromatic heartwood is burnt during ceremonies, times of stress and spiritual reflection.

Table 10. Management scenarios modelled for Semi-Arid Rangelands and Eastern Murchison regions, and default provisions for the Desert regions.

Management scenario		Total living harvest (tonnes)	Total dead wood harvest (tonnes)	Modelled subset	Semi-Arid Rangelands					Modelled subset	Eastern Murchison					Not modelled[3]	Deserts and other regions			
					Harvest quantity			Regeneration programs			Harvest quantity			Regeneration programs			Harvest quantity			Regeneration
					Living	Dead	TOTAL	Licensee seeding *(kg per tonne)*	Routine Operation Woylie *(seeds per stem)*		Living	Dead	TOTAL	Licensee seeding *(kg per tonne)*	Routine Operation Woylie *(seeds per stem)*		Living	Dead	TOTAL	Licensee seeding *(kg per tonne)*
	Conservation estate																			
1	No harvest No seeding	0	0	**1a**	0	0	0	0	0	**3a**	0	0	0	0	0		0	0	0	0
2	No harvest With seeding	0	0	**1b**	0	0	0	5 tonnes seed per year for 10 years		**3b**	0	0	0	15 tonnes seed per year for 10 years			0	0	0	0
	Harvestable tenure																			
1	No harvest No seeding	0	0	**2a**	0	0	0	0	0	**4a**	0	0	0	0	0		0	0	0	0
2	No harvest With seeding	0	0	**2b**	0	0	0	5 tonnes seed per year for 10 years		**4b**	0	0	0	15 tonnes seed per year for 10 years			0	0	0	0
	Total quantity				**Tonnes per year**						**Tonnes per year**						**Tonnes per year**			
3	**2,500**	0	2,500	**2c**	0	1,000	**1,000**	2	0	**4c**	0	1,200	**1,200**	2[1]	0		0	300	**300**	2
4	**2,500**	1,250	1,250	**2d**	500	500	**1,000**	5	200	**4d**	500	500	**1,000**	5[2]	200		250	250	**500**	5
5.1	**2,000**	800	1,200	**2e**	300	500	**800**	5	200	**4e**	300	500	**800**	5	200		200	200	**400**	5
5.2	**2,000**	700	1,300	**2f**	250	500	**750**	5	200	**4f**	250	500	**750**	5	200		200	300	**500**	5
5.3	**1,500**	550	950	**2g**	200	350	**550**	5	200	**4g**	200	350	**550**	5	200		150	250	**400**	5
5.4	**1,000**	500	500	**2h**	200	200	**400**	5	200	**4h**	200	200	**400**	5	200		100	100	**200**	5

[1] Reduced from 5 kg per tonne to account for the licensees applying seed for only 1,000 of the 2,500 total tonnes harvested for this scenario.

[2] Reduced from 5 kg per tonne to account for only 1,000 of the total quantity of 2,500 tonnes being seeded by the licensee, the remainder by additional landscape-scale supplemental seeding.

[3] Not modelled – default allocations only.

Table 11. Additional model simulations to inform the review of the Sandalwood Order.

Model simulation	**Modelled subset**	**Semi-Arid Rangelands**					**Modelled subset**	**Eastern Murchison**				
		Harvest quantity			**Regeneration programs**			**Harvest quantity**			**Regeneration programs**	
		Living	Dead	**TOTAL**	Licensee seeding *(kg per tonne)*	Routine Operation Woylie *(seeds per stem)*		Living	Dead	**TOTAL**	Licensee seeding *(kg per tonne)*	Routine Operation Woylie *(seeds per stem)*
		Tonnes per year						**Tonnes per year**				
Model sensitivity analyses	**2a**	0	0	**0**	0	0	**4a**	0	0	**0**	0	0
	2d	500	500	**1,000**	5	200	**4d**	500	500	**1,000**	5	200
Persistent regeneration failure	**2d**	500	500	**1,000**	5[1]	200[1]	**4d**	500	500	**1,000**	5[1]	200[1]
	2d	500	500	**1,000**	5[2]	200[2]	**4d**	500	500	**1,000**	5[2]	200[2]
Minimum tree size threshold comparison ≥127 and ≥151 mm diameter							**4d**	500	500	**1,000**	5	200
Licensee only seeding at harvest	**2d**	500	500	**1,000**	5	0	**4d**	500	500	**1,000**	5	0
	2f	250	500	**750**	5	0	**4f**	250	500	**750**	5	0
Extended duration harvest for 20 and 100 years with licensee only seeding	**2d**	500	500	**1,000**	5	0	**4d**	500	500	**1,000**	5	0
	2f	250	500	**750**	5	0	**4f**	250	500	**750**	5	0
No harvest and seeding to aim to attain pre-1750 population structure	**2b**	0	0	0	40 tonnes per year for 100 years		**4b**	0	0	0	25 tonnes per year for 100 years	
	2b	0	0	0	120 tonnes per year for 100 years		**4b**	0	0	0	100 tonnes per year for 100 years	
Additional[3] landscape-scale supplemental seeding program (Licensee + Operation Woylie + Additional)	**2c**	0	1,000	**1,000**	Additional 5 tonnes per year		**4c**	0	1,200	**1,200**	Additional 15 tonnes per year	
	2e	300	500	**800**	Additional 1 tonne per year		**4e**	300	500	**800**	Additional 2 tonnes per year	
	2f	250	500	**750**	Additional 2 tonnes per year		**4f**	250	500	**750**	Additional 3 tonnes per year	
	2g	200	350	**550**	Additional 2 tonnes per year		**4g**	200	350	**550**	Additional 7 tonnes per year	
	2h	200	200	**400**	Additional 3 tonnes per year		**4h**	200	200	**400**	Additional 7 tonnes per year	

[1] Operational sowing failure during each year of the 10-year harvest period.

[2] Operational sowing and natural regeneration failure during each year of the 10-year harvest period.

[3] Additional to the routine 5kg per tonne licensee seeding and 200 seeds per stem in routine Operation Woylie program.

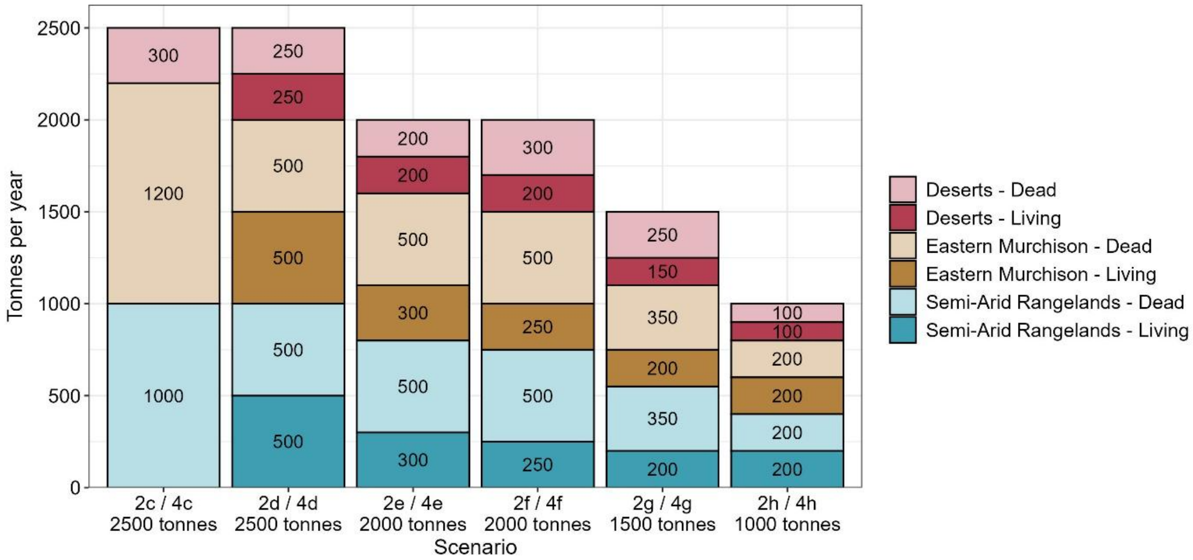

Figure 30. The nominal allocation of different sandalwood quantities across the regions used in scenario modelling.

4.4.6 Additional model simulations to inform the review

Following the initial modelling of scenarios listed in Table 10, a series of further model simulations were conducted on specific scenarios (or combinations) to assist interpretation of model outputs and inform recommendations presented in the *Draft Review Report*. Table 11 lists the set of simulations undertaken to examine the following topics.

4.4.6.1 Sensitivity analysis of model outputs

Given the observed variability in model input values and their trajectories over time, a structured sensitivity analysis for two management scenarios was conducted to illustrate the relative sensitivity of model projections to changes in key model variables and their parameters. These analyses focused on changing the initial diameter size class distribution—which is always subject to potential inventory sampling bias and low sampling intensity—as well as ecological factors such as growth rates, mortality rates and natural regeneration.

Table 12 summarises the variations to input variables used in each management scenario. The sensitivity of model projections to variability in the initial diameter distribution was examined by varying the (default) mean stem numbers in each diameter class by the mean standard error (SE), calculated from the variance in size class distributions across sampled plots in the contemporary dataset (see Section 4.3.2.1 Eastern Murchison and Semi-Arid Rangelands populations structures). Model simulations were conducted using the mean inventory estimate, along with upper and lower bounds defined by ±1 SE. A further simulation examined varying the (default) values for diameter growth rate and natural regeneration factor (each reduced by 25 per cent) with the value for mortality rate increased by 25 per cent (Table 12).

The first management scenario examined in each region comprised a ‘No Harvest, No Seeding’ approach—essentially a passive management or ‘do nothing’ strategy. This scenario seeks to assess ecological dynamics in the absence of intervention, under varying assumptions about inventory and ecological factors. In contrast, the second scenario simulated active management under the same uncertainty conditions, incorporating a harvest limit of 500 tonnes each for living and dead sandalwood, alongside licensee-led and routine Operation Woylie seeding.

Table 12. Values of key input variables adjusted in sensitivity analyses for the management scenarios 'do nothing' (2a/4a) and a harvesting and regeneration scenario removing 500 tonnes each of living and dead sandalwood (2d/4d).

Simulation sequence	Input variable(s) adjusted
1	**Inventory estimate**: initial mean size class distribution
2	**Upper bound inventory estimate**: mean + 1 standard error (SE), reflecting potential overestimation
3	**Lower bound inventory estimate**: mean − 1 SE, reflecting potential underestimation
4	**Adjusted ecological parameters**: inventory, with: • growth rate reduced to 75 per cent; • mortality rate increased by 25 per cent; and • natural regeneration factor reduced to 75 per cent.

4.4.6.2 Persistent regeneration failure

Each of the management scenarios involving harvest of living or dead sandalwood assumed regeneration is established from seed sown by the licensee and the routine Operation Woylie program. The survival rates applied are based on long-term operational results which reflect the episodic nature of drought and other events which affect survival. Simulations were undertaken for the management scenario in each of the Semi-Arid Rangelands and Eastern Murchison of harvesting 500 tonnes of living and dead sandalwood per annum for 10 years, but assuming regeneration failed each year. Although highly unlikely, this extreme situation could arise if licensees failed to sow seed or long-term drought persisted across the region. While natural regeneration would still occur under the former situation, under the latter all regeneration would fail and hence a simulation to examine such an impact on future population structures was also conducted.

4.4.6.3 Minimum size thresholds for harvesting living sandalwood

The implications of increasing the current legal minimum tree diameter for harvest of ≥127 mm and hence only remove larger, older trees was examined for a scenario in East Murchison region. The impact on resulting tree size-class distributions and area cutover to harvest 500 tonnes living sandalwood per year whilst increasing the minimum tree diameter from ≥127 mm to ≥151 mm (both measured 150 mm above ground) was modelled.

4.4.6.4 Licensee only seeding at harvest (no Operation Woylie supplemental seeding)

Model simulations for each harvest scenario in Table 10 all include routine Operation Woylie sowing of 20 tonnes seed per annum to supplement the direct seeding required by the licensee. However, in the absence of an Operation Woylie program the level of regeneration enhancement would depend only on the direct seeding activity. A set of simulations were undertaken to illustrate the impact of harvest-dependent seeding only on future size class distributions.

4.4.6.5 Extended duration of harvesting (beyond 10 years)

Scenarios incorporating harvest of living or dead sandalwood assumed annual quantities were removed for a 10-year period, with no harvest after year 10. The potential impact of continuing the harvest and associated regeneration activities beyond a 10-year period were also examined. Simulations explored the impact of harvesting for a 20-year period and a 100-year period, accompanied by licensee only seeding.

4.4.6.6 Seeding required to approach pre-1750 population structure

The scale of supplemental seeding necessary to restore tree diameter size class distributions to a negative exponential shape at the landscape scale was examined through an iterative sequence of simulations. Assuming no harvests, the annual quantity of seeds to be sown continuously across the region was progressively increased until visual inspection of projected size class distribution at Year 100 resembled a negative exponential shape.

4.4.6.7 Impact of additional landscape-scale supplemental seeding programs

Given the importance of landscape-scale restoration of sandalwood regeneration through seeding and the potential for such additional seeding initiatives to accompany harvesting during the 10-year period, the living and dead wood scenarios in Table 10 were re-run with scaled, hypothetical levels of additional seeding. Modest levels of additional seeding of up to 10 tonnes per annum (combined across the regions) were examined to inform potential sandalwood regeneration strategies.

5. Results and discussion

This section presents the modelling results at both whole-of-region and landscape scales for various scenarios in the Eastern Murchison and Semi-Arid Rangelands. Examples of the sensitivity of model projections to changes in the input data and assumptions are provided to assist interpretation, including simulations of impacts of regeneration failure over the 10-year period on long-term population structure. A separate comparison for one scenario modelled the impact on size class distribution of increasing the minimum tree size for legal take from 127 to 151 mm diameter. Further modelling then explored issues relevant to broader sandalwood restoration strategies, including the projected size-class distributions arising from seeding-only regimes in the conservation estate, the scale and duration of seeding necessary if pre-1750 population structures were to be restored in these regions, and the relative contribution to future size-class distributions of licensee, Operation Woylie and additional landscape-scale supplemental seeding programs. A series of simulations also examined the consequences on population structures of extending the duration of annual harvesting and regeneration activity from 10 years out to 20 years and 100 years.

The lack of suitable datasets precluded detailed modelling of each scenario for the Desert regions. However, tentative preliminary estimates of the current total standing quantity of commercial-sized trees (≥127 mm diameter) potentially available in these regions are presented based on derived inventory. Similar estimates based on model outputs were developed for the Eastern Murchison and Semi-Arid Rangelands. This enabled comparison of the proportion of current living trees at least 127 mm in diameter that would be removed and area cutover under different annual harvest levels—an indirect indicator of potential long-term sustainability of quantities.

5.1 Eastern Murchison and Semi-Arid Rangelands

Using the default data values and model settings described in Section 4.4.2 (Source of default values for model input variables), the suite of management scenarios were simulated[17] for each model subset in the Eastern Murchison and Semi-Arid Rangelands. The simulated effect of varying default settings and assumed quantities of living and dead sandalwood harvested on projected stem numbers per diameter class and number of seed trees (>25 mm[18]) at ‘Year 40’, are illustrated in Figure 31, Figure 32 and Figure 33, relative to the ‘no harvest’ scenarios. The seeding levels accompanying each scenario are listed in Table 10. The rationale for focusing on ‘Year 40’ comparisons is that the impacts of harvesting and seeding recruitment on tree size class distributions would be apparent by this time. Importantly, this period aligns with the 30 to 35-year measurement period of data used in initial calibration and testing of the SPP model. The 40-year outputs can also be considered in the context of published climate projections to 2070.

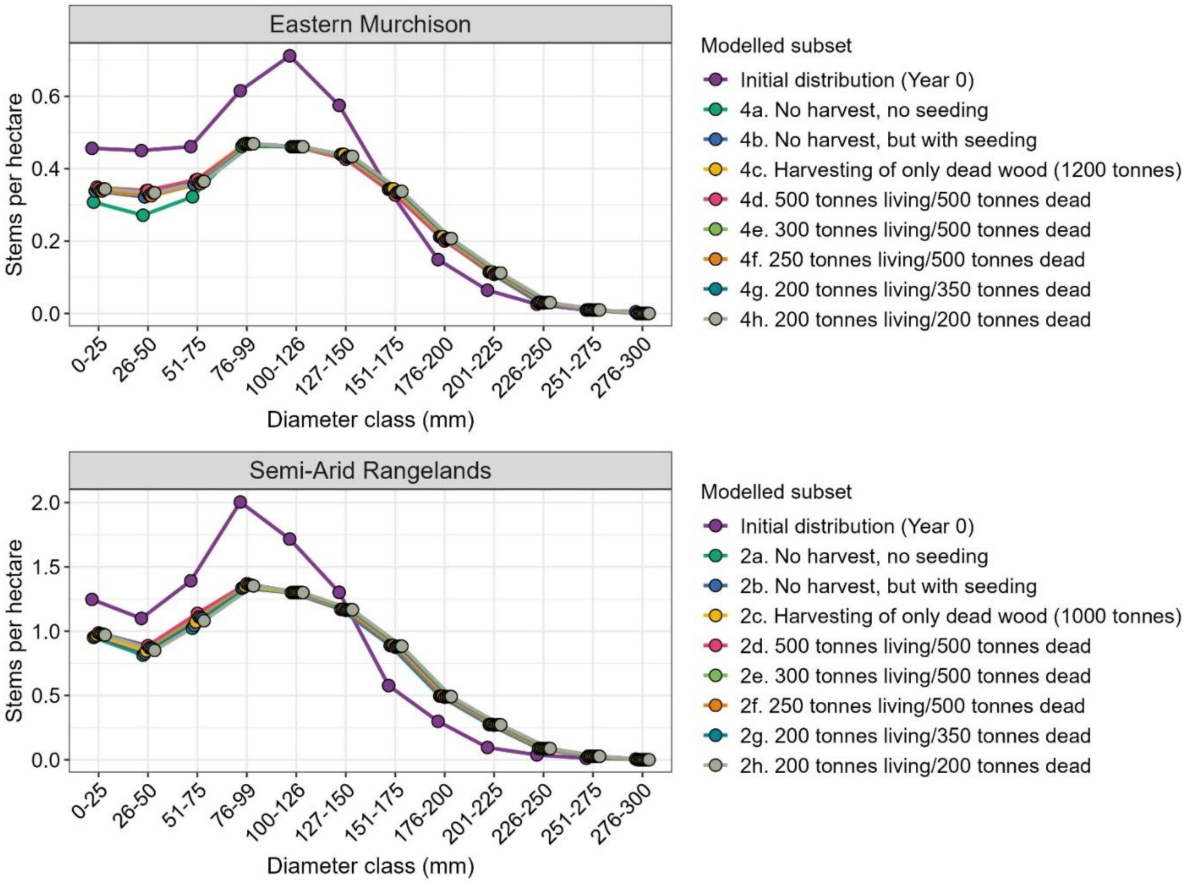

Figure 31. Comparison of stem densities of living sandalwood in 25 mm diameter classes as estimated for a range of management scenarios and modelled subsets for the ‘Whole of the region’ for the Eastern Murchison (top) and the Semi-Arid Rangelands (bottom). All graphs are for the ‘Year 40’ timestep from the simulation modelling, except for ‘Year 0’, which represents the starting values.

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[17] Note that for brevity, some results are presented in tabular form and/or summary results are provided in text.

[18] Sandalwood typically begins producing seeds at around five to seven years of age, although this can vary depending on environmental conditions and host species availability (Brand et al., 2014; Loneragan, 1990).

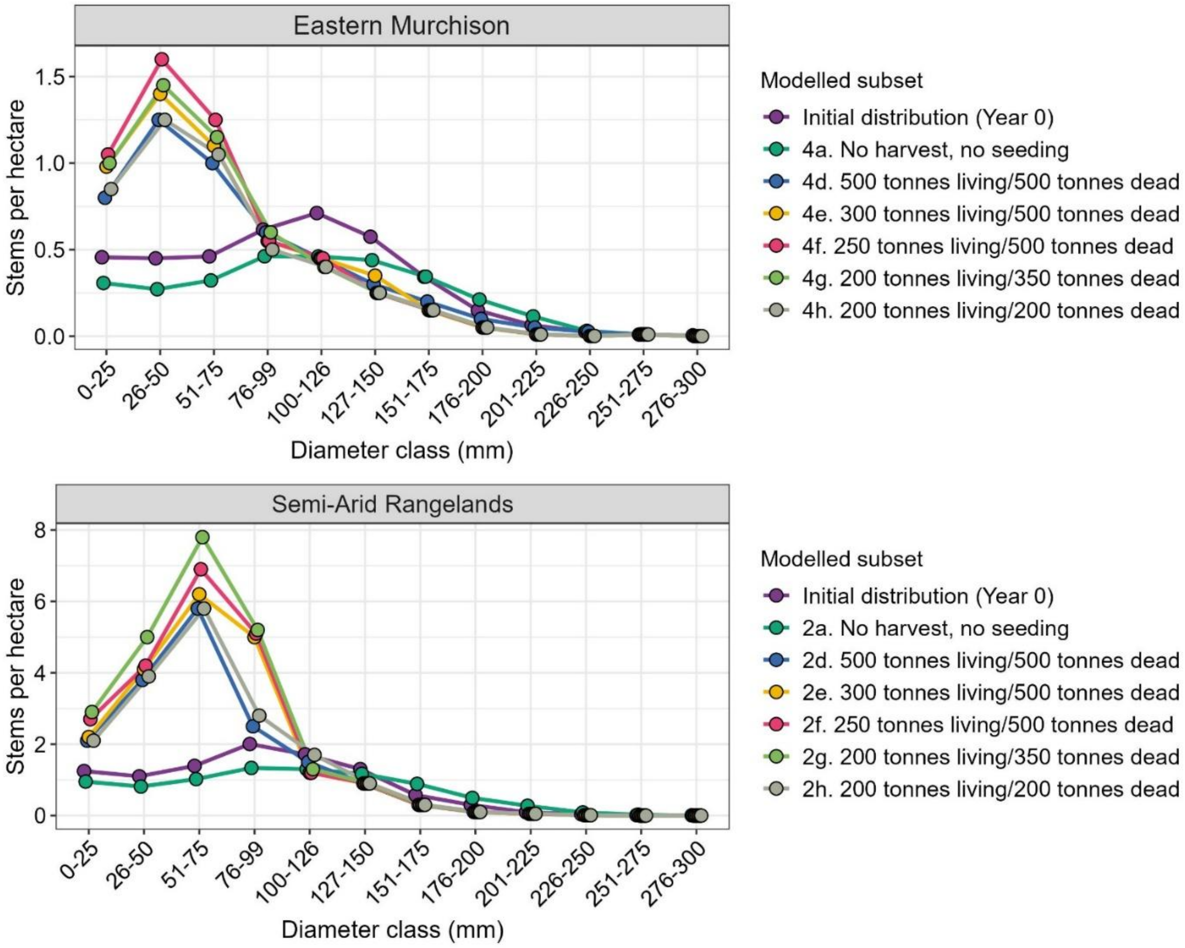


Figure 32. Comparison of stem densities of living sandalwood in 25 mm diameter classes as estimated for a range of management scenarios and modelled subsets for only the proposed harvested areas in the Eastern Murchison (top) and the Semi-Arid Rangelands (bottom). All graphs are for the 'Year 40' timestep from the simulation modelling, except for 'Year 0', which represents the starting values.

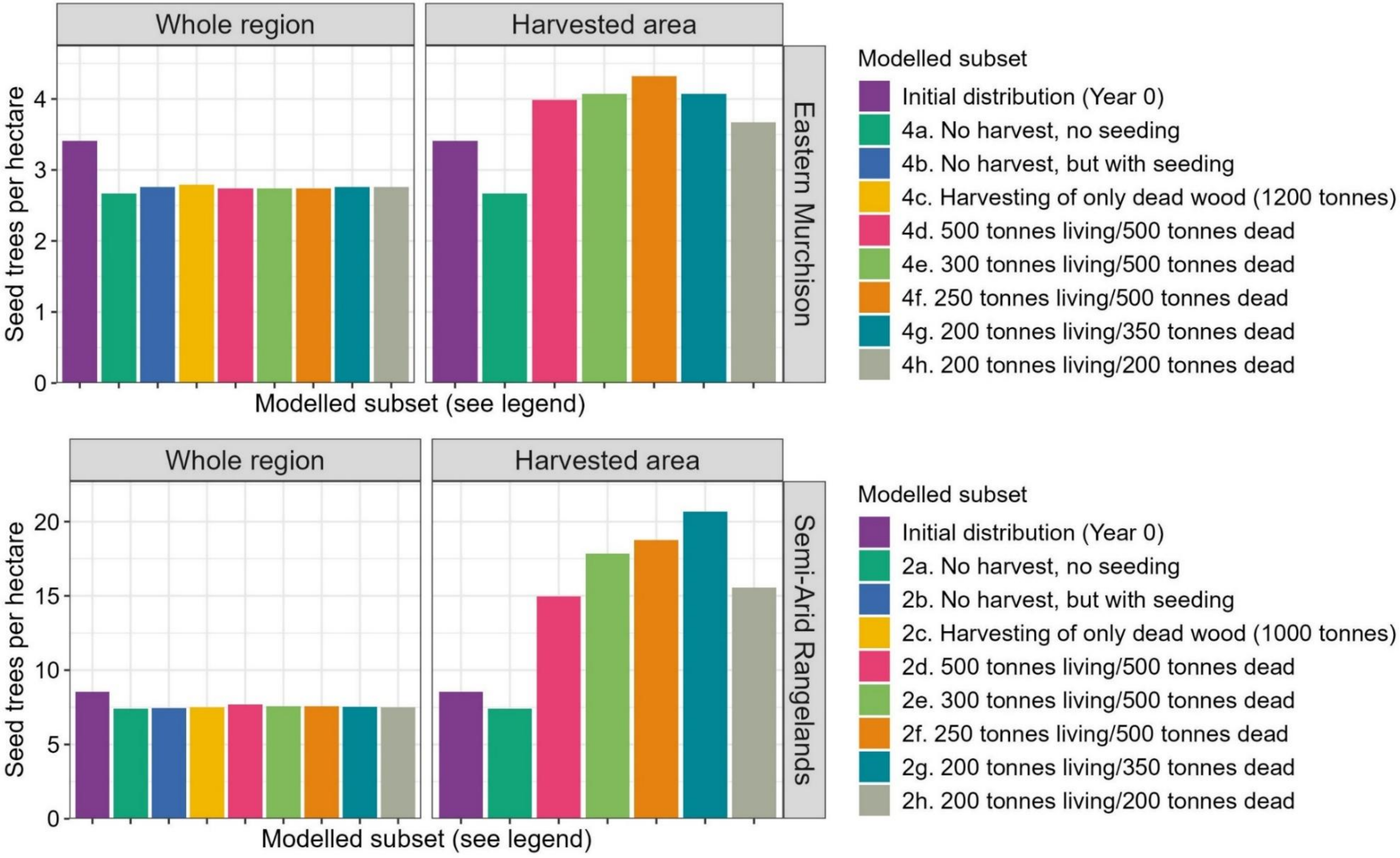


Figure 33. Comparison of number of seed trees (>25 mm) per hectare at Year 40 relative to a baseline of the 'do nothing' scenario (modelled subsets 4a and 2a) for the Eastern Murchison (top) and Semi-Arid Rangelands (bottom).

5.1.1 Demographic trends and regeneration potential

Figure 31 and Figure 32 show the estimated stem densities after 40 years for the management scenarios based on their initial population structure (‘Year 0’ - the initial diameter class distribution) for the ‘Whole of the region’ and for the ‘Proposed harvesting area’, respectively. For both the Eastern Murchison and Semi-Arid Rangelands, all management scenarios at ‘Year 40’ have lower stem densities than the ‘Year 0’ diameter classes ≤150 mm for the whole regions (Figure 31). For larger diameters (151–375 mm), the management scenarios at ‘Year 40’ have similar or slightly higher stem densities than at ‘Year 0’. There is little distinction in the ‘Year 40’ stem densities across management scenarios for the whole regions, including between the least intensive scenarios (no harvest) and the most intensive scenarios (500 tonnes living/500 tonnes dead; Figure 31). The greatest distinction occurred in the Eastern Murchison, where modelled subset 4a (‘no harvest, no seeding’) had slightly lower stem densities than other scenarios for 0–75 mm diameter stems.

The baseline scenarios of ‘no harvest, no seeding’ (modelled subsets 1a, 2a, 3a, 4a) forecast an ongoing decline over time of the total number of living sandalwood seed trees in each region, accompanied by an ageing size class distribution but reducing proportion of young trees in the absence of supplementary seeding to establish a robust regeneration cohort. The modelled population structures indicate this trend is apparent at ‘Year 40’ but over the long-term (by ‘Year 100’) this lack of recruitment and natural progression results in substantial reductions in the number of living trees of seed-bearing age across landscapes.

In contrast, by ‘Year 40’ each of the scenarios combining a take of living and dead sandalwood for 10 years with supplemental seeding (modelled subsets 2c–2h,4c–4h) generated improved numbers of trees in regeneration size classes and higher total stems per hectare in the harvested areas (Figure 32). The magnitude of this trend in each region varied with the total annual quantity of living and dead sandalwood removed relative to the seeding program. Notably, in each region there was no discernible modelled difference between the baseline scenario and all others in the number or shape of the diameter distribution for living trees larger than 150 mm, irrespective of the level of take. Each of these scenarios assume future seeding and resulting recruitment levels are comparable to current operational outcomes for commercial harvest.

As the 10-year harvest scenarios apply to less than seven per cent of the total area of the subregion, the overall diminution of potential seed trees in larger sizes will be moderated such that total seed trees in the landscape should be sufficient to maintain species reproduction potential. An improved, more balanced size class structure with a larger regeneration cohort should provide increased structural diversity and long-term resilience as conservation outcomes. The critical assumption is that the seeding practices will be successful and the regeneration cohort will persist.

Overall, the modelling suggests improved long-term population stability in the living tree size class distribution and higher numbers of potential seed-bearing trees (Figure 33) could be achieved if a combination of modest take levels of living and dead sandalwood and supplemental seeding were undertaken over a 10-year period in these landscapes. The similar size and trend arising from the varied levels of take suggest socio-economic and other factors will inform the acceptable take levels.

5.1.2 Implications for conservation estate

Modelled subsets 1a and 3a examined the potential impacts on population structures of the ‘No harvest, no seeding’ management scenario for conservation reserves within both the Semi-Arid Rangelands and Eastern Murchison regions. Model projections suggest a gradual decline in both tree density across diameter classes and in seed tree abundance over a 40-year period. In contrast, seeding interventions—specifically an annual application of 5 tonnes of seed for 10 years under modelled subset 1b in Semi-Arid Rangeland reserves—are predicted to augment natural regeneration by ‘Year 40’ and propagate higher stem numbers across diameter classes (relative to no seeding in modelled subset 1a) through to ‘Year 100’ (Figure 34).

For Eastern Murchison reserves, modelled subset 3b simulated sowing 15 tonnes of seed per year for 10 years, resulting in an initial increase in recruitment by Year 20 and improved population structure (relative to the no seeding in modelled subset 3a) by ‘Year 40’. The ‘pulse’ of regeneration created by the seeding continues to propagate through the diameter classes over time, persisting through to Year 100 (Figure 35).

This modelling illustrates the potential benefits of supplemental seeding programs at the local and landscape scales in conservation reserves. It suggests a seeding rate of 5 tonnes per year for a decade (totalling 50 tonnes) across 519,139 hectares of ‘Medium’ and ‘High’ probability sandalwood habitat in the Semi-Arid Rangelands would improve local population structure over time but have limited impact at the whole-of-region scale. In the Eastern Murchison reserves (106,717 hectares of ‘High’ probability habitat) the higher seeding rate of 15 tonnes per year over 10 years benefits short and medium-term recruitment, while long-term enhancement of size class distributions are moderated over time.

Whole of Region

Region	Semi-Arid Rangelands		Survival rate per sown seed (Hand sowing)		Attrition rate of dead wood per decade	30%
Tenures	Conservation estate		Survival rate per sown seed (woylie)	1.5%		
Total area available for harvest (hectares)	519,139		Achievable utilisation rate	80%	Natural regeneration factor	100%
Area proposed for harvesting (hectares)	0					
Area still to be harvested (hectares)	519,139		Licensee sowing rate per tonne harvested (kg)	0	Dead wood tonnes per hectare	0.00722
			Seeds per kg	325	Minimum harvest diameter (mm)	127
Proposed harvest levels	Green tonnes per year	0	Routine Woylie sowing (seeds per harvested tree)	0		
	Dead tonnes per year	0	Additional landscape supplemental sowing (tonnes per year)	5		

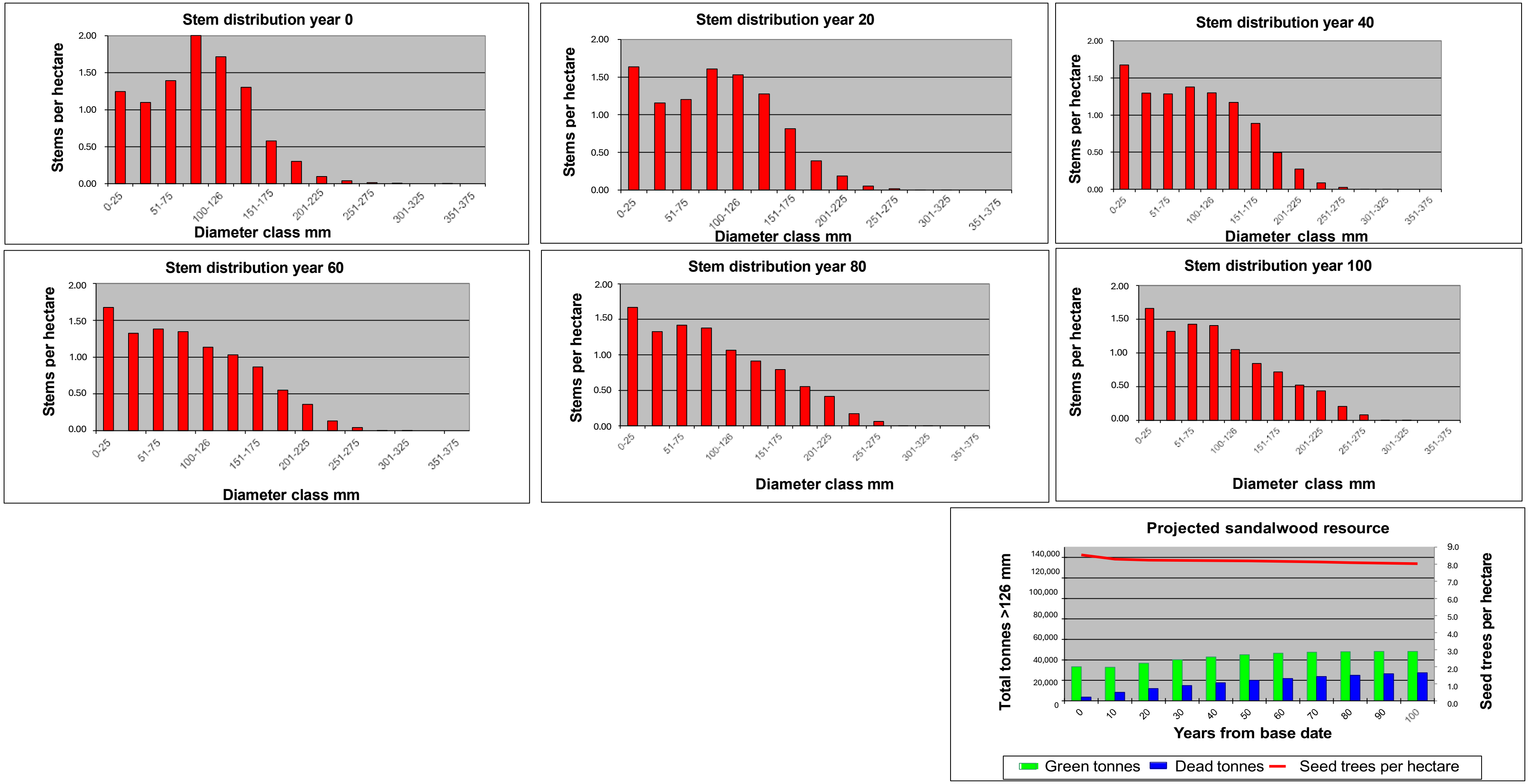


Figure 34. Progressive changes over time in tree diameter size class distribution and tree numbers from a seeding program in Semi-Arid Rangelands conservation reserves (modelled subset: 1b no harvest, seeding).

Whole of Region

Region	Eastern Murchison		Survival rate per sown seed (hand sowing)	5.2%	Attrition rate of dead wood per decade	30%
Tenures	Conservation estate		Survival rate per sown seed (woylie)	1.5%		
Total area available for harvest (hectares)	106,717		Achievable utilisation rate	80%	Natural regeneration factor	100%
Area proposed for harvesting (hectares)	0					
Area still to be harvested (hectares)	106,717		Licensee sowing rate per tonne harvested (kg)	0	Dead wood tonnes per hectare	0.01282
			Seeds per kg	325	Minimum harvest diameter (mm)	127
Proposed harvest levels	Green tonnes per year	0	Routine Woylie sowing (seeds per harvested tree)	0		
	Dead tonnes per year	0	Additional landscape supplemental sowing (tonnes per year)	15		

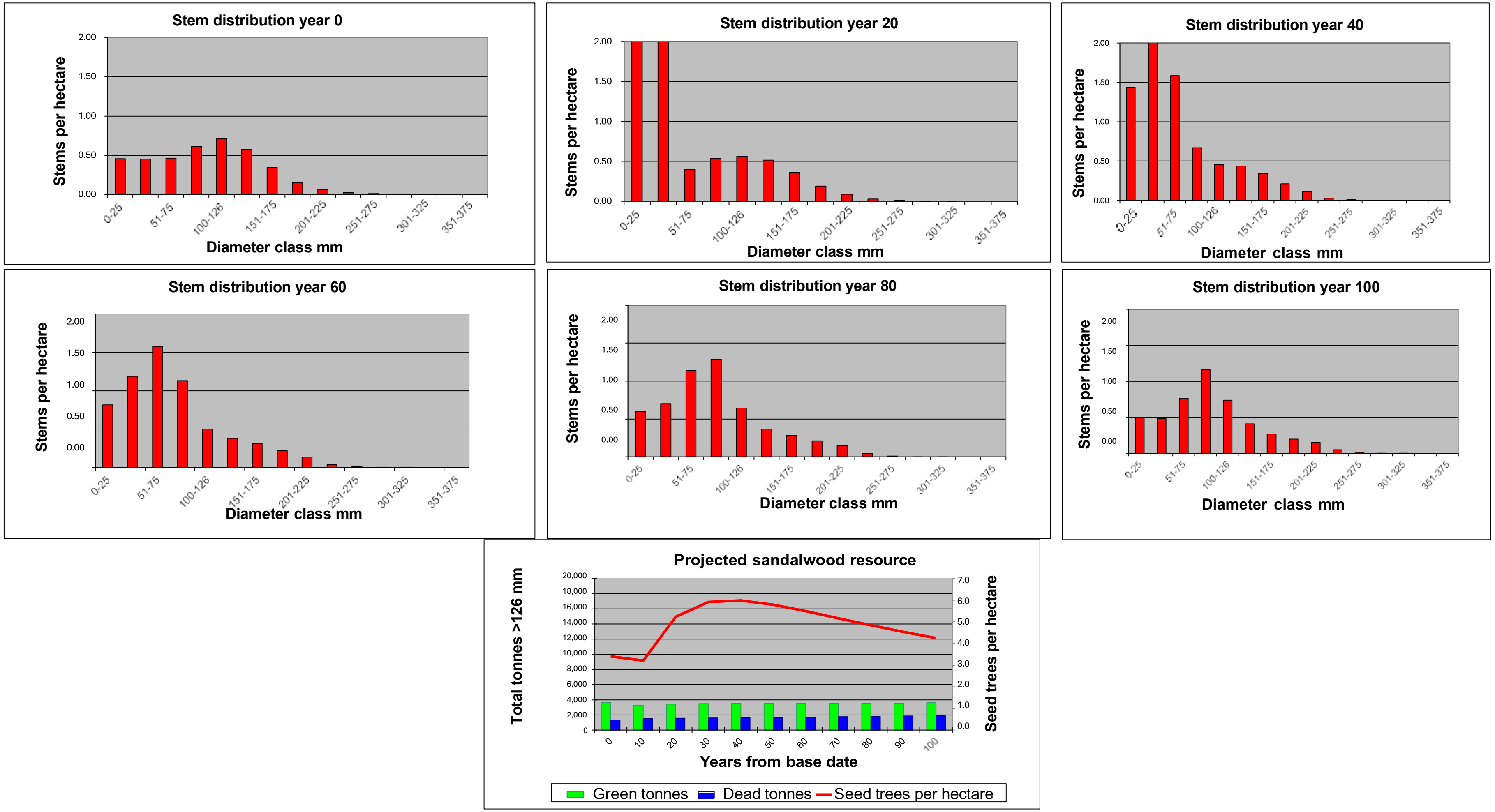


Figure 35. Progressive changes over time in tree diameter size class distribution and tree numbers from a seeding program in Eastern Murchison conservation reserves (modelled subset: 3b no harvest, seeding).

5.1.3 Harvesting of only dead wood

Modelled subsets 2c and 4c examined harvesting only dead wood over the 10-year period, at levels of 1,000 tonnes per year in Semi-Arid Rangelands and 1,200 tonnes from Eastern Murchison region. Accompanied by direct seeding at the local point of take (5 kg seed per tonne of dead wood removed) and an additional landscape-scale supplemental seeding, these simulations maintained a higher proportion of larger seed-bearing trees by 'Year 40' than all other scenarios, with a regeneration cohort created to improve the size class distribution relative to the 'no harvest, no seeding' scenarios (Figure 36).

The modelling suggests retention of all the living trees in landscapes whilst concurrently creating a regeneration cohort should maintain a more resilient population structure and, depending on the level of supplemental seeding, over time restore size class distributions toward a negative exponential shape if threatening processes are managed. While the harvesting of only dead trees and pieces of wood may result in lesser environmental impact compared with harvest of living trees, it is important to recognise the ecological functions of dead woody material in ecosystems and ensure regional protocols for take provide for a level of retention in harvested areas or surrounds. Such protocols would also consider any different impacts arising from the harvest of only dead wood in stand-alone operations, or concurrently with living sandalwood as an integrated operation.

A key factor potentially influencing both the ecological and economic aspects of only dead wood removal is its highly dispersed nature. Aside from localised areas of trees killed in drought, bushfire or other events, dead wood pieces and individual trees can be widely dispersed at low or highly variable frequencies across landscapes. For example, limited inventory data suggests the average yield of dead wood in the Semi-Arid Rangelands and Eastern Murchison regions was approximately 0.0072 tonnes [7.2 kg] per hectare and 0.0128 tonnes [12.8kg] per hectare, respectively. Consequently, achieving a target harvest quantity from dead wood alone necessitates substantially larger areas to be traversed compared to harvesting living sandalwood, which typically yields higher tonnes per hectare.

This disparity implies that harvesting only dead wood can be inherently less efficient if broader spatial coverage is required and potentially result in a larger area cut over for a specified harvest quantity. This has potential for increased vehicles tracks with impacts to soil and hydrology, and for the spread of weeds. Integrated harvesting strategies that combine removal of both living and dead wood from the same area are likely to be more economically viable and operationally efficient if undertaken concurrently. Nevertheless, dead wood harvesting may present viable economic opportunities for small-scale enterprises, particularly where operations are localised and capital investment is limited.

Proposed harvest area 0–10 years

Region	**Eastern Murchison**		Survival rate per sown seed (hand sowing)	2.1%	Attrition rate of dead wood per decade	30%
Tenures	Harvestable estate		Survival rate per sown seed (woylie)	1.0%		
Total area available for harvest (hectares)	2,521,451		Achievable utilisation rate	80%	Natural regeneration factor	100%
Area proposed for harvesting (hectares)	93,603					
Area still to be harvested (hectares)	2,427,848		Licensee sowing rate per tonne harvested (kg)	5	Dead wood tonnes per hectare	0.0128
			Seeds per kg	325	Minimum harvest diameter (mm)	127
Proposed harvest levels	Green tonnes per year	0	Routine Woylie sowing (seeds per harvested tree)	0		
	Dead tonnes per year	1,200	Additional landscape supplemental sowing (tonnes per year)	0		

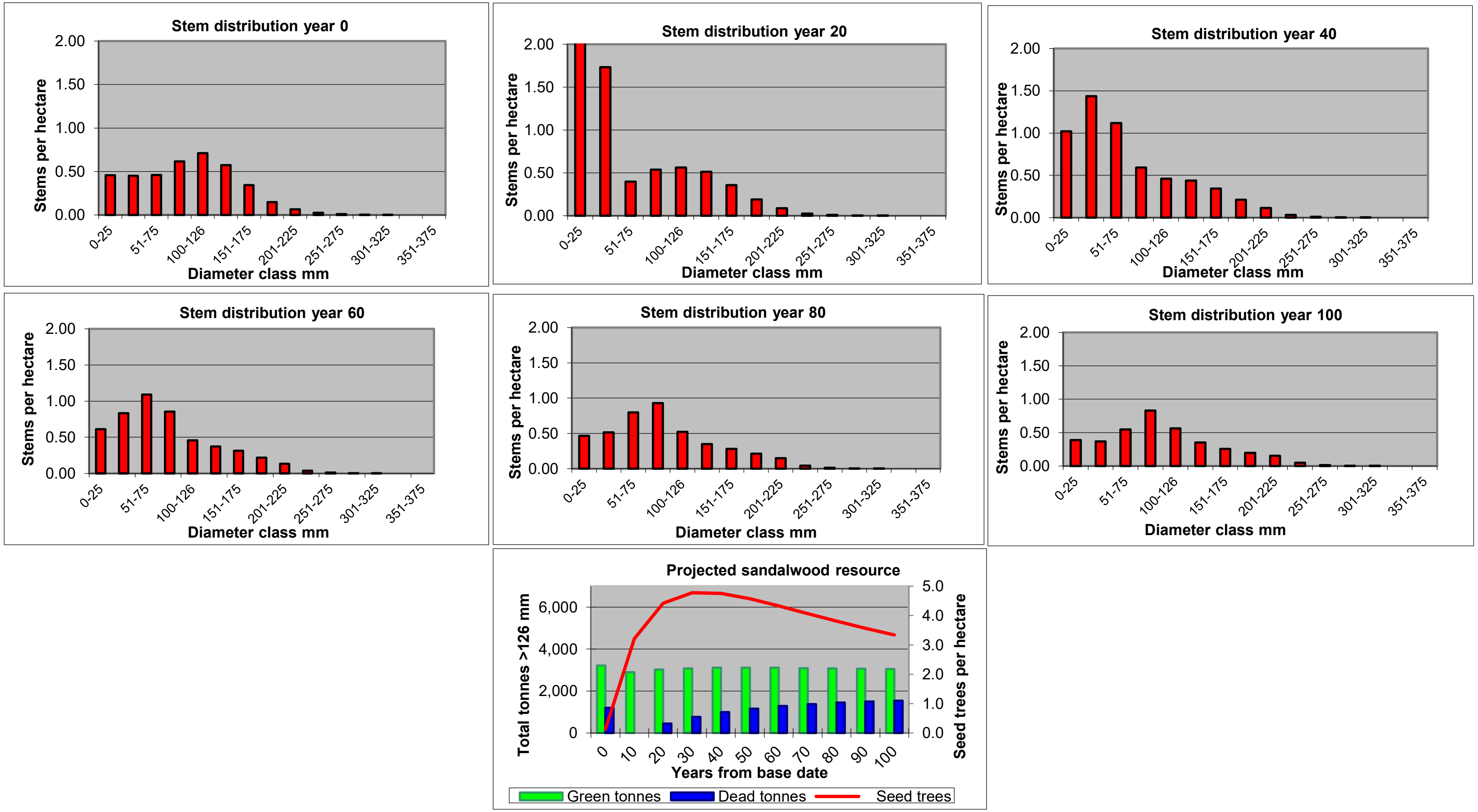


Figure 36. Progressive changes over time in tree diameter size class distribution and tree numbers within areas harvested for dead wood only to supply 1,200 tonnes per year for 10 years in the Eastern Murchison region (modelled subset: 4c dead wood harvest).

5.1.4 Sensitivity analyses

Model sensitivity analyses provide a useful indication of the magnitude of variation that can arise from changes in key model inputs; illustrate the interactive influence of variables; and inform the relative importance of inventory and data collection strategies to improve precision of model projections. To assess the sensitivity of the model projections to varying the initial diameter class distribution, growth and mortality rates, the sequence of model simulations for the two management scenarios described in Table 12 were conducted. Tables 13 and 14 compare the projected diameter distributions and available harvestable tonnes respectively at Year 40 for each of the simulations in each region. Figures 37, 38, 39 and 40 present the graphical output for each of the simulation combinations.

5.1.4.1 Population demographics

Table 13 highlights that SPP model projections of diameter distribution at Year 40 are highly sensitive to the initial diameter size-class distribution. In each region the projected number of stems per hectare across the 25-mm diameter size classes altered markedly when the default mean values derived from the contemporary inventory dataset were varied up or down by one standard error. The relative magnitude of change in each diameter class differed between regions, reflecting in part the difference between the inventory sample sizes contributing to the standard errors but also the inherent variability in the plot data. In each simulation in each region the difference in projected stem numbers per diameter class at Year 40 were greatest in the smaller diameter classes—around 30 per cent more in the 0–25 mm size class for simulations of +1 SE, and around 30 per cent less for simulations of –1 SE. These percentage differences progressively diminished with increasing tree size class in each scenario, highlighting in part the sensitivity of model outputs to the default recruitment and mortality rates applied to the younger trees in the model.

Accordingly, the projected diameter class distributions were also markedly sensitive to a combination of changes in the default values used for growth (-25%), mortality (+25%) and natural regeneration (-25%) variables. These variations to the long-term average default values were applied throughout the 40-year projection period, resulting in estimated stem numbers decreasing by 9 to 41 per cent depending on the diameter class, region and management scenario (Table 13). Note that the percentage change values mentioned here do not include the 276–300 and 301–325 mm diameter classes because they experienced 100 per cent decreases in estimated stem numbers due to having extremely small starting values (<0.001 stems per hectare). Absolute differences in stem numbers between the default scenarios and the alternative variable scenarios were highest for the smallest diameter classes (Table 13).

5.1.4.2 Potential tonnes available

Table 14 presents the sensitivity analyses for ‘Year 40’ projections of total tonnes of available commercial-size living and dead wood in Eastern Murchison and the Semi-Arid Rangelands. In the Semi-Arid Rangelands, varying the initial diameter distribution by a SE in each size class generated a 16 per cent increase (+1 SE) or decrease (-1 SE) in the projected commercial tonnes available by Year 40. However, using the mean diameter distribution but varying the combination of growth (-25%), mortality (+25%) and natural regeneration (-25%) resulted in a 28 per cent decrease in tonnes available, likely reflecting an increased sensitivity of tonnage estimates to the average growth rates applied to mature tree sizes over the projection period.

Similarly, varying the initial diameter distribution in Eastern Murchison projections generated a 12 per cent increase (+1 SE) or decrease (-1 SE) in the commercial tonnes available by Year 40, while varying the combination of growth, mortality and natural regeneration variables resulted in a higher (28 per cent) decrease in estimated tonnes.

The relative magnitude of changes for total tonnes for each region—varying by up to a third in these analyses—suggests a precautionary approach may be warranted when modelling and applying estimates of the potentially available commercial-sized resource to inform acceptable harvest limits. This could involve using initial diameter distributions based on the mean -1 SE values for each tree size class.

Table 13. Sensitivity of projected diameter class distributions at Year 40 to varying initial distribution or SPP model default values for two management scenarios in Semi-Arid Rangelands and Eastern Murchison regions. The blue highlight has been added to improve readability.

Modelled subset	**Basis of initial diameter classes**	**Diameter class (mm)**										
		0–25	**26–50**	**51–75**	**76–99**	**100–126**	**127–150**	**151–175**	**176–200**	**201–225**	**226–250**	**251–275+**
		Per cent change in stem numbers per hectare per class										
Semi-Arid Rangelands												
(2a) No harvest, no seeding	Mean + 1 SE	30.1	28.9	25.7	19.1	14.9	14.1	15.5	16.0	18.0	21.4	27.5
	Mean - 1 SE	-29.6	-28.6	-25.7	-19.1	-14.9	-14.1	-14.5	-16.0	-18.0	-21.4	-27.5
	Mean ± rate variables	-40.7	-35.8	-22.4	-11.2	-10.8	-13.8	-19.8	-29.5	-35.8	-38.6	-37.9
(2d) 500 tonnes living and 500 tonnes dead	Mean + 1 SE	27.1	22.1	17.9	17.4	14.9	14.2	15.2	16.4	18.4	21.8	28.0
	Mean - 1 SE	-30.7	-30.6	-28.2	-19.9	-14.9	-14.2	-15.2	-16.4	-18.4	-21.7	-27.7
	Mean ± rate variables	-40.9	-36.6	-27.1	-12.9	-10.8	-14.1	-20.4	-29.6	-35.9	-38.7	-37.9
Eastern Murchison												
(4a) No harvest, no seeding	Mean + 1 SE	28.2	27.2	18.7	13.5	14.2	10.0	3.3	-3.2	-10.1	-3.6	7.9
	Mean - 1 SE	-38.6	-33.2	-26.1	-19.2	-13.3	-13.1	-17.0	-22.9	-30.7	-33.1	-36.6
	Mean ± rate variables	-34.3	-24.8	-19.4	-13.3	-9.2	-10.9	-15.7	-21.3	-30.7	-30.2	-26.7
(4d) 500 tonnes living and 500 tonnes dead	Mean + 1 SE	30.3	21.8	11.6	12.3	14.2	9.8	3.6	-2.7	-9.7	-3.4	8.4
	Mean - 1 SE	-29.2	-26.0	-27.2	-19.8	-13.3	-14.2	-18.1	-23.7	-31.4	-33.9	-36.8
	Mean ± rate variables	-27.7	-22.1	-22.6	-14.1	-9.2	-11.6	-16.2	-21.6	-31.0	-30.8	-27.4

Table 14. Sensitivity of projected total available harvestable tonnes of living sandalwood at Year 40 to varying initial diameter distributions or SPP model default values for two management scenarios in Semi-Arid Rangelands and Eastern Murchison regions.

Modelled subset	Basis of initial diameter classes	Per cent change in total tonnes
Semi-Arid Rangelands (2a) No harvest, no seeding		
Mean available quantity of living sandalwood at Year 40 estimated as 300,000 tonnes	Mean + 1 SE Mean - 1 SE Mean ± rate variables	16.2 -16.2 -28.2
(2d) 500 tonnes living and 500 tonnes dead		
Mean available quantity of living sandalwood at Year 40 estimated as 296,000 tonnes	Mean + 1 SE Mean - 1 SE Mean ± rate variables	16.4 -16.4 -28.3

Eastern Murchison (4a) No harvest, no seeding		
Mean available quantity of living sandalwood at Year 0 estimated as 84,000 tonnes	Mean + 1 SE Mean - 1 SE Mean ± rate variables	12.2 -12.2 -28.1
(4d) 500 tonnes living and 500 tonnes dead		
Mean available quantity of living sandalwood at Year 0 estimated as 80,000 tonnes	Mean + 1 SE Mean - 1 SE Mean ± rate variables	12.8 -12.8 -28.4

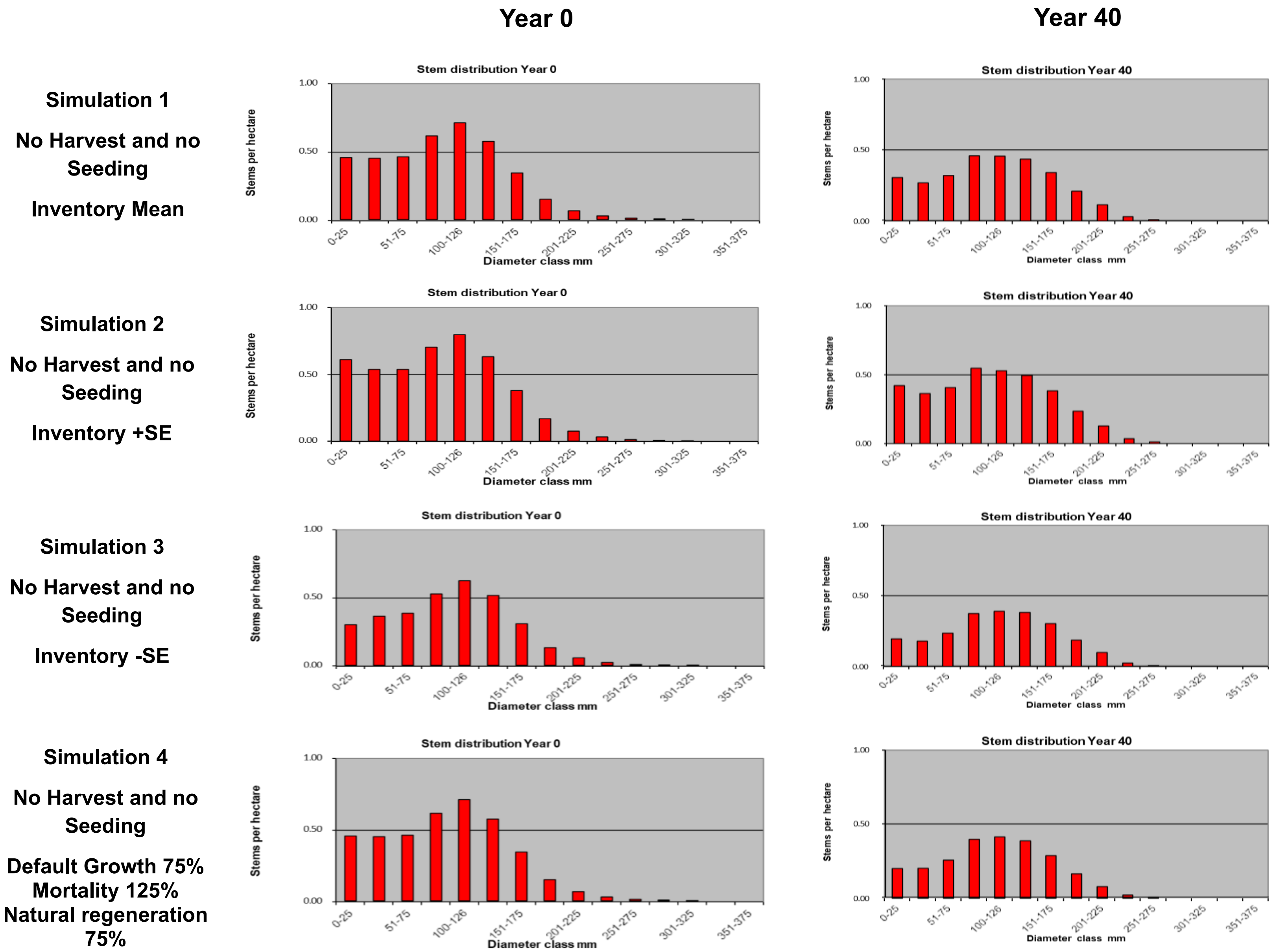


Figure 37. Comparison of diameter distributions at Year 0 and Year 40 from sensitivity simulations for the Eastern Murchison (modelled subset: 4a).

Year 0 **Year 40**

Simulation 1

500 tonnes living (green)
500 tonnes dead

Inventory Mean

Simulation 2

500 tonnes living (green)
500 tonnes dead

Inventory +SE

Simulation 3

500 tonnes living (green)
500 tonnes dead

Inventory -SE

Simulation 4

500 tonnes living (green)
500 tonnes dead
Default Growth 75%
Mortality 125%
Natural regeneration 75%

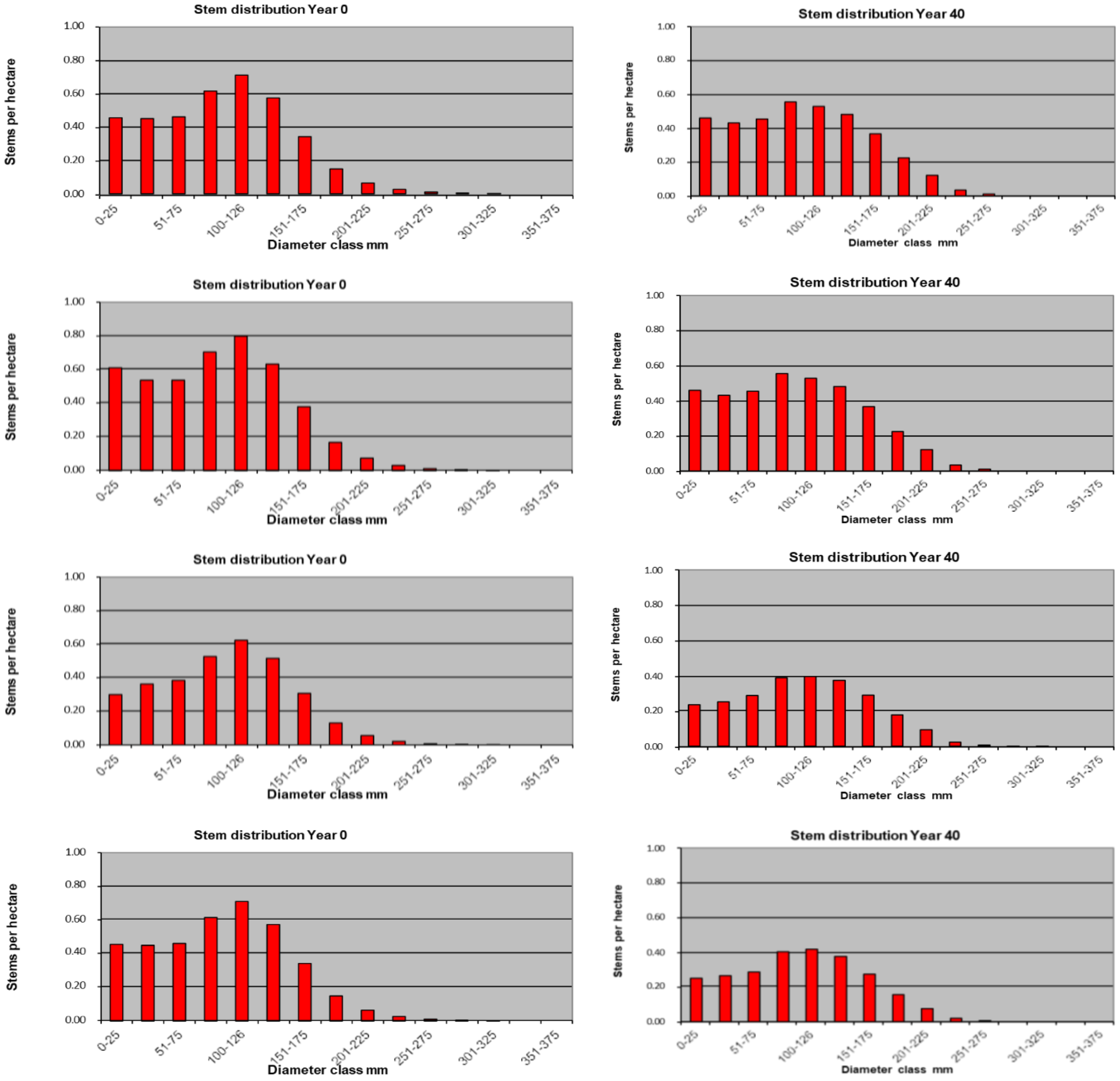


Figure 38. Comparison of diameter distributions at Year 0 and Year 40 from sensitivity simulations for the Eastern Murchison for harvest each year from year 0 to 10 years (modelled subset: 4d).

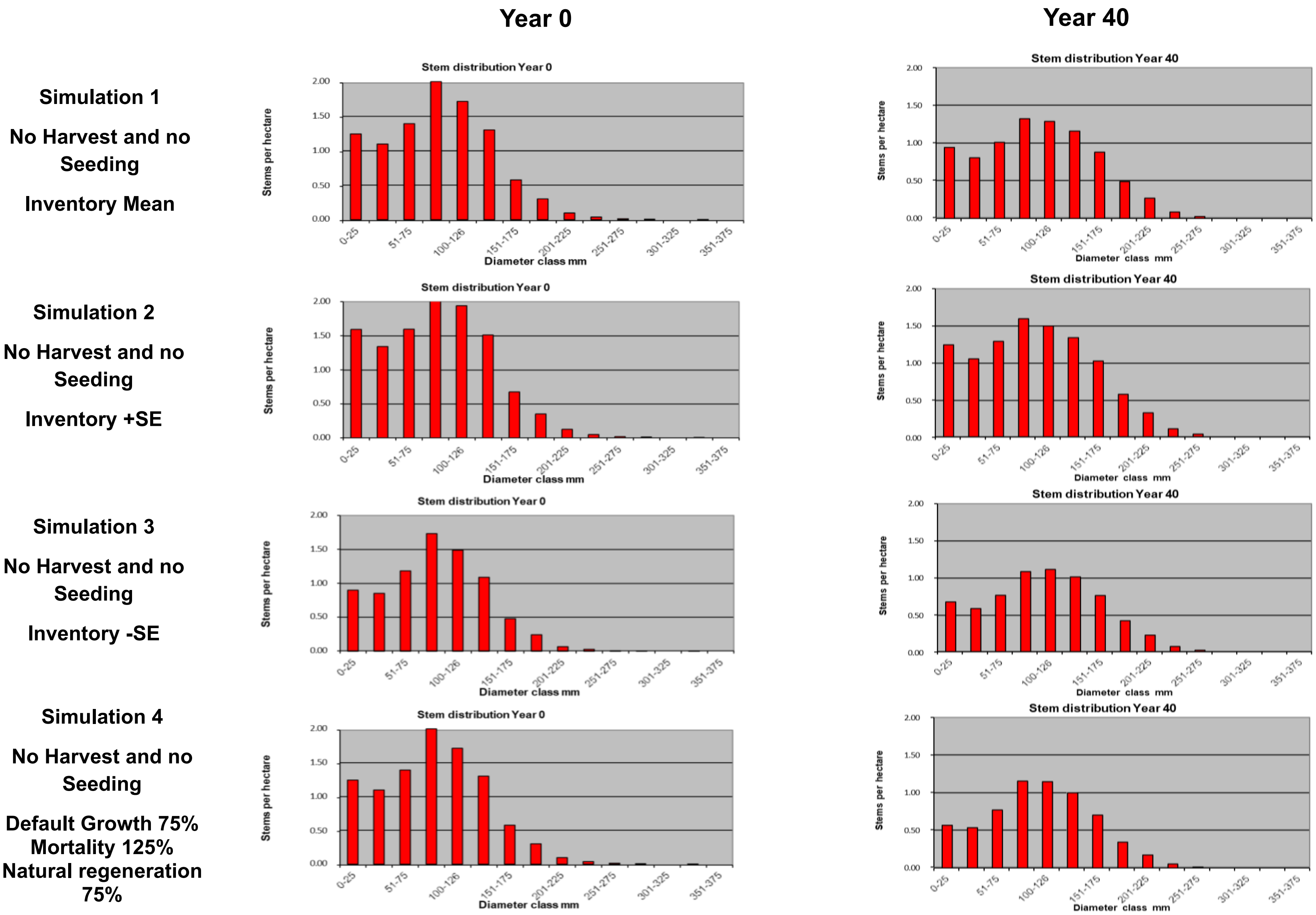


Figure 39. Comparison of diameter distributions at Year 0 and Year 40 from sensitivity simulations for the Semi-Arid Rangelands (modelled subset: 2a).

Year 0 **Year 40**

Simulation 1

500 tonnes living (green)
500 tonnes dead

Inventory Mean

Simulation 2

500 tonnes living (green)
500 tonnes dead

Inventory +SE

Simulation 3

500 tonnes living (green)
500 tonnes dead

Inventory -SE

Simulation 4

500 tonnes living (green)
500 tonnes dead

Default Growth 75%
Mortality 125%
Natural regeneration 75%

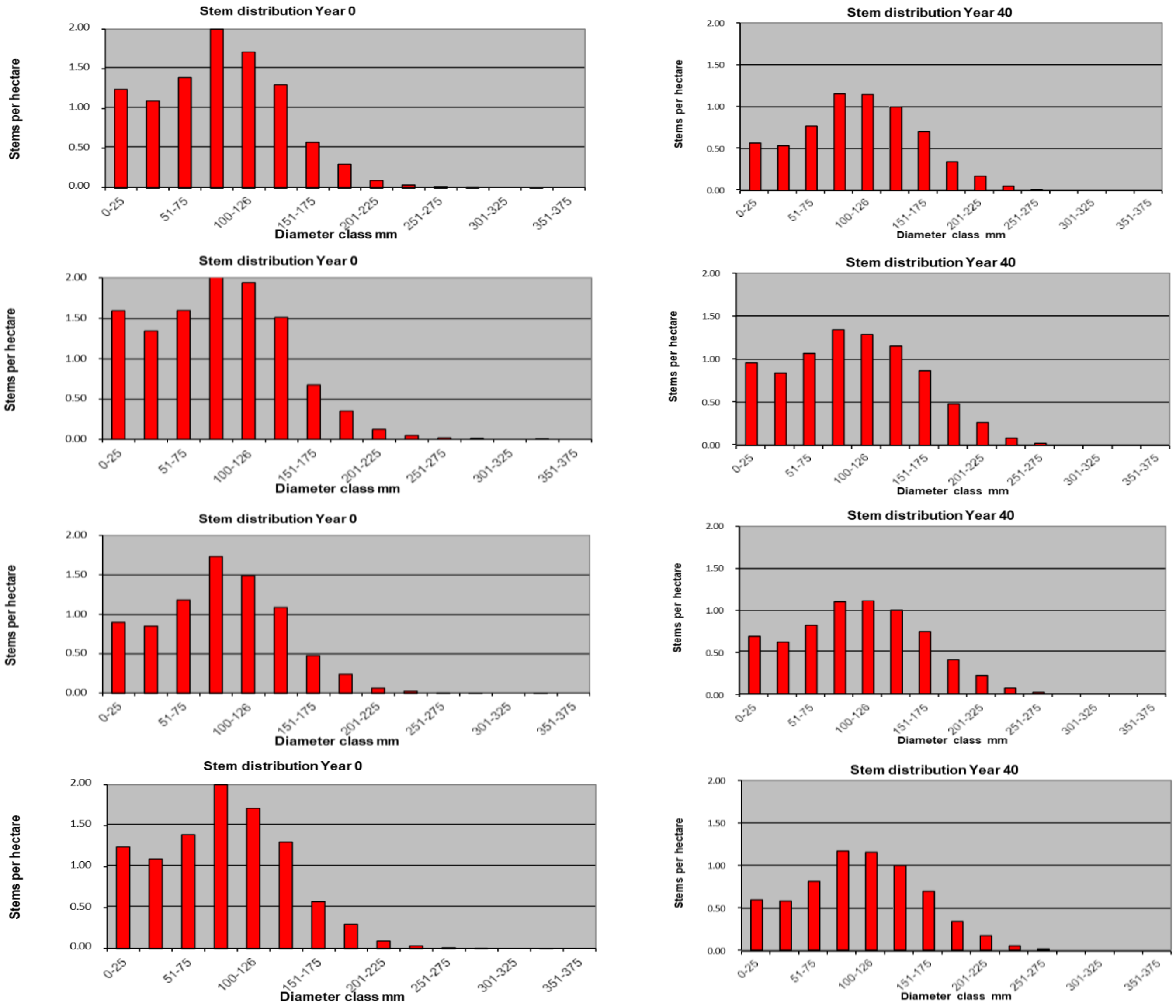


Figure 40. Comparison of diameter distributions at Year 0 and Year 40 from sensitivity simulations for the Semi-Arid Rangelands for harvest each year from year 0 to 10 years (modelled subset: 2d).

5.1.5 Persistent regeneration failure

Each of the management scenario simulations involving harvest of living or dead sandalwood (Table 10) assumed natural regeneration from existing trees was augmented for 10 years by regeneration established from seed sown by the licensee and the routine Operation Woylie program. The survival rates applied are based on long-term operational results which reflect the episodic nature of drought and other events that affect survival.

Simulations were undertaken for the management scenario in each of the Semi-Arid Rangelands and Eastern Murchison of harvesting 500 tonnes of living and dead sandalwood per annum for 10 years, but assuming seeded regeneration failed each year. Although highly unlikely, this extreme situation could arise if licensees failed to sow seed or long-term drought persisted across the region. While natural regeneration would still occur under the former situation, under the latter all regeneration would fail and hence a simulation to examine such an impact on future population structures was also conducted.

The impact of both possibilities for regeneration failure was to reduce the number of trees by Year 40 in the 0–50 mm size class. At the whole-of-region scale in the Semi-Arid Rangelands the number of trees in these size classes was reduced by between four and 25 per cent, reflecting the net contribution to restoration that would be forgone if no new regeneration was established for a decade. In the Eastern Murchison where much lower tree densities occur in each size class, the impact of forgoing regeneration from all sources for 10 years gave rise to major reductions of between 73 and 85 per cent in the 0–50 mm classes by Year 40. Such reductions lead to major declines in population structure relative to unharvested areas over the long term.

5.1.6 Minimum tree size thresholds for harvesting living sandalwood

The implications of increasing the minimum harvestable tree size on long-term population structure and area cutover was examined through simulations of two minimum harvestable tree size limits—≥127 mm and ≥151 mm—for modelled subset 4d (harvest 500 tonnes living, 500 tonnes dead in the Eastern Murchison). Figures 42 and 43 present the graphical outputs from these simulations. Within the areas harvested, higher tree densities are evident at Year 40 and Year 100 for the ≥127 mm tree size threshold compared to the ≥151 mm—more trees per hectare result over time because of the re-seeding quantities per individual tree removed, and those extra tree numbers carry forward over time such that even with subsequent mortality rates there are still more trees per hectare at Year 100 in the areas cutover to ≥127 mm. Moreover, higher numbers of seed trees per hectare are maintained over the simulation period with the ≥127 mm threshold than the ≥151 mm threshold.

For a specified annual quantity of living sandalwood under an Order, harvesting only trees in the ≥151 mm size classes may intuitively be considered more sustainable, as these trees are heavier (29–73 kg per tree) than those in the 127–150 mm class (18–22 kg per tree). Consequently, fewer trees are removed to achieve the same total annual quantity, potentially reducing disturbance per tonne harvested and preserving more seed trees to contribute to ongoing seedfall and regeneration. Further, trees in the larger size classes (≥151 mm) may be closer to senescence and more likely to succumb to environmental stress, making them more suitable for harvest than the younger, more vigorous 127–150 mm cohort. However, because larger trees are less frequent in the landscape, larger areas are necessary to be cut over to meet a specified annual quantity, while locating them in dispersed areas is likely to require more time and effort, which can reduce harvesting efficiency.

Comparatively, harvesting trees in both the 127–150 mm and ≥151 mm cohorts may offer greater economic efficiency, along with the benefit of promoting higher overall tree densities over the long term. The generally higher frequency of trees in the 127–150 mm size class can translate to lower logistical costs and reduced possible need for constructing new access tracks—an activity that carries its own ecological impacts. Their higher density also makes them easier to locate and harvest, improving overall operational efficiency.

The current legal size threshold for living harvestable trees is ≥127 mm diameter over bark, striking a balance between ecological sustainability and economic efficiency. This approach allows for removal of senescent trees while maintaining a higher harvesting efficiency from the more abundant ≥127 mm size class (Table 15).

Table 15. Potential trade-offs between the minimum harvestable tree sizes for a given target quantity of living sandalwood.

Consideration	Minimum diameter ≥127 mm	Minimum diameter ≥151 mm
Ecological	More trees harvested per tonne, proportionately younger age classes removed, but higher tree densities accrue in long term	Fewer trees harvested per tonne, older age classes targeted
Economic efficiency	Higher density of harvestable trees available	Lower density of harvestable trees available
Operational constraints	Easier to locate and harvest trees in concentrated areas	More effort required to locate fewer, dispersed large trees
Spatial extent	Example: 174,679 hectares required for harvest of 500 tonnes per year for 10 years in Eastern Murchison	Example: 252,102 hectares (44% more) required for harvest of 500 tonnes per year for 10 years in Eastern Murchison

The trade-offs listed in Table 15 and simulation comparisons discussed above apply at a strategic level when a set quantity of wild sandalwood is sourced. Other approaches, such as scaling the total annual quantity removed in proportion to the quantity available from trees in each size class grouping, could be considered. For example, the total quantity permitted to be removed if the tree size threshold was ≥151 mm would be proportionately less than if trees in the 127–150 mm size classes were also made available. However, the economics and disturbance arising from a larger cut over area in accessing and locating fewer dispersed trees across landscapes would still be a major consideration.

5.1.6.1 Review of under bark to over bark tree circumference relationship

A secondary task in the Sandalwood Order review is to review the minimum permitted size for take of living sandalwood under BC regulation 67(3)(c). This specifies that a sandalwood tree taken under a licence must not have an over bark circumference less than 400 mm (or 127 mm diameter) and an under bark circumference less than 380 mm, when measured at a point approximately 150 mm above ground level. However, analysis of recent field measurements for sandalwood stem circumference in the Goldfields and Wheatbelt Regions (Figure 41) predicts that for an over bark circumference of 400 mm (current minimum), a mean under bark circumference is 329 mm. This constitutes a difference of 51 mm to the current circumference of 380 mm assumed in the regulation. Further sampling is recommended to investigate the general applicability of the relationship depicted in Figure 41 before consideration of whether to amend the regulation.

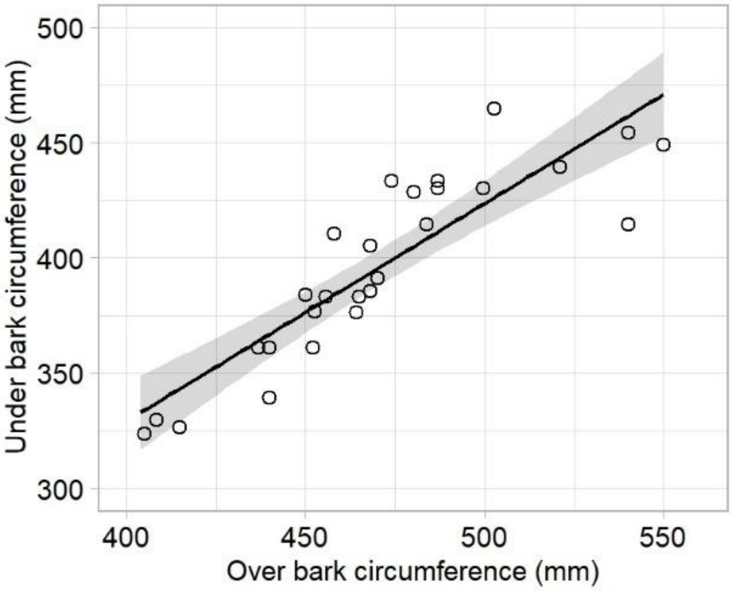


Figure 41. Predicted relationship between under bark and over bark circumference of sandalwood trees measured at 150 mm above ground level. The black line is the fitted model mean, and the grey band represents 95% confidence intervals. Circles depict tree circumference measurements.

Proposed harvest area 0–10 years

Region	Eastern Murchison		Survival rate per sown seed (Hand sowing)	0	Attrition rate of dead wood per decade	30%
Tenures	Available for harvest		Survival rate per sown seed (woylie)	1.0%		
Total area available for harvest (hectares)	2,521,451		Achievable utilisation rate	80%	Natural regeneration factor	100%
Area proposed for harvesting (hectares)	252,102					
Area still to be harvested (hectares)	2,269,349		Licensee sowing rate per tonne harvested (kg)	5	Dead wood tonnes per hectare	0.01282
			Seeds per kg	325	Minimum harvest diameter (mm)	151
Proposed harvest levels	Green tonnes per year	500	Routine Woylie sowing (seeds per harvested tree)	200		
	Dead tonnes per year	500	Additional landscape supplemental sowing (tonnes per year)	0		

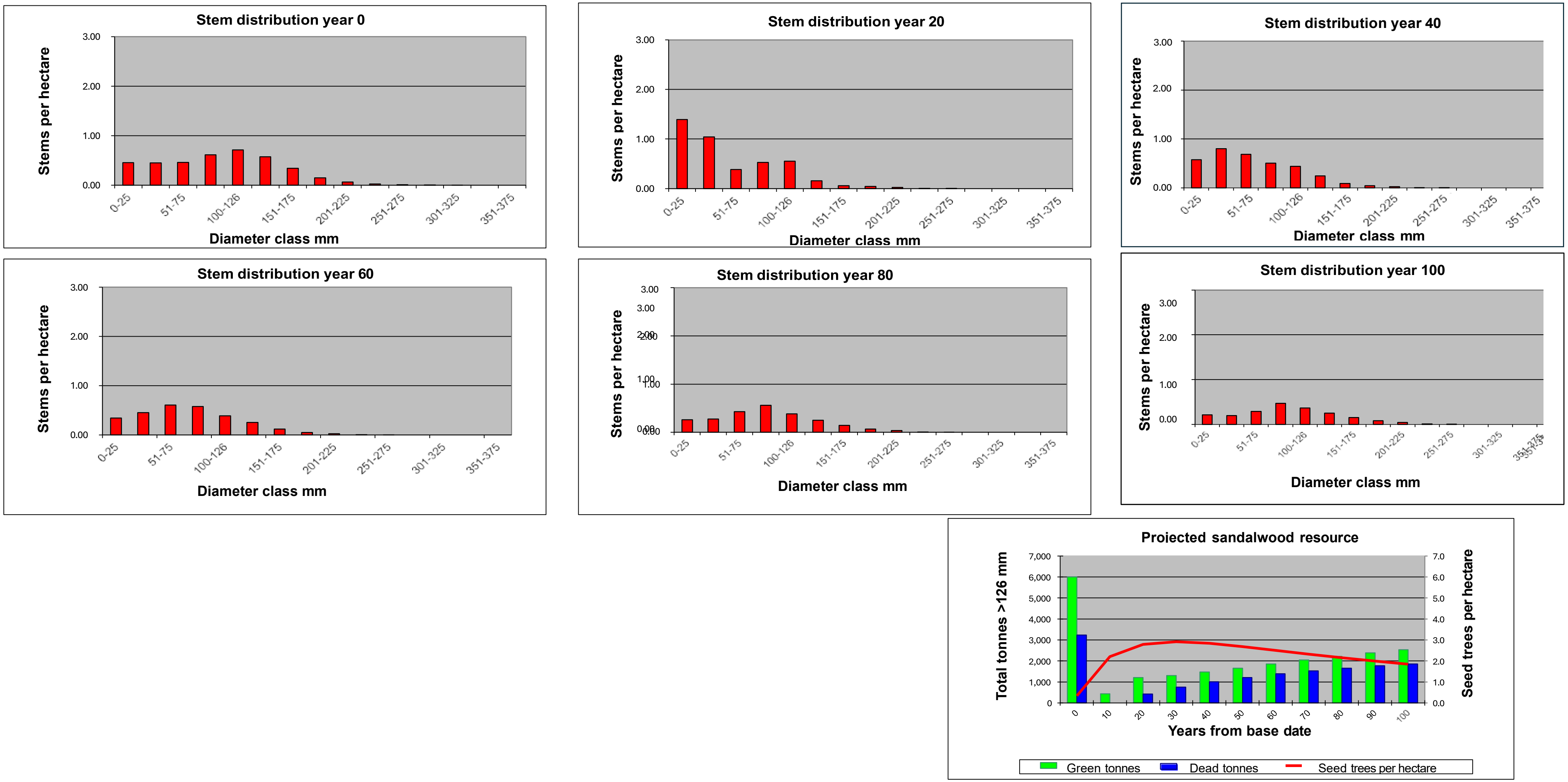
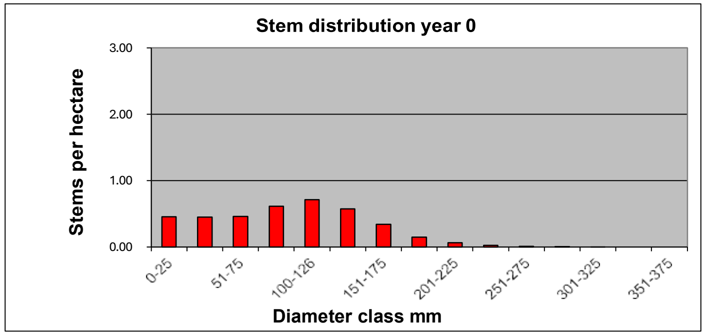
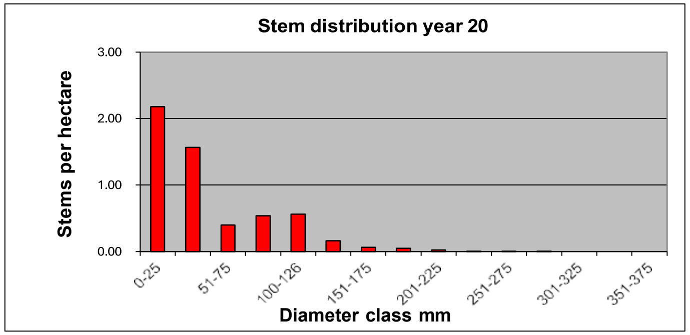


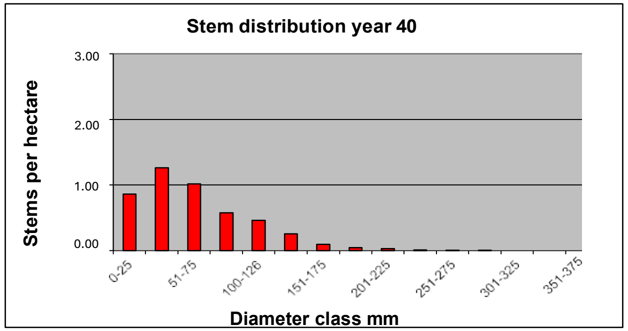
Figure 42. Simulation results for a minimum harvestable (living) tree size of 151 mm diameter for Eastern Murchison (modelled subset: 4d).

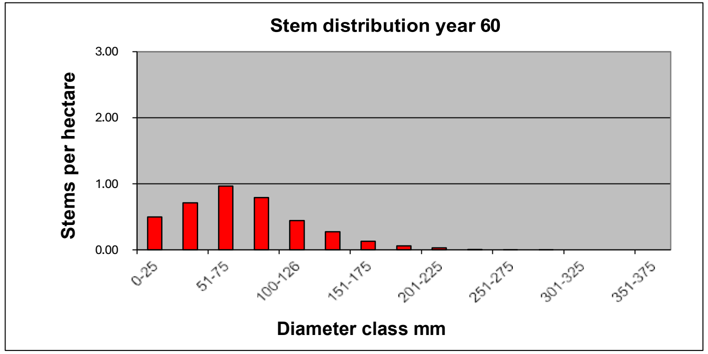
Proposed harvest area 0–10 years

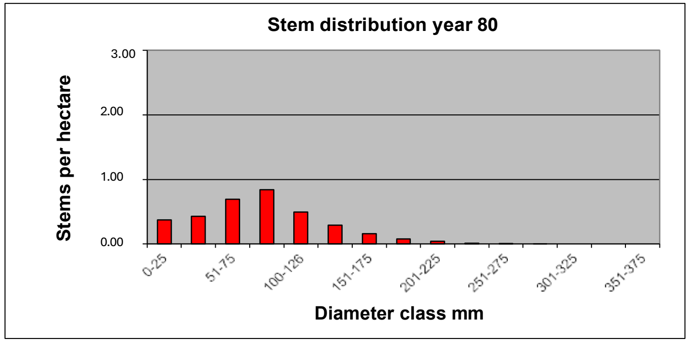
Region	**Eastern Murchison**		Survival rate per sown seed (Hand sowing)	2.1%	Attrition rate of dead wood per decade	30%
Tenures	Harvestable estate		Survival rate per sown seed (woylie)	1.0%		
Total area available for harvest (hectares)	2,521,451		Achievable utilisation rate	80%	Natural regeneration factor	100%
Area proposed for harvesting (hectares)	174,679					
Area still to be harvested (hectares)	2,346,772		Licensee sowing rate per tonne harvested (kg)	5	Dead wood tonnes per hectare	0.01282
			Seeds per kg	325	Minimum harvest diameter (mm)	127
Proposed harvest levels	Green tonnes per year	500	Routine Woylie sowing (seeds per harvested tree)	200		
	Dead tonnes per year	500	Additional landscape supplemental sowing (tonnes per year)	0		

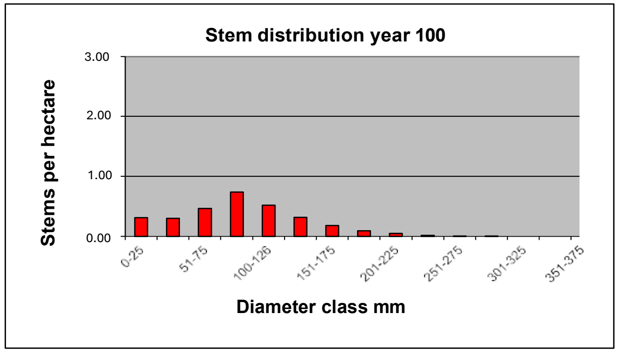












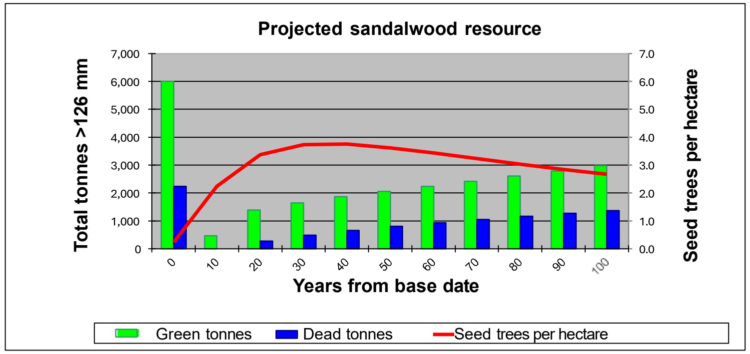


Figure 43. Simulation results for a minimum harvestable (living) tree size of 127 mm diameter for Eastern Murchison (modelled subset: 4d).

5.1.7 Licensee only seeding at harvest (no Operation Woylie supplemental seeding)

If circumstances arose whereby the landscape-scale Operation Woylie program ceased, the regeneration enhancement in harvested areas would depend solely on the direct seeding associated with harvest events. Simulations comparing the impact of licensee only seeding with licensee plus Operation Woylie seeding for modelled subsets 2d (Semi-Arid Rangelands) and 4d (Eastern Murchison) indicate the projected 'pulse' of recruitment into the 1–50 mm tree size classes by year 40 is markedly reduced if generated only from the direct seeding of five kg per tonne of sandalwood removed. The simulations suggest the extra recruitment provided through the Operation Woylie program constituted a further five per cent to tree numbers per hectare in this size class at the whole-of-region scale in the Semi-Arid Rangelands and over 18 per cent in Eastern Murchison (Table 16).

Table 16. Percentage increase in regeneration tree numbers at Year 40 attributed to supplementing licensee seeding with Operation Woylie program for 10 years.

Region	**Modelled subset**	**Annual quantity living sandalwood (tonnes)**	**Duration (years)**	**Percentage increase in tree numbers per hectare at Year 40 (%)[1]**	
				Diameter class (mm)	
				0–25	**26–50**
Semi-Arid Rangelands	2d	500	10	1.6	3.5
Eastern Murchison	4d	500	10	6.7	11.6

[1] Statistics are for whole-of-region, licensee seeding rate of 5 kg seed per tonne sandalwood removed, Operation Woylie at 200 seeds per harvested tree.

The percentage increases are correspondingly higher when calculated for only the harvested areas, but Table 16 highlights the contribution of Operation Woylie-style programs to restoration at the broader regional scale. Importantly, the simulations suggest the relative impact of the same seeding rate can be much higher if targeted toward the lower rainfall landscapes such as the Eastern Murchison where lower initial tree densities occur.

5.1.8 Extended duration of harvesting (beyond 10 years)

The scenario modelling suggested improved long-term population structures may arise from varied levels of harvest and seeding over a 10-year period. Simulations for modelled subsets 2f, 2d, 4f and 4d extending harvest and seeding at the same levels for a further 10-years (20 years in total) or 90 years (100 years in total) indicated a modest improvement in tree densities in the 0–50 mm diameter size classes at year 40 in each region and for the 20-year period relative to 10 years (Table 17). The improvement in stem densities at year 40 for the 100-year period was substantially higher, reflecting the continuous regeneration and recruitment to year 40. These trends at the whole-of-region scale were consistent whether 250 tonnes living and 500 tonnes dead or 500 tonnes living and 500 tonnes dead were removed each year.

Table 17. Percentage increase in regeneration tree numbers at Year 40 relative to 10-year harvest and seeding duration for 20 and 100-year durations.

Region	Modelled subset	Annual quantity living sandalwood (tonnes)	Duration (years)	Percentage increase in tree numbers per hectare at Year 40 (%)[1]	
				Diameter class (mm)	
				0–25	26–50
Semi-Arid Rangelands	2f	250	20	2.6	6.9
			100	25.0	16.7
	2d	500	20	3.3	8.9
			100	32.8	21.9
Eastern Murchison	4f	250	20	7.6	11.0
			100	50.9	21.7
	4d	500	20	9.5	14.1
			100[2]	66.0	28.0

[1] Statistics are for whole-of-region, licensee only seeding at rate of 5 kg seed per tonne sandalwood removed.

[2] Highly likely to be spatially infeasible, as over 72% of total sandalwood habitat would have to be cut over.

By year 100, the Semi-Arid Rangelands simulations suggest markedly higher tree densities would be present relative to year 1 in the larger tree sizes ≥151 mm. In contrast, the Eastern Murchison simulations suggest a marked reduction by year 100 in total tree numbers across all diameter classes ≥51 mm, reflecting the much lower initial tree densities and regeneration survival rates in this region.

The simulations suggest there could be sustained removal of these annual quantity levels in each region for up to 100 years. However, the nature of the SPP model and assumptions of consistent rates for variables across many decades suggest this may not be the case. The simulation is strategic in scope and does not evaluate spatial or economic feasibility. Results suggest that maintaining a 500-tonne annual harvest and seeding rate for 100 years would require harvesting approximately 27 per cent of the 3.63 million hectares of potential habitat in the Semi-Arid Rangelands and over 72 per cent of the 2.52 million hectares in the Eastern Murchison. Among the many assumptions for these multiple-decade simulations the ongoing availability of suitable, healthy host species in these landscapes is also a major consideration.

5.1.9 Seeding regimes required to attain pre-1750 population structures

Strategy 10 of the *Sandalwood BMP* outlines a series of actions to promote sandalwood seeding and regeneration operations across its geographic distribution. To date, implementation of annual landscape-scale seeding operations such as Operation Woylie have sought to enhance seedling numbers to levels beyond replacing the trees removed in harvested areas through sowing approximately 20 tonnes of seed each year. To provide context, the SPP model was used to estimate the scale of annual seeding rates required to restore entire sandalwood populations to pre-1750 structures in the Semi-Arid Rangelands and Eastern Murchison subregions.

Iterative simulations were conducted in which the annual seeding rates were incrementally increased until the tree diameter size class distributions visually approximated a negative exponential form—the structure hypothesised to be typical of undisturbed natural populations (see Figure 14).

Model simulations assumed:

- no harvesting occurs during the 100-year timeframe;
- seeding is applied continuously every year across the entire region;
- seedling survival and subsequent recruitment rates are as per model defaults; and
- used landscape-scale supplemental seeding for seed dispersal.

The amount of seed required to generate a distribution that approximates a negative exponential form and stabilised the number of seed trees per hectare was:

- Eastern Murchison: 25 tonnes per year for 100 years (Figure 44); and
- Semi-Arid Rangelands: 40 tonnes per year for 100 years (Figure 45).

However, while the distribution approximated a negative exponential form, the tree numbers per diameter class were much lower than the target levels in Figure 11. Further model simulations indicated the amount of seed required to achieve the form and tree frequencies hypothesised to have existed prior to disturbance was much higher:

- Eastern Murchison: 100 tonnes per year for 100 years; and
- Semi-Arid Rangelands: 120 tonnes per year for 100 years.

The simulations suggest the Semi-Arid Rangelands would require a higher annual seed input due to the larger sandalwood habitat area of 3.63 million hectares, compared to 2.52 million hectares in the Eastern Murchison. Additionally, achieving the desired tree distribution in younger age classes demands more young stems in the Semi-Arid Rangelands than in the Eastern Murchison, which has a lower stem carrying capacity.

The Operation Woylie program is currently the primary method for landscape-scale targeted seeding, with an estimated annual cost of around $1 million to sow 20 tonnes of seed (approximately 6.5 million seeds), excluding any heritage survey expenses (Sandalwood Manager FPC, personal communication, 15 October 2025). Scaling this cost proportionally to achieve negative exponential distributions in both regions (using 65 tonnes per year) would require a budget of approximately $3.25 million per year or $11 million per year (using 220 tonnes per year) to achieve the hypothesised pre-1750 population structures (Table 18). The supply of this quantity of seed in perpetuity is also unlikely to be available or sustainable.

Table 18. Indicative funding required to apply annual seeding at rates simulated to achieve negative exponential size class distributions in the Semi-Arid Rangelands and Eastern Murchison regions.

Restoration seeding outcome	Seeding quantity (tonnes per year)	Estimated annual cost ($ million)
Approximate negative exponential distributions	65	3.25
Approximate pre-1750 structure and tree numbers	220	11.0

This simplistic analysis, applied to the potential sandalwood habitat in only two regions, illustrates the likely scale, duration and funding needed to fully restore population structures across entire landscapes. These figures highlight the prohibitive financial and logistical demands of implementing large-scale restoration solely through seeding. Moreover, the unattainability of the estimated seed quantities required, and the cost and feasibility of ongoing management of threats to seedling persistence (such as control of grazing animals) has not been considered.

The current funding model, whereby Operation Woylie is financed through revenue from sandalwood sales by FPC, may not be sufficient to support expanded seeding programs. While moderate seeding may be achievable under existing frameworks, intensive restoration scenarios would likely require external funding and strategic partnerships.

A hybrid approach, integrating selective harvesting and broader seeding programs, may offer a more cost-effective approach to assisting restoration of large areas. Re-seeding in conservation reserves may also be an option funded through proceeds of harvest from areas available for harvest and/or other external funding.

Whole of Region

Region	Eastern Murchison		Survival rate per sown seed (Hand sowing)	2.1%	Attrition rate of dead wood per decade	30%
Tenures	Harvestable estate		Survival rate per sown seed (woylie)	1.0%		
Total area available for harvest (hectares)	2,521,451		Achievable utilisation rate	80%	Natural regeneration factor	100%
Area proposed for harvesting (hectares)	0					
Area still to be harvested (hectares)	2,521,451		Licensee sowing rate per tonne harvested (kg)	0	Dead wood tonnes per hectare	0.01282
			Seeds per kg	325	Minimum harvest diameter (mm)	127
Proposed harvest levels	Green tonnes per year	0	Routine Woylie sowing (seeds per harvested tree)	0		
	Dead tonnes per year	0	Additional landscape supplemental sowing (tonnes per year)	25		

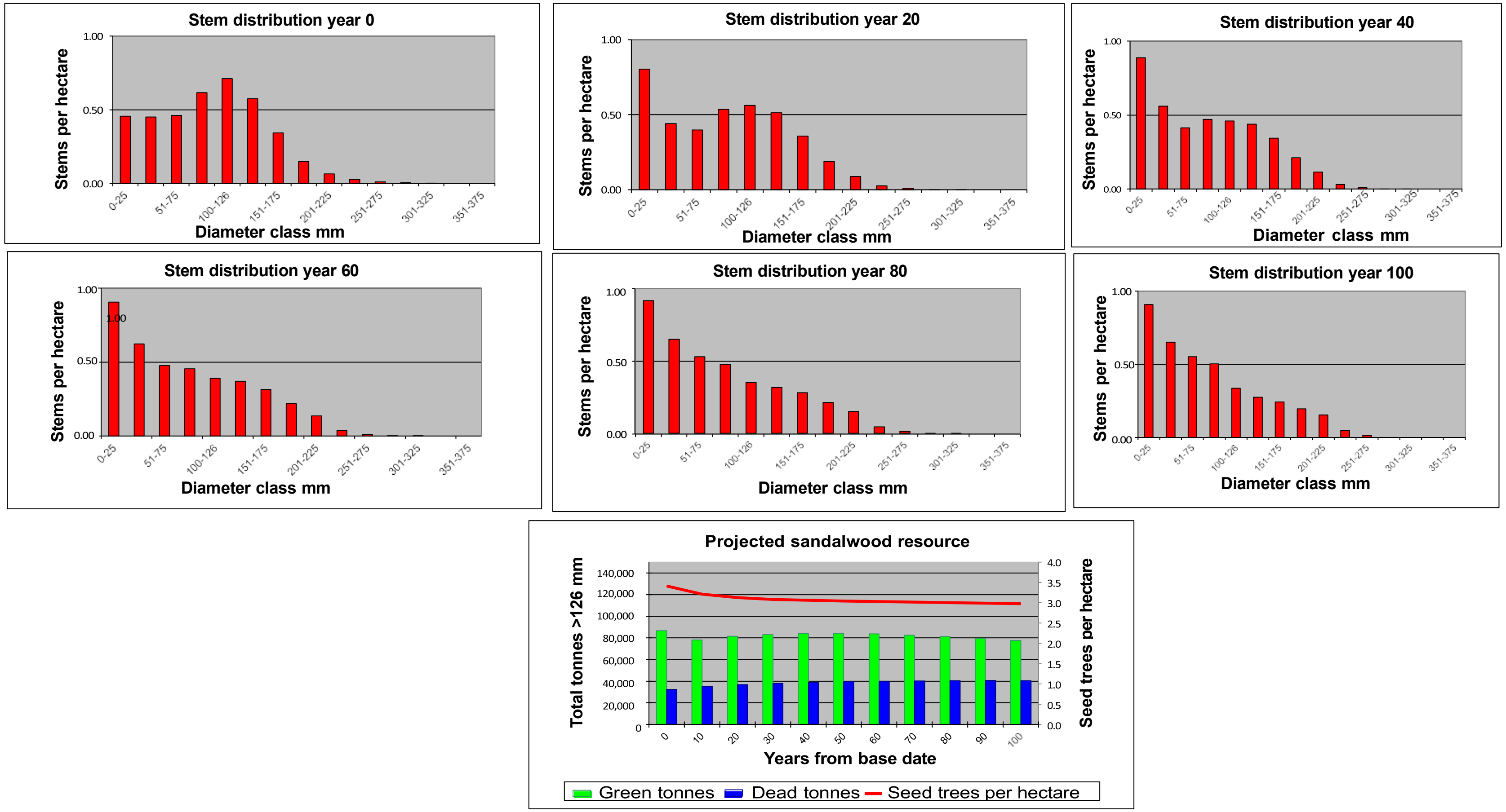


Figure 44. Simulation results to approximate a negative exponential population structure for the Eastern Murchison (modelled subset: 4b no harvest, 25 tonnes of seed per year).

Whole of Region

Region	**Semi-Arid Rangelands**		Survival rate per sown seed (Hand sowing)	2.1%	Attrition rate of dead wood per decade	30%
Tenures	Harvestable estate		Survival rate per sown seed (woylie)	1.0%		
Total area available for harvest (hectares)	3,630,127		Achievable utilisation rate	80%	Natural regeneration factor	100%
Area proposed for harvesting (hectares)	0					
Area still to be harvested (hectares)	3,630,127		Licensee sowing rate per tonne harvested (kg)	0	Dead wood tonnes per hectare	0.01282
			Seeds per kg	325	Minimum harvest diameter (mm)	127
Proposed harvest levels	Green tonnes per year	0	Routine Woylie sowing (seeds per harvested tree)	0		
	Dead tonnes per year	0	Additional landscape supplemental sowing (tonnes per year)	40		

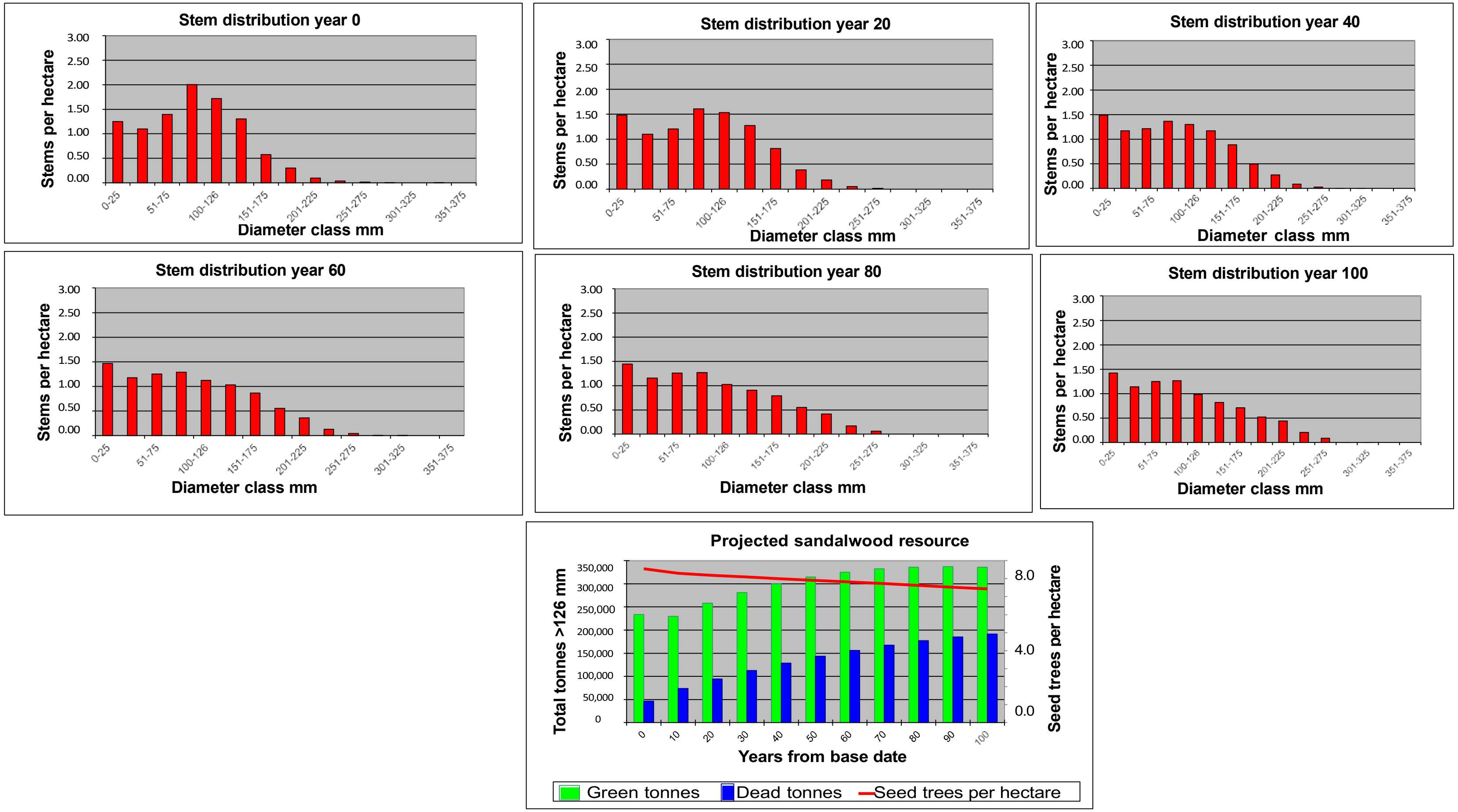


Figure 45. Simulation results to approximate a negative exponential population structure for the Semi-Arid Rangelands (modelled subset: 2b no harvest, 40 tonnes of seed per year).

5.1.10 Impact of additional landscape-scale supplemental seeding programs

Table 11 lists a series of simulations for the Semi-Arid Rangelands and Eastern Murchison in which the quantity and scale of seeding is consecutively increased through licensee seeding, Operation Woylie program, and additional landscape-scale supplemental seeding programs.

In each region, complementing the licensee seeding with Operation Woylie programs (20 tonnes per annum) progressively increased the number of trees in the regeneration cohort at year 40. These ‘pulses’ of regeneration were appreciably enhanced by additional landscape-scale seeding during the 10 years of harvesting, with additions of up to three tonnes each year in Semi-Arid Rangelands and seven tonnes each year in Eastern Murchison. At these highest levels, the density of trees in the regeneration size classes (0–50 mm) increased by up to nine percent at the whole-of-region level.

Overall, these results highlight a key finding from the modelling—that substantive landscape-scale restoration outcomes can only be achieved if supplemental seeding (beyond only the licensee direct seeding at current quantity and averaged survival rates) is also undertaken and maintained over time.

5.1.11 Residual risks and mitigation measures for modelled scenarios

A range of assumptions are inherent in the scenario modelling and hence underpin the interpretation of results. Where assumptions are not met there are risks the long-term viability of sandalwood populations may be impacted by decisions based on the modelling. Mitigation measures can be put in place to address these risks, but a level of residual risk can remain depending on their implementation.

Table 19 summarises key risks for the modelled scenarios and potential mitigation measures. A universal feature of modelling is the uncertainty surrounding both the SPP model and the underlying datasets. While the model provides a structured framework for exploring potential outcomes under different harvesting and restoration strategies, its outputs are sensitive to a wide array of environmental variables such as tree mortality rates, regeneration success, and the uncertain impacts of climate change.

Moreover, the datasets used to initialise model simulations are subject to sampling error and potential bias, which may affect the representativeness of the projections. To mitigate this, the modelling approach has adopted conservative input variables, including the use of lower-bound standard errors where applicable. These measures aim to reduce the risk of overestimating population resilience or regeneration success. However, even with these precautions, the complexity of ecological responses and the potential for compounding climate impacts mean that residual risks remain across all scenarios.

Table 19. Identified risks to sandalwood population decline for modelled management scenarios and potential mitigation measures.

Scenario	Risks to population decline	Mitigation measures	Residual risk
All	Illegal harvesting continues or escalates	Provision of enforcement resources	Failure to resource or declining resources over time
	Projection modelling underestimates rates of change (for example, tree mortality)	Continuation and expansion of DBCA-led inventory and monitoring program	Failure to resource or declining resources over time
No harvesting, seeding	Decoupling of seed collection capacity reduces ability to restore at landscape scale	Maintain wild seed orchards and define acceptable plantation sources Support Aboriginal seed collection and storage initiatives	Poor set seed associated with extended droughts leads to insufficient seed stocks
Annual take and seeding at varying levels for 10 years	Failure of seeding programs to establish regeneration cohort	Licence approvals require evidence of regeneration monitoring	Extended droughts lead to consistently low regeneration rates
		Landscape-scale monitoring programs and partnerships in non-harvest areas	Failure to resource or declining resources over time
	Projection model inputs have large inventory sampling error and imprecise or biassed estimates of growth, mortality and recruitment leading to overestimates of future size class distributions and standing harvestable resource	Consider annual allowable take limits based on conservative lower bounds of inventory estimates and projected growth and mortality rates.	
	Projection modelling underestimates rates of change (for example, disruption of pollination system and declining seed set) and overestimates seeding recruitment success	Continuation and expansion of DBCA-led inventory and monitoring program. Research into sandalwood ecological patterns and processes	Failure to resource or declining resources over time
	Insufficient management of threatening processes (including invasive pests) impacts long-term persistence of regeneration cohort	Licence approvals incorporate plans for management	Failure to monitor compliance with plans
		Expansion of DBCA-led monitoring of population condition	Failure to resource or declining resources over time

Mitigation measures such as increased compliance monitoring, enforcement and expanded population condition monitoring programs are proposed to address many risks, but their effectiveness will depend on sustained resourcing and commitment.

In scenarios where there is no harvesting, there is no associated seed collection for the obligatory establishment program, creating a potential shortage that limits restoration efforts even at a local scale. Mitigation strategies include maintaining wild sandalwood seed orchards, defining acceptable plantation sources (maintaining appropriate genetic diversity), and supporting seed collection initiatives by Aboriginal people. Nonetheless, extended droughts may result in poor seed set and insufficient seed stocks, limiting regeneration potential.

The 'Annual take and seeding at varying levels for 10 years' scenarios introduce further risks related to the completion and success of seeding programs, as well as the long-term persistence of established regeneration. Seeding may fail to achieve sufficient recruitment, particularly under prolonged drought conditions. Licensing requirements that mandate evidence of regeneration monitoring aim to mitigate this risk, but consistently low rainfall could still result in poor outcomes despite compliance.

Management of the residual risks to ensure restoration of sandalwood populations will depend on adaptive management to address ecological and climatic challenges, underpinned by robust monitoring, and managing sociological issues including illegal harvest activity.

5.2 Desert regions

As highlighted in Sections 4.2.3.2 and 4.3.2.2, the inventory datasets sampling the Desert regions were not directly modelled using the SPP model. They were, however, used in combination with the derived areas of potential habitat to develop preliminary estimates (order of magnitude) of total quantities of harvestable-sized sandalwood that might be available in these regions. These provided useful context when developing the nominal regional allocations summarised in Figure 30.

The inventory datasets were extrapolated to the net areas of 'Medium or High probability' sandalwood habitat derived from buffering the creek stratification in respective Desert regions (Table 3). These areas were identified as the most probable sandalwood habitats under current and future climate conditions. Specifically, the number of sandalwood stems equal to or exceeding 126 mm[19] in diameter was estimated within creek systems located in less fire-prone areas and outside conservation reserves.

Using the standard error associated with the demographic data (see Section 4.3.2.2 Great Victoria Desert and Western Deserts population structures), estimates of tree numbers of minimum diameter 126 mm were calculated for each Desert subregion (Table 20). The lowest weight per tree for each diameter size class (see Section 4.4.2.13 Stem weight by tree size class) was then applied to estimate the indicative quantity potentially available in each region. The order of magnitude of these notional quantities informed the range of allocations for Desert regions in Figure 30.

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[19] A minimum size class of ≥126 mm was used here, instead of the minimum legal permissible size class under the BC regulations of ≥127 mm, because the sandalwood licence inventory data was collected in different size classes to the DBCA-led survey (0–24 mm, 25–125 mm and 126–174 mm, and >174 mm).

Table 20. Notional quantities of harvestable sandalwood in the Desert regions extrapolated from derived stratification and limited localised inventory datasets.

IBRA subregion	**Area of 'Medium or High' probability sandalwood habitat in creek systems (hectares)**	**Total quantity of living sandalwood ≥126 mm diameter (tonnes)**		
		Basis of inventory diameter classes applied		
		Mean - SE	Mean	Mean + SE
Shield	236,703	3,372	4,500	5,628
Central	384,438	5,477	7,309	9,140
Carnegie	181,283	2,897	3,937	4,976
Trainor	131,487	2,102	2,856	3,609
Lateritic Plain	274,026	4,380	5,951	7,522
Totals		18,228	24,552	30,877

5.3 Notional harvest levels relative to estimated total growing stock

When considering potential harvest limits, a helpful indicator of long-term sustainability involves consideration of the level of removals relative to the current total estimated 'growing stock' (or quantities)—the total volume (or mass) of commercial-sized living trees in the forest (Montreal Implementation Group, 2018). Removal of a small proportion of the total available quantities, relative to the time required for new growth to replace the quantity removed, provides reassurance that the rate of removals is unlikely to lead to long-term decline in population size and structure if regeneration and recruitment is sustained.

In the case of wild sandalwood, a key challenge is ensuring establishment of a replacement regeneration cohort in the first instance, and then the lengthy period necessary for 'new' regeneration to grow to commercial size (≥127 mm)—potentially 100 to 200 years depending on site and conditions.

The SPP model provides an estimate of the current total quantities based on the initial diameter distribution. In a conservative approach, quantity estimates for each of the regions were compiled using the initial diameter distribution minus one standard error for Eastern Murchison and Semi-Arid Rangelands, and the -1 SE values for Deserts (Table 20). These values were then reduced to make provision for the proportion of mature trees to be retained under licence conditions, and a further reduction for 'available' trees not located during harvest operations. Table 21 illustrates the relative magnitude of notional harvest limits that would correspond to a 200-year replacement period. Importantly, these limits are of similar order of magnitude as the scenarios modelled in Table 10, serving as a gross check that quantities of this magnitude could be removed during the 10-year period of the Sandalwood Order without jeopardising long-term sustainability of the total quantities, provided a replacement regeneration cohort was established.

Table 21. Hypothetical derivation of annual harvest quantities if current quantity levels are to be maintained over a 200-year period.

Region	Standing quantities[1] ≥127 mm (tonnes)	Standing quantities reduced for retention and extraction provisions (tonnes)	Notional quantity available per decade if 200 years to replace (tonnes per decade)	Notional annual quantity (tonnes per year)
Eastern Murchison	75,032	54,023	2,701	270
Semi-Arid Rangelands	186,133	134,016	6,700	670
Deserts	18,228	13,124	656	66

[1] Estimated from (inventory mean minus 1 SE) for each tree diameter size class.

6. Assessment of sandalwood management scenarios for Ecologically Sustainable Use

The modelling and analyses have illustrated the potential impacts on future population structure of a spectrum of management scenarios, from ‘do nothing’ to varying levels of harvesting of living trees and dead wood. A broader assessment of the alignment of each scenario with ESU was undertaken to inform subsequent integration with ESD considerations to recommend an acceptable level of harvest under the next Sandalwood Order. The ESD considerations and integration approach are outlined in the *Draft Review Report*, while the following sections describe the approach, criteria used and outcomes of the ESU risk assessment.

6.1 General considerations

The assessment of current sandalwood population structures (see Section 4.3 Analysis of sandalwood population demographics) and exploration of potential future structures and quantities (see Section 5 Results and discussion) under contrasting harvest and regeneration scenarios provides a sound basis for considering ESU of wild sandalwood. However, while long-term projections of landscape-scale population structure are an important indicator of ESU, a further consideration when harvesting is proposed is that the level does not lead to long-term, irreversible decline in ecological processes that support and maintain biodiversity—including carbon, water, nutrient and energy cycles. These operate at varying spatial and temporal scales, but a key assumption in this work is that the likelihood of long-term disruption and decline of these processes is managed through the hierarchy of regional protocols and local constraints associated with licences to harvest, such as the retention of living trees smaller than the minimum size limit and a proportion of the largest trees, soil disturbance provisions, harvest dispersion constraints, and seeding requirements. These risks increase relative to the quantity of sandalwood harvested (and hence the area cutover and regenerated) relative to the total extent and size of suitable habitat within the region.

6.2 ESU risk assessment approach and criteria

During a workshop, a matrix (Table 22) was prepared by members of the DBCA working group (for the review of the Sandalwood Order) to generate a ranking of each scenario, based on a composite score calculated across selected criteria. Each criterion and their relative weighting to the overall composite score was selected to summarise the potential positive or negative impacts on long-term persistence (health) or decline of sandalwood and associated biodiversity at the landscape scale. Assumptions considered in the assessment included measures in place to mitigate risks, such as risks of regeneration failure for seeding and supplemental seeding.

The ESU criteria examined for each scenario include the relative loss of mature living trees in the landscape (hence potential reductions in fauna habitat and associated biodiversity; genetic diversity, carbon stores and natural regeneration potential) and localised site degradation, contrasted against potential benefits on regeneration and management of threatening processes at the landscape scale. In Table 22, the regeneration and threatening processes criteria are also assessed in relation to funding requirements, but these are also part of a broader ESD assessment discussed in the separate *Draft Review Report*.

Table 22. Relative scores and ranking of wild sandalwood management scenarios assessed against Ecologically Sustainable Use.

Management scenario (refer Table 10)	Potential negative impacts on biodiversity and long-term decline in sandalwood. **Highest score = 15**			Potential benefits on biodiversity and contributing positively to the long-term health of sandalwood. **Highest score = 15**			Overall ranking (Total benefits minus impacts)
	Loss of mature living trees in the landscape leading to loss of fauna habitat and associated biodiversity, as well as loss of genetic diversity, carbon stores and regeneration[1] **Max score = 10**	Localised disturbance[2] **Max score = 5**	Reliance on new funding to carry out the scenario to ensure it is sustained over the long-term **Yes/No**	Regeneration impact at the landscape scale **Max score = 12**	Management of threatening processes at the landscape scale **Max score = 3**	Self-sustaining funding to ensure the scenario is sustained over the long-term **Yes/No**	**Highest score = 15**
1. No harvesting and no regeneration program.	5 Mature living trees will only be lost through natural mortality.	0 If there is no harvesting or active seeding program, there will be no localised disturbance associated with these activities.	N/A	0 Regeneration will be entirely dependent on natural processes and therefore populations will continue to decline.	0 The 'do nothing' approach will not provide for management of threatening processes.	N/A	-5 This scenario is considered the least beneficial for maintaining or improving the condition and persistence of the species at both the local and landscape scales.
2. No harvesting, but with a modest landscape-scale regeneration program (20 tonnes of seed per year = 25,000 hectares of area) that is not funded by industry – approximately $1million per year (minimum).	5 Mature living trees will only be lost through natural mortality.	1 There is likely to be a small amount of localised disturbance from seeding operations. This may vary depending on the regeneration program (machines or hand seeding).	Yes This scenario will require 100 per cent reliance on new funding.	9 This ranking accounts for the risk of regeneration failure (and risks such as potential drought) and that the scale of regeneration under this scenario will have a modest impact on landscape-scale restoration. However, this program can be targeted in areas that will benefit most from seeding including conservation reserves.	1 This ranking assumes that there will be limited funding for management of threatening processes due to funding not being sustained through profits generated through the sale of sandalwood products. An establishment program has higher likelihood of being targeted to known areas with less threatening processes.	No This scenario will require external funding that will not be supported by industry in the absence of wild harvest.	4 This overall ranking is better than a 'do nothing' scenario, but it acknowledges that the overall benefit at a landscape scale is modest. However, this scenario results in approximately 25,000 hectares of area seeded per year over 10 years, including targeted seeding in conservation reserves.
3. Harvesting of only dead wood (2,500 tonne limit) with 20 tonnes per year landscape-scale targeted regeneration program, as well as re-seeding required as	5 Mature living trees will only be lost through natural mortality.	2 The harvest area covers a larger area than Scenario 4, but it should be a lighter footprint, as there is less potential mechanical disturbance. This assumes licence	No The revenue from the harvest to this removal limit of dead wood will help fund regeneration. This assumes that all dead wood harvest	10 Approximately 25,000 hectares of seeding per year will substantially improve regeneration outcomes at a local level and will have a	2 This ranking considers that within the seeded areas (not necessarily harvested areas) there will be greater resources allocated to management of	Yes Seeding programs associated with harvesting of dead wood, are expected to be self-funded due to	5 This has been assessed as providing a better outcome overall than Scenario 2 (mainly due to more resources to manage threatening processes and undertake seeding). This

Management scenario (refer Table 10)	Potential negative impacts on biodiversity and long-term decline in sandalwood. **Highest score = 15**			Potential benefits on biodiversity and contributing positively to the long-term health of sandalwood. **Highest score = 15**			Overall ranking (Total benefits minus impacts)
	Loss of mature living trees in the landscape leading to loss of fauna habitat and associated biodiversity, as well as loss of genetic diversity, carbon stores and regeneration[1] **Max score = 10**	Localised disturbance[2] **Max score = 5**	Reliance on new funding to carry out the scenario to ensure it is sustained over the long-term **Yes/No**	Regeneration impact at the landscape scale **Max score = 12**	Management of threatening processes at the landscape scale **Max score = 3**	Self-sustaining funding to ensure the scenario is sustained over the long-term **Yes/No**	**Highest score = 15**
part of licence conditions.		conditions are met, which means that some dead wood would be retained in the harvest areas (for example, harvest exclusion areas). This also considers that dead wood has a biodiversity value (for example, use by small reptiles such as the pygmy spiny-tailed skink [*Ergernia depressa*]).	is accompanied by seeding operations (which is a requirement of licences issued under the BC Act).	modest impact at a landscape scale.	threatening processes due to the requirements to meet licence conditions.	the licensing requirements.	scenario is ranked higher than other harvest scenarios mainly because living trees are not removed.
4. 'Status quo' (modelling current maximum harvest levels and regeneration of 2,500 tonnes total living (green) and dead sandalwood).	8 This scenario is expected to lead to the highest level of removal of living trees (across about 45,000 hectares per year combined across Eastern Murchison, Semi-Arid Rangelands and Deserts regions) of all the scenarios, and thus has the highest potential impact on fauna habitat and biodiversity.	4 Highest risk of disturbance of all scenarios due to the highest total area cutover through harvest activity.	No This scenario assumes industry structure supports a landscape-scale regeneration program.	9 This ranking considers that due to the removal of mature living trees there is proportionally less seed bank in localised areas compared with the other harvest scenarios. This is offset to an extent by the larger area regenerated at this harvest level.	2 This ranking considers that within areas harvested there is greater resources put into management of threatening processes due to the requirements to meet licence conditions.	Yes This level of take would be expected to generate the most funding for seeding programs.	-1 At a landscape scale this scenario does not fully address the issue of long-term natural decline in populations but there is localised improvement.
5.1 and 5.2 These scenarios reflect a combined total of 2,000 tonnes combined living (green) and dead sandalwood. This	7 This scenario equates to about 25,000 hectares cutover per year for mature living sandalwood. This	3 Less overall take than 4, which equates to less disturbance, but more than Scenarios 5.3 and 5.4.	No This level of take will potentially generate sufficient funding to make available an appropriate level of	8 This scenario assumes that this volume of harvest allows scope for a self-funded landscape-	2 This scenario represents a reduced area of harvest activity thereby reducing potential scope and extent of	No Although less funding is likely to be generated from sales of sandalwood	0 These scenarios have better ecological outcomes with a higher proportion of dead wood harvest compared with harvest of living trees.

Management scenario (refer Table 10)	Potential negative impacts on biodiversity and long-term decline in sandalwood. **Highest score = 15**			Potential benefits on biodiversity and contributing positively to the long-term health of sandalwood. **Highest score = 15**			Overall ranking (Total benefits minus impacts)
	Loss of mature living trees in the landscape leading to loss of fauna habitat and associated biodiversity, as well as loss of genetic diversity, carbon stores and regeneration[1] **Max score = 10**	Localised disturbance[2] **Max score = 5**	Reliance on new funding to carry out the scenario to ensure it is sustained over the long-term **Yes/No**	Regeneration impact at the landscape scale **Max score = 12**	Management of threatening processes at the landscape scale **Max score = 3**	Self-sustaining funding to ensure the scenario is sustained over the long-term **Yes/No**	**Highest score = 15**
scenario assumes a landscape-scale regeneration program of 20 tonnes per year may require some external funding.	scenario is based on a higher proportion of dead wood harvest than scenario 4. However, there is greater uncertainty associated with harvest in areas where information is more limited.		landscape-scale seeding operations.	scale regeneration program. This has been ranked similar to the 'status quo' scenario in acknowledgement that less living trees (seed bank) are removed.	management of threatening processes (compared to scenario 4).	products because of the lower take limits, the level would probably be sufficient to support some level of landscape-scale regeneration and localised seeding based on the current industry structure.	A separate scenario of 750 tonnes of living and 1,250 tonnes of dead sandalwood, which has living and dead harvest levels between scenarios 5.1 and 5.2, is preferred. This scenario is considered to have better environmental outcomes compared with other variations of a 2,000 tonne annual limit.
5.3 This scenario reflects a combined total of 1,500 tonnes living (green) and dead sandalwood. This scenario assumes a landscape-scale regeneration program of 20 tonnes per year would be dependent on external funding.	7 The level of take in this scenario may equate to about 21,000 hectares per year cutover for living sandalwood, and therefore a substantial reduction when compared to the highest limit under Scenario 4.	2 Less overall take than 5.1 and 5.2 equates to less disturbance, but more than 5.4.	Yes Based on current industry settings, there is increased likelihood of external funding required to support a landscape-scale regeneration program.	6 This scenario assumes a landscape-scale regeneration program may not occur without adequate funding. However, more seedbank is retained in the landscape.	1 This scenario represents a further reduction in area of harvest activity thereby reducing potential scope and extent of management of threatening processes (compared to scenarios 5.1 and 5.2).	No This scenario assumes this harvest level does not allow as much scope for a landscape-scale regeneration program in the absence of external funding.	-2 As there is less likelihood of a landscape-scale regeneration program under this scenario, as well as a lower ranking for management of threatening processes, it is ranked lower than scenarios 5.1 and 5.2.
5.4 This scenario reflects a combined total of 1,000 tonnes living (green) and dead sandalwood. This scenario assumes a landscape-scale regeneration program of 20 tonnes per year would be dependent on external funding.	6 This scenario removes a smaller proportion of living trees from the landscape (about 18,000 hectares cutover annually) compared to the other harvest scenarios involving living take.	2 Less overall take than scenario 5.3 equates to less localised disturbance.	Yes This level of harvesting is likely only to allow for localised seeding programs and will be insufficient to generate funding that could be used for landscape-scale regeneration efforts.	6 This scenario assumes a landscape-scale regeneration program may not occur without adequate funding. However, more seedbank is retained in the landscape than the other harvest scenarios.	1 This level of harvesting is unlikely to generate sufficient funding to support landscape-scale management of threatening processes (for example, camel control), which could negate seeding efforts.	No This scenario assumes that this volume of harvest does not allow as much scope for a landscape-scale regeneration program in the absence of external funding.	-1 The potential benefits of this level of take, which represents the smallest cutover area, may be outweighed by the limited impacts of seeding efforts at this scale, and the inability to fund the management of threatening processes at an appropriate scale. While this scenario has the same score

Management scenario (refer Table 10)	Potential negative impacts on biodiversity and long-term decline in sandalwood. **Highest score = 15**			Potential benefits on biodiversity and contributing positively to the long-term health of sandalwood. **Highest score = 15**			Overall ranking (Total benefits minus impacts)
	Loss of mature living trees in the landscape leading to loss of fauna habitat and associated biodiversity, as well as loss of genetic diversity, carbon stores and regeneration[1] **Max score = 10**	Localised disturbance[2] **Max score = 5**	Reliance on new funding to carry out the scenario to ensure it is sustained over the long-term **Yes/No**	Regeneration impact at the landscape scale **Max score = 12**	Management of threatening processes at the landscape scale **Max score = 3**	Self-sustaining funding to ensure the scenario is sustained over the long-term **Yes/No**	**Highest score = 15**
							as Scenario 4, less living trees are removed from the landscape making this a more precautionary scenario and thus this is considered slightly more favourable than scenario 4.

Notes:

- This assessment was informed by best available information, results of the sandalwood population modelling, and an iterative process of group analysis and ranking of criteria for scenarios by the DBCA Working Group for the review of the Sandalwood Order.
- The ‘do nothing’ scenario is a ‘worst-case’ scenario.
- [1]All scenarios assume there will be funding to control illegal harvest, and there will be natural mortality of mature living trees with limited replacement due to inadequate natural regeneration.
- [2]Localised disturbance refers to impacts associated with machinery and equipment potentially causing damage to soil, hydrological and surrounding vegetation values. This includes disturbance that may be caused through harvest activity or seeding. However, this considers there are mitigating measures to manage the localised disturbance. Note that the removal of mature living sandalwood trees in the first criteria is already given a score separately. Removal of dead trees is considered as part of localised disturbance.
- The ‘Regeneration impact at the landscape level’ has the highest weighting than any other criteria and has been assessed as being a higher weighting than the loss of mature living trees in the landscape mainly because regeneration is critical for the long-term health of sandalwood and natural regeneration is lacking. The loss of mature living trees is restricted through requirements to only harvest at a minimum size and retain sufficient seed-bearing trees in the landscape.
- A lower assigned weighting of ‘management of threatening processes’ considers that local management of threats has a limited impact on threats across the landscape scale.

Due to the consistent lack of regeneration and lack of young sandalwood trees across all regions and the varied depletion of mature trees from historic harvest or disturbance events, the primary (or highest weighted) ESU criteria were the loss of mature living trees in the landscape and the capacity of the management scenario to promote regeneration impact at the landscape scale. These were scored based on perceived potential for the long-term retention of mature trees in the landscape, and ongoing establishment and persistence of a regeneration cohort. For example, the negative impacts of removing mature trees on habitat fragmentation, potential reductions in seed banks, genetic diversity, carbon storage and faunal food resources scored progressively higher for increasing levels of annual harvest, while the positive impacts of retaining mature trees in the landscape reflected positively on the score for the non-harvest scenarios.

The criterion of localised disturbance associated with management activities reflects the documented importance of minimising disturbance footprints (at all scales) in these arid landscapes (Prober *et.al*, 2023).

Scenarios were also scored on potential to contribute to establishment of a regeneration cohort, based on direct seeding and landscape-scale regeneration program assumptions underpinning the modelling results presented in Sections 5.1 (Eastern Murchison and Semi-Arid Rangelands) and 5.2 (Desert regions), which presume any annual harvest and seeding occurs for a 10-year period. A direct correlation between the quantity of living sandalwood harvested and area regenerated is assumed, such that higher scores are associated with increasing levels of harvest. The capacity to maintain a landscape-scale regeneration program such as Operation Woylie is also considered relative to the scale of harvest activity, and whether a stand-alone supplemental program might be funded independently of harvesting.

The importance of managing the multiple threats to regeneration persistence (for example, introduced herbivores, fire) and ecosystem function under a changing climate is recognised throughout this report. In addition, a recent paper on sandalwood knowledge gaps and research priorities also highlights key considerations (Northover et al., in press). Accordingly, the risk assessment also considered the likelihood of funding and capacity to actively manage regeneration outcomes and management of threats (noting obligatory licence conditions).

6.3 Outcomes

Table 22 provides a simplified comparison between management scenarios of their relative impacts on biodiversity and long-term condition of sandalwood populations.

Under Scenario 1 (the ‘do nothing’ scenario) involving no harvest or regeneration program sandalwood habitat would remain undisturbed, but regeneration would be entirely dependent on natural recruitment. This is projected to result in continued, long-term population decline due to insufficient natural recruitment and limited management of threatening processes. While this passive management might be considered acceptable by some, this approach is inconsistent with maintaining sandalwood populations and associated biodiversity over the long-term. In the absence of extensive seeding and protection programs most of the wild sandalwood populations will, by default, be subjected to this management scenario over the 10-year period of a new Sandalwood Order.

In contrast, Scenario 2 which involves no harvesting but with a landscape-scale regeneration program is scored highly for maintaining mature living trees in the landscape and promoting active restoration through regeneration of sandalwood. The scale of the targeted regeneration program is a key consideration, as large programs are necessary to promote a self-sustaining population at landscape scales over the long term.

Scenario 3 focuses solely on dead wood harvesting, accompanied by a landscape-scale regeneration program. While the removal of dead wood may pose risks such as habitat loss for decomposer organisms and small fauna, or the potential for a broader disturbance footprint due to the highly dispersed location of dead sandalwood, this scenario avoids removal of living trees from the landscape. The direct seeding at harvest, combined with a landscape-scale regeneration program, expands the potential area regenerated beyond Scenario 2, and hence the combined scores for Scenario 3 rank it superior to all other scenarios examined.

Scenarios 4 and 5 involving harvesting to varying quantities and combinations of living trees and dead wood all reduce mature living tree density and increase spacing between larger trees in the landscape, with potential consequences for reduced connectivity, local pollination processes and fewer mature seed trees. These negative impacts are counterbalanced by the opportunity to create regeneration. The comparative scale of impacts, and hence scores allocated to each scenario, are linked to the harvest quantity and hence annual area cut over. The relative area cut over and regenerated each year for select harvest levels are presented in Table 23. While these figures indicate the area harvested (negative impact) would typically comprise a very small percentage of the total sandalwood habitat in each region, the corresponding area potentially regenerated (positive impact) reduces as the quantity harvested reduces.

Table 23. Indicative annual area harvested and seeded for select quantities of living sandalwood removed, assuming inventory mean statistics and no spatial or economic constraints on access to areas.

Region	Modelled subset	Quantity of living sandalwood removal (tonnes)	Indicative annual area harvested and seeded[1] (hectares)	Proportion by area of total sandalwood habitat[2] (%)	Proportion that quantity comprises of total standing living[3] at Year 0 (%)
Semi-Arid Rangelands	2f	250	4,850	0.15	0.15
	2d	500	9,700	0.30	0.30
Eastern Murchison	4f	250	9,100	0.35	0.35
	4d	500	18,200	0.70	0.70
Deserts	-	250	17,500	1.45	1.01

[1] An annual Operation Woylie program applying 20 tonnes seed per year would add a further 25,000 hectares of seeded area, irrespective of harvest level.

[2] Total net area potentially available for harvest (excluding conservation reserves) is estimated for Semi-Arid Rangelands as 3.63 million hectares; Eastern Murchison as 2.52 million hectares; Deserts as 1.21 million hectares.

[3] Based on inventory mean statistics.

Within these harvest scenarios, there is an increasing number of mature trees removed as the harvest quantity increases, with scores correspondingly graduated to reflect the expected increasing negative impacts. Similarly, localised disturbance increases as the harvest area footprint increases, with scores near maximum for Scenario 4 with current maximum harvest levels.

Conversely, the expected positive impacts on regeneration establishment are higher as harvest quantities increase due to larger area cut over and regenerated from the associated direct seeding. However, there is an anticipated threshold level of harvest below which the landscape-scale supplemental seeding program such as Operation Woylie would be less likely to proceed unless funded independently of harvest activity. Given the imperative for landscape-scale restoration, application of a landscape-scale seeding program (or composite series of smaller programs) to complement the direct seeding at harvest is considered a key component of achieving ESU. Consequently, the scores allocated to regeneration impact of Scenarios 5.3 and 5.4 are substantially lower as the level of harvest is considered unlikely to support an industry funded landscape-scale regeneration program. The capacity to actively manage threatening processes at the landscape scale is also linked to the level of harvest and corresponding financial returns, with lower scores allocated to scenarios with low or no harvest levels.

The overall scoring of each scenario in Table 22 reflects the difference between the scored negative and positive impacts on sandalwood and associated biodiversity over the long-term. While most scenarios can be interpreted as approaching ESU, a preferred scenario is one in which restoration activities can be self-funding whilst also meeting the range of socio-economic objectives as discussed in the *Draft Review Report*.

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8. Glossary

‘Carbon stores’ Carbon is stored in various reservoirs such as the atmosphere, plants and animals, water, soil and many types of rocks. Carbon flows (transfers or exchanges) between these reservoirs or ‘stores’ through a variety of processes which together describe the carbon cycle, like water, nutrient and energy cycles.

‘Conservation reserve or estate’ A type of Crown reserve set aside primarily for the conservation of natural ecosystems, but which may allow a level of recreation or other uses consistent with the proper maintenance and restoration of the natural environment. Examples of conservation reserves include national parks, nature reserves and conservation parks.

‘Cultural Knowledge’ refers to a range of knowledge held and continually developed by Aboriginal peoples and includes:

- traditional cultural expressions such as stories, dance, art, etc; and
- traditional knowledge relating to a range of areas such as science, ecology, agriculture, medicine, etc.

‘Demographics’ means statistical data relating to a population and particular groups within it.

‘Desert regions’ refers to the combined IBRA subregions of Shield, Central, Carnegie, Trainor and Lateritic Plain.

‘Ecologically Sustainable Development’ (ESD) is as per the principles of ecologically sustainable development listed in the BC Act Section 4(a) to (e).

‘Ecologically Sustainable Use’ (ESU) has the meaning given in Section 5 of the BC Act, and specifically in relation to biodiversity components, means use of the biodiversity components in a way and at a rate that does not lead to the long-term decline of biodiversity, thereby maintaining the potential of the biodiversity components to meet the needs of present and future generations.

‘GDA94’ is the Geocentric Datum of Australia 1994, a static coordinate system for Australian mapping that was fixed to Australia's tectonic plate on January 1, 1994. It has since been superseded by GDA2020, as Australia's plate has moved, causing a mismatch with modern satellite-based positioning systems like GPS.

‘Heterogeneity’ means the quality or state of being diverse in character or content.

‘Inventory’ is the systematic collection of data and information about the state of an environment or feature (such as sandalwood) for assessment and analysis.

‘Landscape-scale’ refers to a mosaic where the mix of local ecosystems and landforms is repeated in a similar form over a kilometres-wide area. Several attributes including geology, soil types, vegetation types, local flora and fauna, climate and natural disturbance regimes tend to be similar and repeated across the whole area. In the rangelands context, ‘landscape’ may comprise areas of a few thousand to tens of thousands of hectares (Source: adapted from the Forest Management Plan 2014-2023).

‘LiDAR’ or ‘Light Detection and Ranging, is a remote sensing technology that uses pulsed laser light to measure distances and create precise 3D maps of the Earth's surface and other objects.

‘Local-scale’ refers to a discrete area of land to which one or more operations (such as harvest or seeding) have been or are planned to be applied. In the rangelands context a single operation may extend across hundreds to a few thousand hectares.

‘Mesic’ In ecology, a mesic habitat is a type of habitat with a moderate or well-balanced supply of moisture.

‘Pre-European/pre-1750 vegetation’ means original natural vegetation that is presumed to have existed prior to European settlement.

‘Regeneration’ means the population establishment and recruitment process of sandalwood in the wild through either natural processes involving seed production, dispersal, germination and hemi-parasitic establishment via haustoria or by artificial processes of ‘seeding’ involving the sowing of seed into the landscape via mechanical or hand methods either as part of harvest operations or by supplemental means (such as FPC’s Operation Woylie), which also result in hemi-parasitic establishment via haustoria.

‘Senesce/senescence’ or biological aging is the process of gradual deterioration of functional characteristics with age.

‘Stream order’ is a classification of the hierarchy of streams, creeks or tributaries where the order of the stream increases when streams of the same order intersect.

‘Take’ of sandalwood (flora) under Section 5 of the BC Act includes the following –

(i) to gather, pluck, cut, pull up, destroy, dig up, remove, harvest or damage flora by any means;

(ii) to cause or permit anything referred to in subparagraph (i) to be done.

‘Tenure/land tenure’ is the legal regime in which land is owned, leased, reserved or unallocated to a defined purpose.

‘Xeric’ in ecology means an environment or habitat that is very dry and contains little moisture.

Appendix 1. Sandalwood occurrence by Land System and Pre-European Vegetation Association for Past Inventory

Land systems

High probability		Medium probability		Low probability	
Land system	% of plots with sandalwood	Land system	% of plots with sandalwood	Land system	% of plots with sandalwood
Campsite	54%	Wilson	26%	Aganemnon	0%
Nerramyne	56%	Ero	27%	Bunny	0%
Tindalarra	56%	Sunrise	29%	Cole	0%
Deadman	57%	Gundockerta	30%	Helag	0%
Sherwood	58%	Hamilton	33%	Joy	0%
Euchre	59%	Mulline	33%	Kalli	0%
Laverton	59%	Tallering	33%	Kil	0%
Kirgella	60%	Watson	34%	Koomarra	0%
Bevon	62%	Cunyu	35%	Merbla	0%
Norrie	63%	Hootanui	35%	Nallex	0%
Waguin	65%	Windarra	35%	Roderick	0%
Marlow	66%	Yilgangi	35%	Sturt	0%
Dryandra	73%	Bandy	37%	Yarrameedie	0%
Eden	80%	Bannar	37%	Bullimore	3%
Graves	81%	Pindar	38%	Tyrrel	3%
Austin	100%	Gransal	41%	Melalueca	4%
Lawerence	100%	Leonora	41%	Marmion	9%
Tooloo	100%	Nubev	41%	Cyclops	10%
		Rainbow	41%	Desdemona	10%
		Violet	41%	Felix	11%
		Barwidgee	42%	Gabanintha	13%
		WIndarra	42%	Kal	13%
		Doney	45%	Duketon	14%
		Moriarty	46%	Monk	14%
		Brooking	47%	Mileura	15%
		Challenge	47%	Ararak	16%
		Olympic	47%	Trn	16%
		Singleton	47%	Gle	17%
		Carnegie	48%	Monitor	17%
		Gumbreak	48%	Steer	17%
		Illaara	48%	Tealtoo	17%
		Tuetonic	50%	Ranch	18%
		Weld	50%	Tiger	18%
		Yanganoo	50%	Yewin	20%
				Yalbalgo	21%
				Joseph	22%
				Woodline	23%
				Yowie	23%
				Darlot	24%
				Boodanoo	25%
				Crete	25%
				Jundee	25%

Pre-European Vegetation Associations

High probability		Medium probability		Low probability	
Pre-European Vegetation Association	% of plots with sandalwood	Pre-European Vegetation Association	% of plots with sandalwood	Pre-European Vegetation Association	% of plots with sandalwood
521	53%	468	29%	10	0%
9	54%	20	33%	18	0%
141	56%	504	33%	24	0%
2009	58%	540	33%	29	0%
481	65%	8	39%	107	0%
520	67%	502	40%	125	0%
1413	70%	127	40%	204	0%
39	80%	435	49%	221	0%
40	100%	522	49%	400	0%
128	100%	109	50%	483	0%
453	100%	529	50%	506	0%
501	100%	2901	50%	511	0%
				1241	0%
				676	10%
				509	14%
				936	16%
				488	17%
				480	25%
				542	25%
				555	25%

Appendix 2. Sandalwood occurrence by Land System and Pre-European Vegetation Association for the DBCA Inventory

Disclaimer: Note that high or low stem densities within limited sample plots does not necessarily correlate with probability of occurrence in Appendix 1.

Land Systems

Name	Description	Stems per hectare (plot level)				
		Mean	Median	Minimum	Maximum	Number of plots
Latimore Land System	Gently undulating gravelly plains and low rises on laterite with acacia tall shrublands and occasional eucalypts.	14.14	14.14	14.14	14.14	1
Dryandra Land System	Ridges of banded iron formation supporting dense mixed shrublands with emergent native pines, mallees and casuarinas.	12.64	12.64	11.13	14.14	2
Euchre Land System	Low granite breakaways with alluvial plains and sandy tracts supporting eucalypt woodlands and acacia shrublands.	8.74	8.74	5.64	11.85	2
Binneringie Land System	Hills and plains supporting dense tall acacia shrublands with scattered eucalypt trees.	7.19	7.19	7.19	7.19	1
Illaara Land System	Plains with ironstone gravel or calcrete mantles supporting eucalypt woodlands and mulga-casuarina shrublands.	10.3	6.99	1.54	22.36	3
Brooking Land System	Prominent ridges of banded iron formation supporting mulga shrublands and occasional minor halophytic communities.	9.23	6.79	1.12	26.42	6
Wiluna Land System	Low greenstone hills with occasional lateritic breakaways and broad stony slopes, lower saline stony plains and broad drainage tracts; supporting sparse mulga and other acacia shrublands with patches of halophytic shrubs.	7.67	6.79	2.36	14.72	4
Doney Land System	Calcareous alluvial plains with eucalypt woodlands adjacent to salt lake systems.	6.47	6.47	5.67	7.26	2
Moriarty Land System	Low greenstone rises and stony plains supporting chenopod shrublands with patchy eucalypt overstoreys.	9.31	5.76	1.42	40.36	10
Campsite Land System	Alluvial plains supporting eucalypt woodlands with halophytic understoreys and acacia shrublands.	7.01	5.68	2.05	15.71	6
Cunyu Land System	Calcrete platforms, intervening drainage floors and channels and minor alluvial plains, supporting acacia shrublands, occasional casuarina woodlands and minor halophytic shrublands.	5.47	5.47	2.82	8.13	2
Carnegie Land System	Salt lakes with fringing saline alluvial plains, kopi dunes and sandy banks, supporting halophytic shrublands and acacia tall shrublands.	8.60	5.24	1.54	24.01	10
Gumbreak Land System	Low granite breakaways with extensive lower saline alluvial plains, supporting halophytic low shrublands.	8.45	5.12	1.03	29.54	6
Bunyip Land System	Gilgaied drainage tract, draining greenstone hills supporting mixed halophytic shrublands occasionally with a black oak overstorey.	5.39	5.03	1.85	10.53	6
Kirgella Land System	Gently undulating sandplains, with scattered granite outcrop supporting spinifex hummock grasslands, mulga shrublands and mallees.	5.87	4.76	3.80	10.32	8

Name	Description	Stems per hectare (plot level)				
		Mean	Median	Minimum	Maximum	Number of plots
Rainbow Land System	Hardpan plains supporting mulga tall shrublands.	6.84	4.59	0.97	23.20	8
Marmion Land System	Gently undulating sandplains with mixed tall shrublands and hummock grasslands.	4.77	4.53	1.07	11.18	6
Yowie Land System	Sandy plains supporting tall shrublands of mulga and bowgada with patchy wanderrie grasses.	4.57	4.14	0.60	7.71	11
Graves Land System	Basalt and greenstone rises and low hills supporting eucalypt woodlands with prominent saltbush and bluebush understoreys.	4.85	3.91	2.70	8.38	5
Lawrence Land System	Low greenstone hills with ironstone ridges supporting pearl bluebush shrublands and eucalypt woodlands with halophytic undershrubs.	3.87	3.87	3.39	4.35	2
Deadman Land System	Calcareous plains supporting acacia, black oak and mallee shrublands/woodlands adjacent to salt lake systems.	3.48	3.87	0.95	5.31	6
Laverton Land System	Greenstone hills and ridges with acacia shrublands.	4.13	3.60	1.03	8.38	8
Gabanintha Land System	Greenstone ridges, hills and footslopes supporting sparse acacia and other mainly non-halophytic shrublands.	3.49	3.49	3.49	3.49	1
Helag Land System	Hardpan plains and central drainage tracts with mulga shrublands and minor chenopod shrublands.	14.41	3.46	1.07	68.58	7
Leonora Land System	Greenstone hills and ridges with acacia shrublands.	3.93	3.34	0.34	7.49	5
Mulline Land System	Greenstone hills supporting eucalypt and black oak woodlands and mulga shrublands.	3.26	3.26	3.26	3.26	1
Norie Land System	Granite hills with exfoliating domes and extensive tor fields, supporting acacia shrublands.	3.03	3.03	0.42	5.64	2
Crete Land System	Breakaways and lower plains based on weathered granites, supporting halophytic shrublands.	10.3	2.81	1.42	26.69	3
Gundockerta Land System	Extensive, gently undulating calcareous stony plains supporting bluebush shrublands.	4.15	2.62	0.67	11.96	13
Nubev Land System	Gently undulating stony plains, minor limonitic low rises and drainage floors supporting mulga and halophytic shrublands.	5.23	2.56	0.34	14.23	6
Bevon Land System	Irregular low ironstone hills with stony lower slopes supporting mulga shrublands.	3.23	2.40	1.10	10.20	22
Challenge Land System	Gently undulating gritty and sandy surfaced plains, occasional granite hills, tors and low breakaways, supporting acacia shrublands and occasional halophytic shrublands.	2.74	2.23	2.03	3.97	3
Waguin Land System	Sandplains and stripped granite or laterite surfaces with low fringing breakaways and lower plains; supports bowgada and mulga shrublands with wanderrie grasses and minor halophytic shrublands.	1.86	1.69	0.70	3.33	4
Sherwood Land System	Breakaways, kaolinised footslopes and extensive gently sloping plains on granite supporting mulga shrublands and minor halophytic shrublands.	1.97	1.66	0.12	6.56	16
Monk Land System	Hardpan plains with occasional sandy banks supporting mulga tall shrublands and wanderrie grasses.	2.20	1.61	0	6.28	7

Name	Description	Stems per hectare (plot level)				
		Mean	Median	Minimum	Maximum	Number of plots
Violet Land System	Gently undulating gravelly plains on greenstone, laterite and hardpan, with low stony rises and minor saline plains; supporting groved mulga and bowgada shrublands and occasionally chenopod shrublands.	2.13	1.37	0.11	6.74	7
Woodline Land System	Almost flat sandy-surfaced hardpan wash plains supporting tall shrublands and woodlands of mulga.	1.36	1.36	1.36	1.36	1
Bandy Land System	Gritty-surfaced plains and low outcrops of granite with scattered acacia shrublands.	1.09	1.09	1.09	1.09	1
Bullimore Land System	Gently undulating sandplain with occasional linear dunes and stripped surfaces supporting spinifex grasslands with mallees and acacia shrubs.	0.87	0.87	0.87	0.87	1
Wyarri Land System	Granite domes, hills and tor fields with gritty-surfaced fringing plains supporting mulga and granite wattle shrublands.	0.87	0.87	0.87	0.87	1
Nallex Land System	Gently undulating stony plains supporting acacia tall shrublands and chenopod low shrublands.	0.70	0.70	0.70	0.7	1
Gransal Land System	Stony plains and low rises based on granite supporting mainly halophytic low shrublands.	0.83	0.67	0	1.84	6
Jundee Land System	Hardpan plains with variable gravelly mantles and minor sandy banks supporting weakly groved mulga shrublands.	1.76	0.61	0	6.95	6
Yanganoo Land System	Almost flat hardpan wash plains, with or without small wanderrie banks and weak groving; supporting mulga shrublands and wanderrie grasses on banks.	0.57	0.57	0.57	0.57	1
Hamilton Land System	Hardpan plains, stony plains and incised drainage lines supporting mulga tall shrublands.	0.45	0.48	0	0.87	3
Tindalarra Land System	Near level hardpan wash plains, narrow drainage lines and moderately saline drainage floors; supporting tall mixed acacia shrublands with wanderrie grasses, also minor saltbush/bluebush low shrublands.	0.26	0.26	0.26	0.26	1
Marlow Land System	Alluvial plains with numerous small drainage foci supporting acacia and melaleuca shrublands with non-halophytic and halophytic undershrubs.	0.18	0.18	0.18	0.18	1
Wilson Land System	Large creeks with extensive distributary fans, supporting mulga and chenopod shrublands.	0	0	0	0	1

Vegetation Associations

No.	Description	Stems per hectare (plot level)				
		Mean	Median	Minimum	Maximum	Number of plots
9	Medium woodland; coral gum (*Eucalyptus torquata*) and Goldfields blackbutt (*E. le soufii*), (also some e10,11)	50.55	24.77	1.65	285.55	27
521	Medium woodland; salmon gum and red mallee	15.48	15.48	4.41	26.54	2
936	Medium woodland; salmon gum	24.21	11.29	0.17	107.85	10
19	Low woodland; mulga between sand ridges	10.75	11.13	6.99	14.14	3
520	Shrublands; *Acacia quadrimarginea* thicket	17.09	10.99	7.03	33.25	3
435	Shrublands; *Acacia neurophylla*, *A. beauverdiana* and *A. resinomarginea* thicket	9.45	9.45	9.45	9.45	1
202	Shrublands; mulga and *Acacia quadrimarginea* scrub	9.54	8.25	0.87	26.42	5
141	Medium woodland; York gum, salmon gum and gimlet	8.60	7.57	0.82	15.71	14
128	Bare areas; rock outcrops	5.36	7.37	1.29	7.42	3
502	Medium woodland; Goldfields blackbutt and red mallee	6.36	6.36	6.36	6.36	1
8	Medium woodland; salmon gum and gimlet	6.17	5.64	1.50	12.05	5
20	Low woodland: mulga mixed with *Allocasuarina cristata* and Eucalyptus sp.	7.91	5.63	1.07	68.58	41
251	Low woodland; mulga and *Allocasuarina cristata*	5.55	5.55	5.33	5.77	2
389	Succulent steppe with open low woodland; mulga over saltbush	6.62	4.91	2.82	13.85	4
2901	Mosaic: Medium woodland; *Allocasuarina cristata* and Goldfields blackbutt Shrublands; *Acacia quadrimarginea* thicket	4.76	4.76	4.40	5.12	2
182	Low woodland; mulga and bowgada (*Acacia ramulosa*)	4.42	4.42	4.42	4.42	1
533	Low woodland; mulga and cypress pine	4.41	4.41	2.37	6.46	2
417	Succulent steppe with open scrub; scattered wattles over saltbush	10.1	3.97	2.33	24.01	3
508	Succulent steppe with open scrub; scattered mulga over saltbush	7.76	3.91	3.19	16.19	3
555	Hummock grasslands, mallee steppe; red mallee over spinifex, *Triodia scariosa*	4.85	3.81	0.95	10.82	4
10	Medium woodland; red mallee group	3.24	3.21	2.26	4.64	5
525	Mosaic: Medium woodland; salmon gum and gimlet/Medium woodland; merrit and red mallee	3.20	3.20	3.20	3.20	1
400	Succulent steppe with open low woodland; mulga over bluebush	2.66	3.16	1.42	3.39	3
468	Medium woodland; salmon gum and Goldfields blackbutt	4.51	3.15	0.84	13.30	6
522	Medium woodland; redwood (*Eucalyptus transcontinentalis*) and merrit (*E. floctoniae*)	6.97	3.05	0	21.79	4
529	Succulent steppe with open low woodland; mulga and sheoak over bluebush	3.44	2.96	1.85	5.96	5
39	Shrublands; mulga scrub	3.73	2.92	0.34	13.02	23
420	Shrublands; bowgada and jam scrub	2.75	2.47	0.42	5.64	4
501	Medium woodland; Goldfields blackbutt	2.41	2.41	1.88	2.94	2
2121	Mosaic: Open low woodland; mulga/Succulent steppe; saltbush and bluebush on greenstone	5.98	2.36	0.87	14.72	3
676	Succulent steppe; samphire	2.09	2.09	2.09	2.09	1

No.	**Description**	**Stems per hectare (plot level)**				
		Mean	**Median**	**Minimum**	**Maximum**	**Number of plots**
484	Shrublands; jam thicket	10.9	2.06	1.09	29.54	3
18	Low woodland; mulga (*Acacia aneura*)	3.28	1.96	0	26.69	106
504	Low woodland; mulga and red mallee	1.19	1.19	1.19	1.19	1
415	Succulent steppe with open scrub; scattered mulga and other wattles over saltbush and bluebush	0.86	0.86	0.18	1.54	2
480	Succulent steppe with open low woodland; mulga and sheoak over salt bush	0.71	0.71	0.71	0.71	1