A report on silvicultural guidelines for the 2024-2033 Forest Management Plan to the Western Australian Department of Biodiversity, Conservation and Attractions

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Karri (*Eucalyptus diversicolor*) regrowth forest (photo Neil Burrows)

Executive summary

The Forest Management Plan (FMP) 2014-2023 commits to a review of silvicultural practices by a panel of independent experts to inform the development of the next FMP (2024-2033). In addition, in September 2021 the WA government announced that south-west native forests are to be protected from logging from 2024. The announcement noted that from 2024, timber taken from native forests will be limited to forest management that improves forest health, and clearing for approved mining operations. Further, a Department of Biodiversity, Conservation and Attractions (DBCA) Explanatory Note (2022) (Appendix 1) specifies that harvesting in native forests will be restricted to 'ecological' thinning.

The current FMP (2014-2023) covers 1,935,030 hectares (ha) of forest across all tenures. Much of this is in tenures in which timber harvesting or thinning, is not permitted (e.g., parks and reserves). The primary focus of this report is on the ~220,000 ha of regrowth forests within the 960,000 ha of forests that are available for timber harvesting under the current FMP. These regrowth forests are the forests that are potentially available for, and would most likely benefit from, ecological thinning. Management recommendations specific to ecological thinning are made for three broad forest communities (the jarrah, karri, and wandoo forests). A fourth category, mining rehabilitation sites, is included because mining is a major and ongoing activity that impacts areas of these forests and results in a completely reconstituted forest.

South-west Western Australia has a long history of timber harvesting in native forests. For decades the standard silvicultural systems have primarily focused on long-term timber production in an ecologically sustainable forest management (ESFM) framework. As a result, there are now 144,770 ha of even-aged jarrah regrowth and 74,820 ha of even-aged karri regrowth. Nearly 80% of the jarrah regrowth has been established since 1970, with the majority in the southern jarrah forests. In addition, 24,540 ha of forest has been rehabilitated after mining using non-native species (3,760 ha) or with jarrah and marri (20,780 ha). An estimated 7,000 ha of further mining and rehabilitation in State forests is planned for 2024-2033.

Many of these regrowth stands are young stands with very high levels of stocking and poor vigour. However, they use large amounts of water, which reduces the water available for groundwater recharge or streamflows. Regional reductions in rainfall and global increases in temperatures mean that the amount of water available to terrestrial and aquatic ecosystems in south-west WA is likely to decline over the next century. The combination of a drying climate and large areas of heavily stocked regrowth will predispose these forests to acute moisture stress. As water availability declines, tree vigour will decline and the potential for increased mortality rates within stands and forested landscapes will increase and riparian areas will continue to dry. A drying climate and changed forest water balance may also increase the severity of bushfires within these landscapes.

Over the past 20 years, forest scientists and hydrologists around the world have demonstrated that thinning in stands with high levels of stocking can improve soil moisture balance and improve tree vigour. This can make stands more resistant to the impacts of drought and heat waves and landscapes more resilient to changing disturbance regimes. Thinning also has other potential benefits. It can improve the water balance in riparian ecosystems and in some circumstances enhance streamflow, and increase soil and groundwater storage. Thinning also increases the growth rates of trees, which may accelerate the development of habitat features such as tree hollows, and reduce susceptibility to fire-induced mortality. However, thinning to achieve these ecological outcomes has not been widely practiced. Most (but not all) thinning activity in south-west WA has focused on improving tree growth for timber production rather than for specific ecological and environmental outcomes.

In the wake of the government's announcement to pivot from a native forest management regime focused primarily on timber harvesting to one that manages forest health, the DBCA developed an Explanatory Note that defines ecological thinning as the selective removal of trees to reduce current and future moisture stress on the site for an extended period (DBCA 2022). The Panel is of the view that the DBCA should consider a broader role for ecological thinning that focuses on two outcomes that together will promote forest adaptation to climate change:

1. To improve forest water balance in the face of a drying climate to reduce physiological stress at the tree level, minimise the risk of widespread mortality at the stand and landscape scales, and support a variety of ecological communities and populations within these landscapes.

2. To promote a diversity of forest structures at the stand and landscape scales that more closely resembles pre-European forests, is more resilient to recurrent fires and drought, and increases the availability of habitat features such as tree hollows.

The first outcome will increase the ability of forests to endure acute climatic stressors by improving tree and forest vigour and reducing water stress. The second will increase forest resilience by creating a more diverse range of forest structures across the landscapes of the south-west. However, we emphasise that we advocate for a restoration-focused approach only where those historical structures make the forests better suited to future climates. If there are conditions under which such an approach makes the forests more vulnerable to climate change, then new strategies will be required.

While there are many potential benefits from thinning, it is important to acknowledge some of the challenges it may bring, particularly when applied across extensive areas. First, thinning will result in a considerable volume of woody and canopy residue. If left on the forest floor, this residue can present a long-term fire hazard. Second, mechanically thinning young stands dominated by small trees will require different machinery to that currently available. Forest contractors may have little appetite for investing in retooling if there are not long-term guarantees of harvest volume. Third, any commercial utilisation of thinnings (i.e., stems, thinning residues) may be perceived as the driver of ecological thinning, rather than as a by-product. This may not be socially acceptable. Fourth, like other harvesting operations, thinning can have an impact on the understorey vegetation and soils (e.g., soil compaction, profile mixing). If thinning is to occur, it is important that extraction systems and techniques that minimise understorey impact and soil disturbance are used. Finally, the costs of ecological thinning will need to be considered. If thinning is conducted on a non-commercial basis, it will need to be funded by government. The 2014-2023 FMP recommended thinning 100,000 ha of forest. This was not achieved. If thinning is to occur at that scale in the next FMP (2024-2033), then significant costs to government may occur.

Based on discussions with DBCA staff, a series of site visits, review of the scientific literature and a range of unpublished reports on forests and forest management in south-west WA, we make the following recommendations for the silvicultural management of native forests under the next FMP. While there are many management issues, our focus is primarily on establishing priorities for silvicultural management that aims to enhance forest health. We do not address the economic or financial aspects of forest management, such as the valuation of environmental services (e.g., carbon, water, recreation, biodiversity) or forest products. Nor do we consider in any detail, other important aspects of forest management, such as weeds, pests and diseases, and feral animals. Because fire management is an issue of great cultural, social, ecological, and economic importance, we discuss it in the context of forest thinning and how it might impact fire behaviour.

Recommendation 1 -- Jarrah forest

The benefits of thinning for forest restoration, water supply, habitat, fire resilience and resilience to threats associated with climate change are clear. Overstocked stands are vulnerable to many stressors and provide few benefits. We recommend that the DBCA initiate a program of thinning across dense young regrowth stands of jarrah. Preliminary analyses of stocking levels using density management principles can be used to prioritise stands for thinning and guide the development of the thinning. This would provide an empirical basis for identifying potentially vulnerable stands and would provide a useful indication of the extent of thinning that would be required in specific landscapes. These can then be further prioritised based on measures of site productivity (e.g., soil depth, soil water-holding capacity) to identify stands particularly vulnerable to drought stress. It is our view that the current range of proposed thinning objectives and prescriptions is too narrow and that adaptive management trials that consider new thinning prescriptions be implemented and the outcomes for a range of ecological and environmental values be monitored.

There are also large areas of mature mixed jarrah forest that remain within the State forest tenure. While there may be some basis for thinning these stands, we feel that the priority is to manage the overstocked regrowth stands. However, where large patches of dense regeneration occur within mature stands, there may be grounds for early thinning to encourage growth and minimise long-term water stress.

Recommendation 2 -- Karri forest

Regrowth forests of karri self-thin more rapidly than regrowth forests of jarrah. The resultant differentiation of karri within even-aged stands means that they are less prone to stagnation and lock-up than jarrah. Consequently, thinning to reduce overstocking is generally less of a priority in karri stands. However, thinning may be desirable to maintain water balance for riparian communities and habitats, and to maintain streamflow for potable use for rural communities and irrigated farmland. Shifting even-aged karri regrowth stands to uneven-aged stands may also yield a range of benefits, such as greater fire resilience, faster development of tree hollows, and greater security of carbon stores. However, this would require harvesting operations that specifically focused on generating conditions suitable for regeneration, which are usually more intense than thinning prescriptions.

Recommendation 3 -- Wandoo forest

We do not recommend any broad-scale silvicultural management in wandoo forest. Under certain conditions thinning may be required to maintain water balance for riparian communities of high conservation value that may be at risk in a drying climate. However, forest management activities around at-risk communities would need to be carefully developed with a range of stakeholders. Defining the extent of these potential management actions in wandoo forest will require further investigation.

Recommendation 4 -- Mined and rehabilitated forest

Prior to 1988, mining rehabilitation predominantly involved planting tree species that were not native to WA. After 1988 jarrah and marri were the primary species for reforestation. However, many sites, particularly in the early years of restocking with native species, were regenerated at high densities. We recommend that these pre-1988 sites be converted to native forest species. This may involve repeated heavy thinnings or regeneration-focused harvesting with supplemental seeding or planting of jarrah and marri. To maintain forest health, the post-1988 sites should be thinned to reduce stand density, to increase individual tree growth, and to increase structural heterogeneity of individual stands.

Rehabilitated mine pits are not natural forests. They are engineered forests that attempt to replicate native forests previously managed for timber as well as conservation and water values. While timber and water values should not be the drivers of management, the Panel is of the view that these reconstituted forests could continue to provide these values without compromising forest health.

Recommendation 5 -- Fire management

Thinning operations have the potential to generate substantial additional flammable fuel loads on the forest floor. Forest managers will need to develop strategies, such as prescribed burning and on-site mulching or chipping, to mitigate this risk. These practices will need to be carefully coordinated with any thinning activities. Thinning that is done very early in stand development may reduce the accumulation of flammable fuels by reducing the amount of self-thinning and self-pruning that occurs within a stand. Reducing stand density early in stand development or initiating stands at much lower densities than in the past should be explored as a future management option.

Recommendation 6 -- Research and development

The new policy of forest management to improve the ecological health of forests will require new ways of thinking about silviculture in south-west WA's forests. A substantial focus will necessarily be on thinning prescriptions for regrowth jarrah and karri forests. There are key areas that require a sustained investment of research and development. These include:

1. Density management guidelines to provide an empirical and transparent tool for identifying the level of stocking in a stand and when stands are at risk of overstocking.
2. New thinning prescriptions to better align silvicultural outcomes with natural disturbance patterns and desired forest structures. The proposed thinning prescriptions are relatively limited and will tend to homogenise stand structure. Variable density thinning and crown thinning have been applied in other regions of the world to create more heterogeneous forest structures. We recommend that a program of experimental thinnings applied at operational scales be implemented in each of the major forest types. These can be compared with the existing long-term thinning trials to identify the prescriptions for specific desired outcomes, recognising that no single prescription will be the best for multiple values. A comparison of existing and proposed trials will provide the empirical basis for developing landscape-scale implementation strategies to improve overall forest health and resilience. It will also provide a useful way to demonstrate the outcomes of different thinning prescriptions to interested stakeholders within the community.
3. We recommend that a program of monitoring be developed and applied to evaluate the outcomes of thinning at the landscape scale. This could include modernising and re-aligning FORESTCHECK with the forest management objectives of the next FMP. This might also include integrating a re-purposed FORESTCHECK with existing long-term thinning trials.
4. We recommend that a detailed modelling exercise that assesses the costs and benefits of ecological thinning at the landscape scale be undertaken to better understand the consequences of this shift in forest management and to provide guidance on how different ecological thinning prescriptions might be best implemented across these landscapes over the coming decades.

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Introduction

The 2014-2023 Forest Management Plan (FMP) committed to a review of silvicultural practices by a panel of independent experts to inform the development of the next FMP (2024-2033). This report focuses on native forests managed by the Department of Biodiversity, Conservation and Attractions (DBCA) that were available for timber production and subject to silvicultural management under the current FMP (2014-2023). We do not consider the conservation estate and other tenures where timber harvesting is not permitted, nor do we consider specific protected areas (e.g., old-growth forests) within the State forests that are protected or excluded from harvesting under the FMP. This report does not consider the management of native forests on private land, although the recommendations regarding silvicultural and associated fire management practices may be directly relevant to private landowners.

Here we provide a general overview of the forests of south-west WA, their historical management, and an overview of the potential impacts of climate change. We then consider the specific points outlined in the terms of reference with particular emphasis on the role of 'ecological' thinning and current understanding of what it is and how it might be implemented in the forests of south-west WA. We conclude with key recommendations for consideration in the development of the next FMP (2024-2033).

State forests of south-western Western Australia and their management

Under the current FMP (2014-2023) 1,935,030 ha of native forests are managed by the DBCA (see Table 1 for details). Of these, 1,085,850 ha are protected under various tenures (e.g., parks and reserves) and are unavailable for timber harvesting, and 849,180 ha are in State forests and available for timber harvesting. The majority of the forests available for harvest are jarrah forests that have been selectively harvested in the past and are known as mixed-mature forests (614,520 ha). However, 126,280 ha of jarrah forest is even-aged regrowth, nearly 80% of which was regenerated after 1970. There are also 52,130 ha of even-aged regrowth karri, 32,440 ha of wandoo, and 23,810 ha of mining rehabilitation sites that are available for timber harvest in State forests.

In September 2021 the State government announced that it would end logging in the native forests of south-west WA from 2024. However, the announcement also noted that there would be allowances made for forest management activities that improved forest health, and for clearing of forests for approved mining operations.

Much of the extant south-west native forests have a history of timber harvesting, which commenced soon after European colonisation. Over that time forest management has evolved in response to changing forest structure, advances in knowledge, and changing community expectations. Since the 1980s the area available for timber harvesting has declined as an increasing proportion of the forest estate was set aside for conservation. The rich and complex history of past management practices across the forests of south-west WA has generated considerable variation in forest structure and composition (Figs. 1 and 2). This has important implications for developing potential management prescriptions.

Until the late 1970s the primary objective of silvicultural systems applied to south-west native forests available for timber harvesting was to promote sawlog production. In 1977 the principle of multiple-use forestry, where forests were managed for a range of values including timber, potable water, recreation, conservation, and mining, was formally adopted (WAFD 1977; Havel 1989). In the subsequent decades this approach to forest management evolved into ecologically sustainable forest management (ESFM) aligned with the framework defined by the Montreal Protocols and related international standards.

Increasing knowledge of forest ecosystems has broadened the range of desirable forest values and changing social values have led to a shift in management priorities. Silvicultural practices have had to evolve and adapt to these changes. Over the past century there have been a number of widely applied forest silvicultural regimes. These include:

Selective harvesting: Since the early 1900s the jarrah forests have been selectively harvested. Selective harvesting typically involved the removal of one or a few trees per hectare. This created small- to medium-sized gaps in the forest canopy and generated a heterogeneous mixture of tree sizes and ages (Stoneman *et al*. 1989). This contributed to structural diversity at the stand and landscape scales. In selectively harvested forests, regrowth usually occurred in small patches or as scattered individuals within the canopy gaps.

Clear-felling: This involves the removal of all trees within a stand. It has been typically applied, at various scales, to karri forests with the objective of establishing a well-stocked, even-aged stand (Bradshaw 2015a). Concerns about the loss of habitat trees led to the adoption of large-tree retention practices in the 1994-2003 FMP. These are designed to promote structural diversity and the retention and development of hollow-bearing trees as the young stand grows.

Gap creation: Gap creation is carried out in jarrah forest stands that have sufficient established, young regeneration to effectively 'release' the regeneration from (overhead) competition (Bradshaw 2015b).

Thinning: Thinning is undertaken to reduce competition between regrowth trees and to accelerate growth on the trees that remain.

Single tree selection: In the single tree selection method in high impact dieback areas, the treatment allows for a portion of the merchantable trees to be removed while retaining a sufficiently high basal area to avoid increasing surface soil moisture or temperature, which could favour disease development (Bradshaw 2015b).

Mining (and rehabilitation): Since the 1960s areas of jarrah forest have been cleared for bauxite mining. In the early years, non-native eucalypt species mostly from the eastern states, were used to re-establish forest on the mining sites. Since 1988, jarrah and marri (*Corymbia calophylla*) have been used to rehabilitate mining sites.

The total area of the various forest types and management types are shown in Table 1. Even-aged regrowth forests (jarrah and karri) comprise about 220,000 ha, or about 11.3% of State forests (excluding mining rehabilitation).

Table 1: Forest type and structure categories across all tenures for DBCA-managed forests within the Forest Management Plan 2014-2023 area (Source: DBCA).

Forest type	Category	Area available for harvest (ha[1])	Area unavailable for harvest (ha)	Total area (ha)
Mining rehabilitation	Exotic species	3,710	50	3,760
	Jarrah and marri	20,100	680	20,780
Jarrah (northern)	Selectively harvested mixed mature	341,620	290,540	632,160
	Even-aged regrowth pre-1970	18,440	1,850	20,290
	Even-aged regrowth post 1970	26,330	4,730	31,060
	Old-growth forest	0	24,120	24,120
Jarrah (southern)	Selectively harvested mixed mature	272,900	280,880	553,780
	Even-aged regrowth pre-1970	8,380	490	8,870
	Even-aged regrowth post 1970	73,130	11,420	84,550
	Old-growth forest	0	233,560	233,560
Karri	Karri two-tiered	0	38,550	38,550
	Karri even-aged regrowth	52,130	22,690	74,820
	Old-growth forest	0	65,160	65,160
Wandoo	Wandoo forest and woodland	32,440	98,950	131,390
	Old-growth forest	0	12,180	12,180
Total		849,180	1,085,850	1,935,030

[1] It should be noted that the WA Government's September 2021 announcement provides for at least an additional 400,000 hectares of karri, jarrah and wandoo forests to be protected.

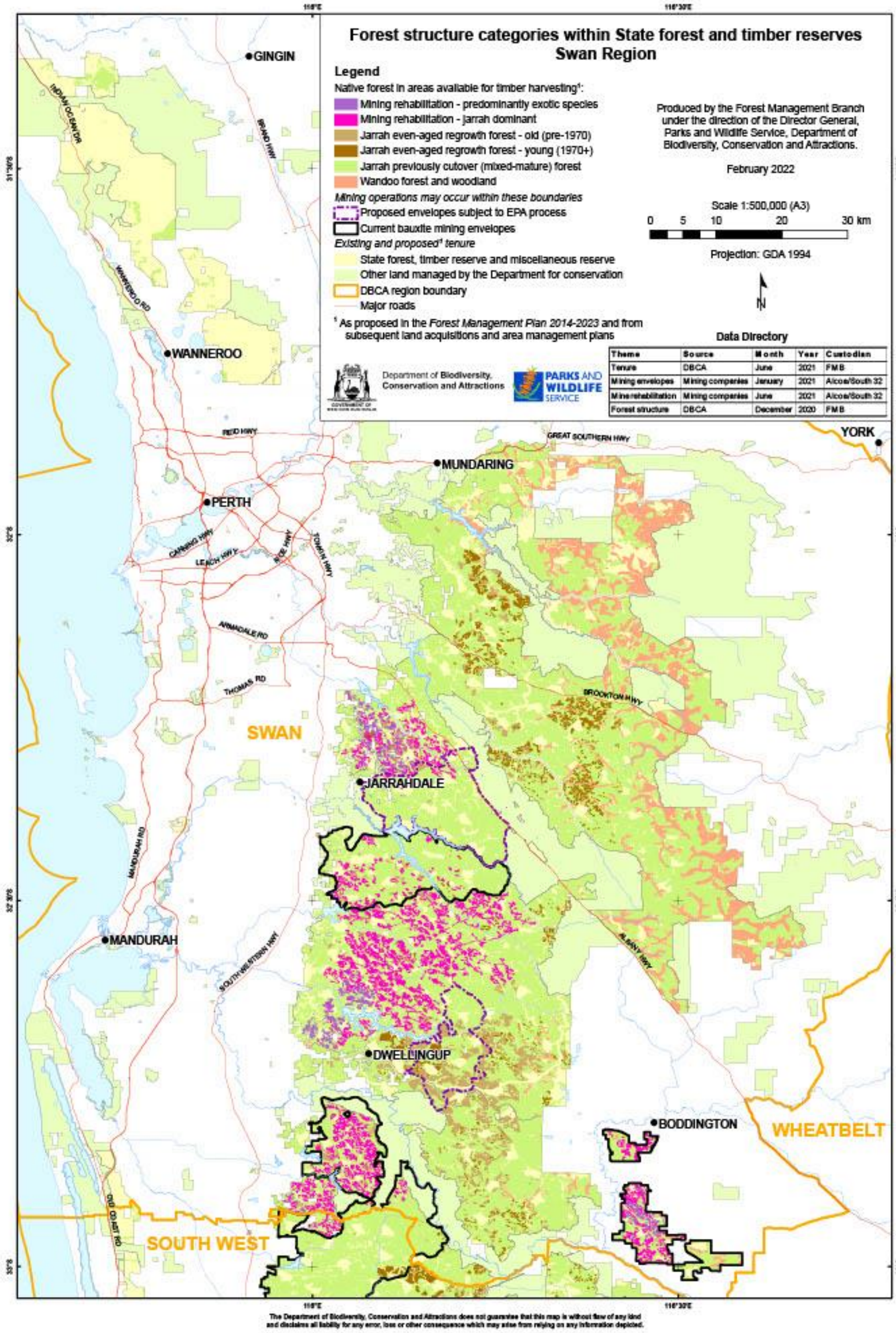

Figure 1: Example of the structural mosaic in the northern jarrah forest (State forests and timber reserves). (Source: DBCA)

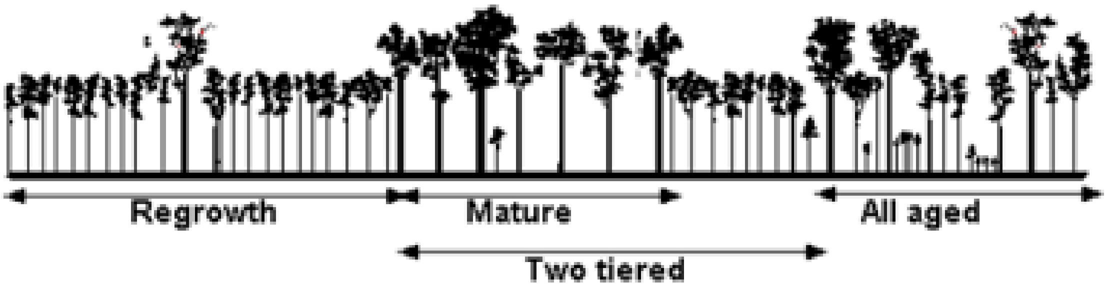

Figure 2: The jarrah forest exists as a mosaic of patches of different growth and structural stages (source: Bradshaw 2015b).

Climate change and potential impacts

Climate change is a major issue for the forests of south-west WA. Since the mid-1970s, the south-west forest region has experienced a warming and drying trend. From 1970 to 2000 there was a 20% decline in May–July rainfall in the region relative to the 1900–1969 average. Since 2000 that has increased to a 28% reduction in rainfall (Bureau of Meteorology and CSIRO 2020). Mean annual rainfall has declined by ~20% relative to pre-1975 rainfall amounts (Croton *et al*. 2015) (Fig. 3). This has also been associated with an increase in the mean annual temperature of 0.15°C per decade (Bates *et al*. 2008). There has also been an increase in extreme climatic events such as acute droughts and heatwaves in recent decades (Brouwers *et al*. 2013a; Matusick *et al*. 2013; Matusick *et al*. 2016; Ruthrof *et al*. 2018; Walden *et al*. 2019; Breshears *et al*. 2021).

In terms of future climate change the most recent assessments for south-west WA suggest the following outcomes (Department of Water and Environmental Regulation (DWER) 2021):

- An increase in mean maximum temperatures and the number of days with extreme temperatures (i.e., above 40°C).
- A decrease in annual winter and spring rainfall.
- An increase in extreme rain events across Australia (although this effect may be muted in south-western WA because of the overall reduction in rainfall).
- An increase in the frequency and length of droughts in southern Australia.
- An increase in potential evapotranspiration because of increasing temperatures.

These changes will further alter the regional hydroclimate and have potential consequences for all native ecosystems across the region.

We do not provide a comprehensive review of changes to the regional climate or the potential impacts of these changes – this is outside the scope of this review, and is dealt with elsewhere. However, there are several outcomes of the changing climate that have already begun to manifest in forests of south-west WA. The most obvious is an increasing incidence of physiological stress causing stress-induced mortality and stand-level dieback across the region, but particularly in areas of shallow or stony soils (e.g. Brouwers *et al*. 2013a and 2013b). The projected increased warming and drying across south-west WA will likely exacerbate these patterns in the coming decades. In addition, these trends have the potential to reduce the growth rates and carrying capacity of forests, increase the risk of widespread regeneration failure after disturbances, increase the risk of major pest and pathogen outbreaks, and increase both the frequency and intensity of fires. The warming and drying trend in regional climate may also have some positive impacts. For example, reductions in groundwater levels may lead to decreases in salinity risk, and reductions in soil moisture may reduce the spread and severity of *Phytophthora* outbreaks. However, the general expectation is that the future climate conditions on balance will have mostly negative consequences for the forests in the region. We consider two of these in more detail in the following sub-sections.

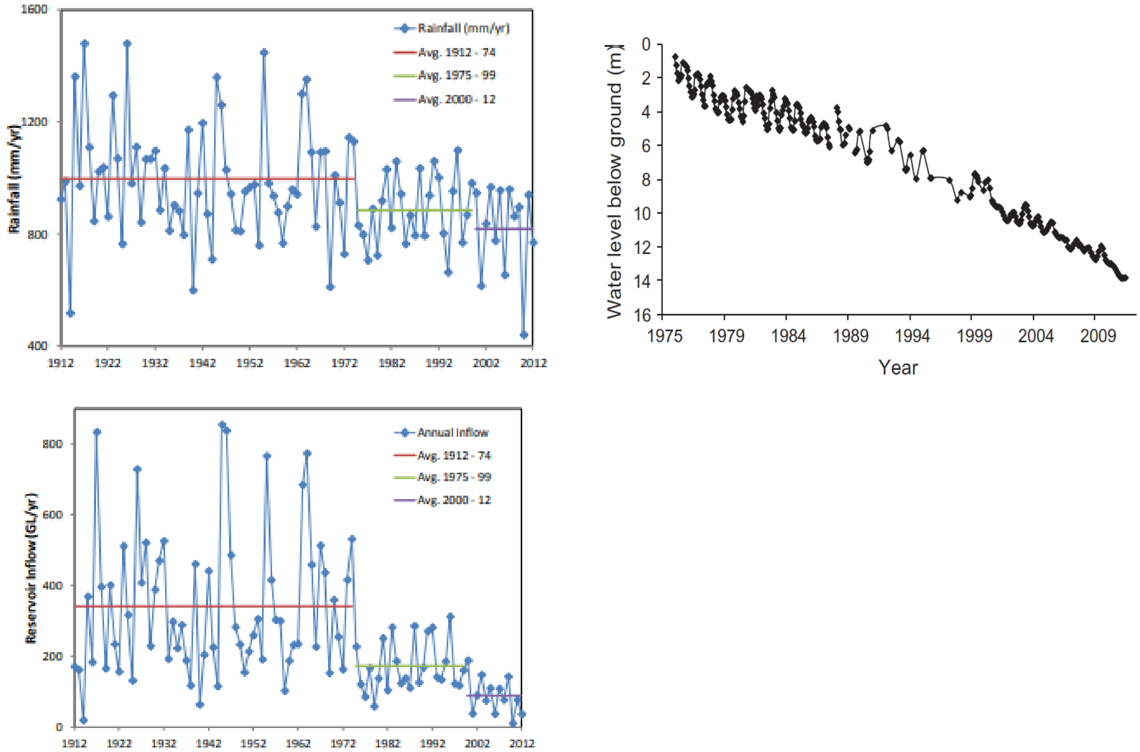

Figure 3: The water balance of the northern jarrah forest has changed. Annual rainfall has decreased (upper left; Croton et al. 2015), groundwater levels have dropped markedly (upper right; Kinal and Stoneman 2012), and streamflow into Perth water supply reservoirs has collapsed (lower left; Croton et al. 2015).

Hydrological impacts

In some landscapes, reduced rainfall has resulted in falling groundwater levels (Petrone *et al*. 2010; Hughes *et al*. 2012; Silberstein *et al*. 2012); in others the combination of reduced rainfall and areas of dense, even-aged regrowth has contributed to significant reductions in streamflow in jarrah forests (Kinal and Stoneman 2012) (Fig. 3). Dense eucalypt regrowth stands often develop in response to disturbances such as fire and timber harvesting. Because of their high proportion of sapwood, these regrowth stands use more water than mature or old-growth stands with a similar total leaf area or basal area (Macfarlane *et al*. 2010). This may lead to some stands transpiring more water than is being received from incoming rainfall (Smettem *et al*. 2013; Liu *et al*. 2019). As the regrowth stands develop, competition for resources, especially soil water, increases and can reach a point where there are insufficient resources to sustain growth, and the stand stagnates. This condition, locally known as 'lock-up', is more prevalent in jarrah forests.

The continuing reduction of streamflow associated with climate change has ecological implications for riparian, wetland, and aquatic ecosystems (Carey *et al*. 2021). Reduced streamflow is causing many once-perennial streams to become ephemeral and many ephemeral streams to become permanently dry. Wetter parts of the landscape, such as seasonal wetlands, peat swamps, riparian ecosystems, and other mesic habitats, are drying as streamflow diminishes or ceases and depth to groundwater increases. These habitats often contain unique flora and fauna that are not as well adapted to fire and drought as drier parts of the landscape. In addition, they often persist after mild fires due to their moister microclimatic conditions, and thus provide vegetated refugia for fauna in the wake of fires. As these mesic ecosystems dry, they will become more vulnerable to damaging bushfires, which may have adverse consequences for biodiversity.

Fire

As the climate warms and dries and extreme heatwaves and droughts become more common, fire regimes in south-west WA will change. This is likely to result in fires that are larger, more intense, and more frequent (Bushfire and Natural Hazards CRC 2017). Recent analyses have shown that dangerous fire weather days are likely to occur more frequently within south-west WA (Dowdy *et al*. 2019) consistent with similar global analyses (e.g., Smith *et al*. 2020). Given the projected increases in dangerous fire weather, forest and fire managers have focused on landscape scale fuel management to moderate the risk and intensity of fires. Silvicultural operations such as thinning may be able to modify the structure and amount of fuel in strategic locations. However, the dynamics of post-thinning fuel loads are complex and would need to be integrated with other management activities, such as prescribed burning, to manage periods of elevated fuel hazard and fire risk.

Terms of reference

The purpose of this Expert Panel is, "*to assist the DBCA and the Conservation and Parks Commission (CPC) in adapting silvicultural guidance and practices to deliver enhanced forest health and resilience, and to advise on practical approaches to integrate management actions at the local and landscape scales*." The geographic scope of the Panel's deliberations *"is the jarrah, karri and wandoo forests on lands vested in the CPC within the area to be covered by FMP 2024-2033*."

The Expert Panel was asked to address the following Terms of Reference (ToR):

1. Examine national and international trends on forest practices applicable to enhancing forest health, to identify those relevant and practical for application in jarrah, karri, and wandoo forests.

2. Undertake field inspections of contemporary silvicultural practices, bushfire, or salvage operations, historic silvicultural experiments and adaptive management trials that inform catchment management and ecological thinning.

3. Consider the DBCA draft proposed approach to ecological thinning and recommend practical changes or refinements necessary to deliver improved forest health outcomes at the local, stand and landscape levels.

4. Review current silvicultural guidelines and procedures and recommend adjustments and improvements necessary to prioritise enhanced forest health within an ESFM context.

5. Provide recommendations on silvicultural research and integrated monitoring programs to inform progressive adaptive management and evaluation of ecological thinning outcomes.

The full Terms of Reference are available at Appendix 2.

To inform its advice to DBCA, three of us spent 10 days in the field in February 2022 visiting operational and experimental sites, and discussing past, present, and future forest management issues with a range of forest ecologists, silviculturists, hydrologists and forest managers. The field trip focussed on experimental and operational thinning in jarrah and karri forests and in mining rehabilitation sites. The panel was also provided with a range of scientific papers, reports, maps, guidelines, and prescriptions pertaining to the management of the relevant forest types.

In the following sections we address ToR 1, 3, 4 and 5 [The field trip and discussions described in the preceding paragraph met the requirements of ToR 2 and their outcomes are described in the context of the other four ToR]. We begin by providing a set of definitions to ensure there is a common understanding of specific terminology used throughout the report. We then consider the ToR, noting that there is overlap in the information related to ToR such that some information that we present for one of the ToR may be relevant to one or more of the other ToR. To minimise repetition, we note areas of overlap in the text and indicate where more detailed consideration of specific issues has been provided.

Definitions

The expressed aim of the government policy announced in September 2021 is to address the increasing impacts of a warming and drying climate, preserve and protect, as far as practicable, biodiversity and forest health, and improve the carbon capture and storage of the south-west forests. However, there are key challenges regarding the viability of the forest industry that is needed to support these forest management activities despite the declining timber resource.

The change in policy to manage State forests primarily for improved forest health and ecological resilience implies that there is agreement on what constitutes a *healthy and resilient* forest so that any managed intervention is appropriately targeted to meet these aims. Additionally, there needs to be guidelines on appropriate activities and justifiable levels of active interventions, because any intervention, no matter how well intentioned, may have unintended consequences. The desirability of these activities needs to be weighed against the expected outcome and associated risks.

Here we provide working definitions of key terms relevant to the report to ensure some clarity about our assumptions. Specific definitions of forest health and what constitute appropriate intervention activities should be developed independently.

Forest health

Many definitions of forest health have been proposed. Few are completely satisfactory, and all are somewhat dependent on the perspective of the observer. For the purposes of this report, we propose a broad definition in which a *healthy forest* is one in which the natural processes that have sustained all components of the ecosystem continue.

To some, forest health may be about maintaining tree vigour, high growth rates, and a sustainable yield of merchantable timber or wood products. To others, forest health may be about maintaining a diverse assemblage of flora, fauna and fungi. However, a common feature of any vision of forest health is that forests are not static. Natural disturbances impact forests at various scales and lead to changes in communities and populations. Tree mortality occurs but within the bounds of past natural variability at the landscape or regional scale. Indeed, dead and dying trees are often an important resource for other organisms within an ecosystem and disturbances may ameliorate soil conditions by promoting nutrient cycling and water infiltration. Management activities within forested landscapes do not necessarily make the forest less healthy, just as the absence of management activities does not necessarily make the forest healthier.

As the changing climate and legacies of past management practices begin to interact, forest dynamics may begin to deviate from the range of known natural variability. Forest management activities may be able to mitigate or avoid some of the negative impacts of these interactions.

Forest resilience

Forest resilience is the ability of a forest ecosystem, and all of the species within it, to recover from disturbances and stressors, either natural or anthropogenic, without having components of the forest ecosystem collapsing or species becoming extinct. It is an important component of forest health. In the past, the forests of south-west WA have been impacted by fires, timber harvesting, mining, fragmentation, prolonged heat waves and droughts, pests and diseases, and introduced plants and animals. They were subjected to Aboriginal burning and lightning fires long before European's arrived, so are well adapted to a range of fire regimes. Over millennia the resilience of these forests has allowed them to maintain a dynamic equilibrium in species richness and community composition across these landscapes.

In recent decades the resilience of south-west WA's forests has increasingly been challenged. This is the result of more than a century of forest fragmentation, disease, introduced plants and animals, several decades of a drying and warming climate, and a fire regime that includes bushfires that likely differ in scale and intensity from pre-European fire regimes. Any one of these may have negative impacts on forest health, but together they are likely to far exceed the capacity of the forests to recover. This may lead to dramatic shifts in the composition and structure of these forests as well as threaten more mesic ecosystems such as aquatic and riparian ecosystems embedded within the forest landscape. These ecosystems are most at risk of permanent, irreversible change as they dry and more drought-tolerant species spread across the landscape.

Natural forest

In developing management strategies to improve forest health and resilience, considerable attention has focused on the forest structures that have resulted from past forest management practices and how they differ from the forests that existed at the time of European colonisation. The forests of the pre-colonisation landscape would have been more heterogeneous at the stand and landscape scales and they would have been considerably less fragmented. In the near term, it is neither feasible nor possible to recreate the same type of forest structures at the landscape scale. The tree species in these landscapes are limited in their rate of growth and forest managers are limited in their capacity to modify stand structure at such large scales. However, developing long-term plans to accelerate the growth of slow-growing stands, to increase stand-level heterogeneity, and to foster connectivity between forest fragments are important components of developing forests that are more resilient to future stressors.

Stocking and stand density

A concern for forest managers in regions that are projected to become warmer and drier is the fate of dense stands of young trees. This issue was raised repeatedly in discussions, field visits, and reading materials for this review (including the ToR and the DBCA Explanatory Note on ecological thinning (DBCA 2022)). There has been a considerable (and rapidly growing) body of research around the world focused on reducing stand density to increase the resilience of forests to climate change. However, there is considerable confusion regarding the definition of density and how to incorporate it into decision-support systems that help to identify stands at risk and guide thinning prescriptions. Here we define the terms as used in this document and clarify some of the issues that have caused confusion.

In the context of forest health and resilience, the primary concern is how close a stand is to its maximum carrying capacity. Stand density is the number of trees per unit area within the stand. However, stand density *per se* does not necessarily indicate how crowded the trees are or whether there is likely any competition for resources within the stand. That depends on how large the trees are. For plant populations this is typically defined by size-density relationships, which are often graphically represented relative to a self-thinning line that describes the maximum number of trees of a given mean size that can occur in a stand (e.g. Reineke 1933; Yoda *et al*. 1963; Harper 1977). These allow for an empirical estimate of stand stocking relative to a maximum level. Stocking is a commonly used term to describe how close a stand is to its maximum density for a given mean tree size. When a stand is fully stocked the trees are using all resources within the stand, but competition for these resources is not greatly limiting tree growth. If the trees continue to grow and no mortality occurs, the stand will eventually become overstocked. When a stand is overstocked, the trees are competing intensely for resources. In some species this will lead to self-thinning (which reduces stand density). However, some species do not self-thin well. In stands dominated by these species, the lack of self-thinning will eventually lead to a stand of trees with low vigour and little growth that are particularly susceptible to pests and pathogens. These latter stands are referred to as 'locked-up' or stagnated. In these cases, thinning the stand can reduce stand density and the level of stocking and make more resources available for the trees that are retained. This can increase vigour and growth in the stand.

Climate change in the south-west forests will have the effect of reducing the carrying capacity of a stand. In the context of size-density relationships, the self-thinning line will be lowered. This means that stands that are fully stocked will become overstocked due to fewer resources (notably water) being available. And stands that are overstocked will become dangerously compromised and likely suffer substantial mortality (e.g. Horner *et al*. 2009). The change in the position of the self-thinning line may be transient if the warming and drying is short-lived (i.e., one to a few years) or it may be permanent if there is a state change in the climate system (Fig. 4).

Density management diagrams (DMDs) are graphical representations of the empirical relationship between stand density and average tree size and are widely used in North America and Europe. In Australia they have not been used much for forest management. DMDs can be developed from standard inventory data, although new approaches to estimating self-thinning lines use data from permanent inventory plots that have multiple, repeated measurements (e.g. Trouvé *et al*. 2017). Preliminary DMDs have been developed for some forests in south-west WA, but have not been used for assessing whether stands are over- or under-stocked. It is also important to note that DMDs are primarily for single-species, even-aged stands and have known limitations for forests with multiple species, multiple ages, or both.

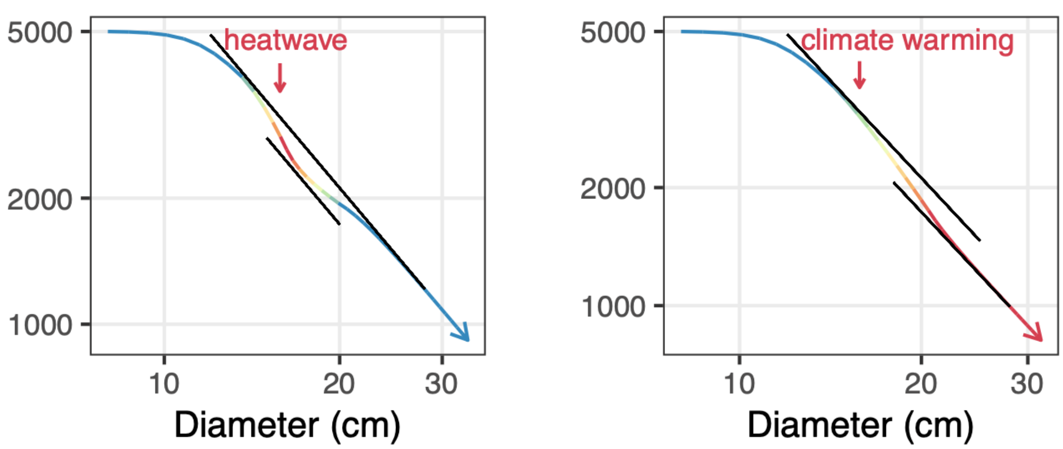

Figure 4: Self-thinning diagrams showing transient reduction in stand carrying capacity associated with a heatwave (left panel) and a permanent reduction in stand carrying capacity associated with climate change (right panel). In the heatwave scenario the self-thinning line is lowered briefly, then returns to its original position. In the climate change scenario, the self-thinning line is lowered permanently. These figures are illustrative of general patterns; they do not represent a specific tree species.

ToR 1: Examine national and international trends on forest practices applicable to enhancing forest health, to identify those relevant and practical for application in jarrah, karri, and wandoo forests.

The recent policy announcement by the WA government regarding native forests in the next FMP (2024-2033) noted that while large-scale timber harvesting would stop, forest management practices, including timber harvesting, that improved forest health would be allowed. This is a significant change in policy that has implications for government, industry, and the public. It will have far-reaching ramifications for forest and fire management, biodiversity conservation, and regional land-use planning. However, as in most other parts of the world, forest management in the south-west State forests has been largely driven by the production of wood and wood products. Eliminating large-scale commercial harvesting from the forests will require a profound re-envisioning of what forest management might look like in the next decade and beyond. While few other regions of the world have changed policy direction so suddenly across such a large area, there has been a growing interest in the development and application of ecological silviculture – that is, an approach to silviculture that emulates natural disturbances and development processes, sustains biological legacies, and allows time to take its course in shaping stands (e.g. Palik *et al*. 2020). This is particularly relevant in the context of pervasive, but temporally and spatially uncertain, threats to forested ecosystems such as climate change, invasive species, pest and pathogen outbreaks, and changing disturbance regimes. In this section we synthesise trends in forest practices from around the world that are relevant to managing forests to improve forest health. We first present a general framework for considering silvicultural strategies and approaches to adapt forests to climate change that can be used to assess the utility of specific forest management practices and their contribution to forest health. We then discuss ecological thinning, which has been proposed as a key tool for promoting forest health in warming and drying climate. Together these can provide a useful roadmap for adapting forest management practices to improve the health and resilience of the jarrah, karri, and wandoo forests of south-west WA.

Managing for healthy forests in a changing world – a framework

Forests around the world are experiencing unprecedented threats as the result of global change. Rising temperatures, declining rainfall, invasive pests and pathogens, fragmentation, and changing disturbance regimes are impacting landscapes that bear the legacy of centuries of extractive management. In recent decades our understanding of the scale and intensity of these threats and their impacts has improved exponentially. However, the paradigms that underpin our forest management and conservation practices remain firmly based on historical variability and ecological integrity and sustainability. Foresters and conservationists have long assumed that the best way to maintain ecosystems and the values that are associated with them is to restore them to, or maintain them in, their historical condition. The mismatch between this approach to management and conservation and the changes occurring to ecosystems around the world, particularly in the context of climatic conditions that are increasingly outside the range of the past centuries or millennia, represents a profound threat to these ecosystems and the biodiversity that they support (Millar *et al*. 2007). Specifically, if forests are managed to targets that are based on past conditions that may not exist in the future, individuals and species may eventually be unable to perform even the most basic demographic functions such as growing and reproducing. This may lead to gradual or sudden loss of individuals or populations within forests and shifts to a depauperate forest type or to a non-forest ecosystem.

Over the past two decades forest scientists worldwide have begun to grapple with the problem of how to adapt forests to climate change (e.g. Millar *et al*. 2007; Blate *et al*. 2009; Millar and Stephenson 2015). The framework that has emerged from these discussions is not limited to the threat of climate change; it is broadly applicable to forests subject to any chronic threatening process. The core insight is that forests will need to adapt to changing conditions and chronic stressors. Adaptation strategies can be broadly classified into three groups: resistance, resilience, and transition. We summarise them here (adapted from Palik *et al*. 2020):

Resistance: Forest management practices adapt the existing forest to endure the changing conditions by modifying stand structure and composition.

Resilience: Forest management practices adapt the forest to be more flexible in terms of responses to changing conditions by incorporating species and structures that are more adaptable to change. These may not be common in the current landscape, but will have occurred within the range of past conditions experienced in this landscape.

Transition: Forest management practices adapts the forest by changing species composition and stand structures to be more suitable to future conditions. These species may not currently occur within these landscapes and may require assisted migration (translocation).

In the context of the next FMP (2024-2033), proposed management strategies that improve forest health largely fall under the resistance and resilience strategies, the exception being pre-1988 mining rehabilitation, which could fall under the transition strategy. As the climate warms and dries in south-west WA, the forests will experience a range of stressors. These include drought, fire, pathogen outbreaks, invasive weeds, and feral animals. The degree to which these stressors will impact forests will depend on the forest type, the structure of the forest, and the local site conditions. For example, a year with particularly dry conditions may lead to moisture stress for drought-sensitive species, on sites with shallow or stony soils, or in stands with overstocked young regrowth. Forest management strategies that use a resistance paradigm may reduce stocking rates through thinning to increase the amount of water available to trees. This will enable the retained trees to endure the stressful conditions and grow vigorously once they have passed. If particularly dry conditions do not occur too frequently, this may be sufficient to avoid substantial change in the stand in the long term. If they become more frequent, then further reduction of stocking levels might be required. However, if such conditions become more frequent or persistent, then resistance-based strategies might need to be combined with resilience strategies that create different stand structures that allow the forest to recover more quickly from drought conditions or incorporate other species from the landscape that are better suited to drought conditions.

Thinning is widely used to increase the resistance of stands to various stressors because reducing stand density provides individual trees with more resources, which can increase their vigour and individual health. This is the basis for the application of ecological thinning strategies in forests in many parts of the world (e.g. Bradford and Bell 2016; Sohn *et al*. 2016) and that we discuss in detail below.

Resilience strategies are often applied where disturbance regimes are changing. The goal of this approach is to create a range of stands that vary in structure and composition such that a subset will survive disturbances and stressors in the near- to medium-term. This approach has been widely applied in western North America to address the profound changes in fire regimes that have accompanied more than a century of fire suppression and more recently a warming and drying climate. In these systems a combination of thinning and prescribed burning has been used to modify stand composition and structure to create more resilient forests (e.g. Stone *et al*. 1999; Larson *et al*. 2012; Dagley *et al*. 2018b). An important corollary to this approach is that forest management strategies that create more uniform stand structures over large areas will likely make the forest estate *less* resilient to change and increase the risk of catastrophic change at large scales.

Density management is a fundamental tool for adaptation strategies focused on increasing the resistance of and resilience to disturbances and stressors. In established stands, thinning is the primary management tool for controlling stand density to modify stand structure. In the following section we provide a broad overview of ecological thinning and its potential benefits in the context of adapting forest management practices to improve forest health.

Ecological thinning

Ecological thinning will likely be a central element of the next FMP (2024-2033). As we discuss in detail below, we consider ecological thinning to mean a reduction of tree density to enhance ecological values or ecological resilience to stress. In recent years ecological thinning has been proposed as a tool to help improve forest health and adapt forests to a rapidly warming and drying climate. In the south-west forest context, ecological thinning has been somewhat narrowly defined as removing trees to reduce moisture stress on the site (DBCA 2022). However, despite widespread interest in ecological thinning in many parts of the world, the specific ecological objectives remain largely undefined and the specific prescriptions are largely *ad hoc*. In the absence of a clear sense for what ecological thinning is and does, it is often difficult to determine its limitations. Here we consider recent national and international trends in the application of thinning to achieve a range of ecological and environmental benefits. We discuss what ecological thinning is (and might be), why it might be used, when and how it can be applied, and some of the potential limitations of a programme of ecological thinning.

What is ecological thinning?

The term 'ecological thinning' has been used in several, mostly Australian, studies (e.g. Sprugel *et al*. 2009; Archibald *et al*. 2010; Pigott *et al*. 2010; Jones *et al*. 2015; Gorrod *et al*. 2017) and reports to government (e.g. Cunningham *et al*. 2009; NSW Natural Resources Commission 2009) over the past two decades. It is important to recognise that not all studies that use thinning prescriptions to achieve specific ecological values use the term 'ecological thinning'. Many studies have applied thinning prescriptions to generate ecological benefits, but have not explicitly referred to the treatments as 'ecological thinning'. Examples from Australian forests include Horner *et al*. (2009), Craig *et al*. (2010), Barr *et al*. (2013), Gonsalves *et al*. (2018), and Keenan *et al*. (2021). Other studies have used the term 'restoration thinning' in a similar context, but with a specific objective of restoring past stand structures or processes in forests that have been impacted by a century or more of land- or forest-use practices (e.g. Stone *et al*. 1999; Dwyer *et al*. 2010; Larson *et al*. 2012; Dagley *et al*. 2018a). In North America there are many studies that have considered the potential for using thinning to restore forest ecosystems (e.g. Brown *et al*. 2004; O'Hara *et al*. 2010). Stanturf *et al*. (2014) provide a broad review of forest restoration techniques (including thinning) around the world.

Ecological thinning is typically defined by its objectives. Specific definitions vary, but all are based on the core idea that ecological thinning is a reduction in stand density to improve ecological values in a forest. In the broadest sense, it is focused on delivering benefits that are not related to commercial wood production. However, this includes many potential objectives, not all of which are specifically 'ecological'. These include restoration of pre-European forest structures and fire regimes, accelerated development of hollow-bearing trees, increased resilience of forests to drought and disease, but also increased water availability for catchments and for riparian ecosystems, improved aesthetics for recreation, and carbon sequestration. Ecological thinning is also often proposed as a potential tool to improve the 'ecological health' or 'ecological vigour' of forests, particularly trees; however, these terms are often poorly defined and measures of success difficult to quantify.

For the purposes of this review, we propose the following definition:

Ecological thinning is the partial reduction of overstory stand density to achieve one or more objectives unrelated to the commercial production of wood or wood products.

Ecological thinning generally targets dense stands of small, often young, trees. The trees in these stands are vulnerable because the available resources for growth (i.e., water, nutrients, sunlight) are divided amongst many trees. This means that there are few resources available for any single tree. This limits the ability of all of the trees in the stand to produce new roots and leaves, grow in height or diameter, resist insect or pathogen attacks, and recover from injury. By reducing the number of trees in the stand, a greater pool of resources becomes available to each of the retained trees, increasing their ability to grow and to endure adverse environmental conditions.

Why is ecological thinning used?

There are many existing and potential reasons why ecological thinning might be used in forests. Most studies that can be classified as ecological thinning have focused on three specific benefits; improving forest health, creating structural heterogeneity in stands, and increasing water yields.

Ecological thinning to improve forest health typically focuses on increasing the ability of trees within a stand to specific stressors. In Europe and North America there have been many studies highlighting the benefits of thinning for drought resilience (e.g. Bradford and Bell 2016; Sohn *et al*. 2016; D'Amato *et al*. 2017; Gavinet *et al*. 2020; Bradford *et al.* 2021). When stand-level density or basal area is reduced in overstocked stands, the remaining trees are better able to withstand droughts and better able to recover after droughts (e.g. Horner *et al*. 2009). This means the stands will be both more resistant and more resilient to drought. For example, in a recent study, Bradford *et al*. (2022) showed that reducing stand basal area by 50% reduced drought-induced mortality in conifer forests in the south-western US by 20-80%. Sohn *et al*. (2016) conducted a meta-analysis of thinning studies and showed that moderate to heavy thinning mitigated growth reductions, improved water-use efficiency, and improved post-drought recovery in trees, particularly conifers. In broad-leaved tree species, heavy thinning increased soil water availability; however, they noted that relatively few studies of broad-leaved species had been undertaken. The benefits of thinning decreased over time, but were positively correlated with the intensity of the thinning.

Over the past decade, thinning treatments to mitigate drought stress have been a central focus of forest science as drought-induced mortality in forests is becoming more frequent, more extensive, and more severe. As noted earlier, this is happening in south-west WA where recurrent droughts already occur but are likely to be exacerbated by future climate change with a decrease in annual rainfall accompanied by the drying of soil water stores (Harper *et al*. 2019) In principle, thinning is anticipating the reduction in carrying capacity of stands and ensuring that stand density is well below the future climate-adjusted carrying capacity (Fig. 4).

The key physical limit to forest health under a changing climate is water availability. Reducing moisture stress will fundamentally come from a reduction in forest water demand, which requires a reduction in leaf area. This can be achieved by reducing tree density within a stand. However, not all trees transpire water equally. In general, young, fast-growing trees use more water per unit leaf area than large, older trees. Consequently, reducing the density of dense, young stands of regrowth is likely to yield the greatest benefits for stand and landscape water balance.

Ecological thinning can be used to relieve this stress by removing vegetation that competes for water at the expense of forest elements that may be seen as more ecologically valuable or likely to develop into habitat in future. For example, riparian vegetation and low landscape positions with moist or wet soils and swamps may be threatened due to water use by forest stands higher up in the landscape. Thinning in these upper stands will likely increase water availability to ecosystems lower in the landscape that depend on having water for longer period, or permanently. The question then becomes how much vegetation should be removed, how often, and where the activity would be most effective to achieve the result.

Retaining the largest trees will also support biodiversity and improve ecological values by providing the greatest opportunity for larger hollows and habitat attributes (e.g. Whitford 2002; Whitford and Williams 2002). Where there may not be sufficient trees in this condition the largest trees that will reach this condition soonest should be retained. It is important to note that the moisture balance benefits of thinning are transient as the canopies of the retained trees grow and leaf area increases. Therefore, repeated thinning will likely be necessary.

Thinning to improve forest health is not limited to responding to increasing moisture stress. Thinning treatments to reduce susceptibility to pathogen and pest attacks have been applied in various forests around the world. Larger trees are also the most resistant to fire damage (Burrows 1987; Walden 2020; Trouvé *et al*. 2021). Thinning has also been prescribed for stands that are experiencing dieback or mortality due to pests and pathogens (and their interactions with climatic conditions). Much like thinning to improve drought resilience, thinning for forest health focuses on giving individual trees access to more resources by reducing competition from neighbouring trees. This may lead to greater resistance to insect and pathogen attacks (e.g. McDowell *et al*. 2007).

A large body of work has been conducted in the south-western and western forests of North America where fire suppression since the early 1900s has fundamentally changed forest structures, species composition, and fire regimes (Moore *et al*. 1999). Landscapes that were historically dominated by low-density stands with large trees and frequent, low-intensity fires now support high-density stands of small trees and experience infrequent, catastrophic fires. Landscape-scale treatment of these stands using a combination of thinning and prescribed burning has restored many of the features of pre-European forests (Waltz *et al*. 2003), improved growth and survival of large trees (Stone *et al*. 1999), and had little negative impact on most guilds of animals in the forest (Kalies *et al*. 2010).

The improved growth and survival of large trees, particularly in the context of fire activity, is directly relevant to Australian forests. Thinning can accelerate the growth of trees and reduce the period that they are exposed to damaging or lethal fire risk because larger trees have thicker bark and their crowns are further from fuel on the forest floor (Burrows 1987; Burrows *et al*. 2002; Trouvé *et al*. 2021). Increasing the number of large trees in the landscape will increase the probability of some trees surviving a given fire. This will reduce carbon losses and increase forage opportunities for animals that survive the fires.

Thinning has also been proposed to improve stand-level water yields in catchments that provide drinking water to municipalities. By reducing the density of trees, the total amount of leaf area is reduced and the amount of water transpired or intercepted by the trees in a stand is reduced. This may lead to more water leaving the site as groundwater or streamflow, as has been demonstrated for the jarrah forest with the Yarragil thinning/water yield studies (Kinal and Stoneman 2011). Overall, in south-west WA there is a clear relationship between leaf area, groundwater levels, and stream yield (Harper *et al*. 2019; Liu *et al*. 2019).

Any increases in water availability as a result of thinning are often short-lived. Several studies have shown that increases in streamflow may persist for as little as two years, although some (e.g. Bari and Ruprecht 2003) have reported increases in water yield for 12-15 years after a thinning treatment in the jarrah forest. A meta-analysis of catchment management treatments in the north-eastern USA showed that increased water yields were only maintained when forests were clear-felled and annually sprayed with herbicide to prevent regrowth (Hornbeck *et al*. 1993).

When should ecological thinnings be applied?

Ecological thinning studies have generally focused on relatively young, even-aged stands. Early reduction of stand density accelerates development of the retained trees during their period of highest potential growth rates. Historically, silviculture for wood production has focused on maintaining full stocking of stands to maximise the use of available resources. In practice, this has meant regenerating stands at high densities to ensure adequate stocking, to minimise branch size (and knot formation) and to improve stem/bole form. Thinning is used to focus stand-level growth on specific trees to increase merchantability and stand value. The timing and intensity of thinning is determined by the expected magnitude and duration of growth response, as well as the impact on branch size and wood quality. In ecological thinning these trade-offs between stand density and wood quality are largely irrelevant. Indeed, there may be ecological benefits to growing trees at low densities because the large branches that grow may develop hollows sooner than trees grown at high densities. Consequently, the timing of thinning for ecological purposes may be more flexible than thinning for commercial purposes. In particular, ecological thinning may be conducted earlier or delayed longer than timber-oriented thinning. However, dense, young stands often continue to grow in height even after diameter growth has slowed or stopped. So, delaying thinning may lead to the retained trees becoming more susceptible to collapse or breakage after thinning has occurred.

It is important to have a transparent tool based on empirical observations to determine if a stand has become overstocked and might be suitable for thinning. In North America density management diagrams (DMDs, sensu Reineke 1933) are widely used for this purpose. DMDs use the self-thinning relationship for a species under certain growing conditions to establish a maximum number of trees that can occur for a given average tree size. This is conceptually analogous to carrying capacity in animal populations. When a stand is at its maximum density for a given average tree size, it is 100% stocked. It is possible to calculate densities that represent lower proportions of stocking. Preliminary stocking guidelines have been developed for jarrah forests (Martin Rayner, DBCA, personal communication) and there is likely sufficient data to do so for karri forests, although further work may be required to capture the influence of variability in site productivity on stocking guidelines. If suitable DMDs can be developed, then a simple stand inventory should be able to indicate whether a stand was approaching a critical level of stocking and should be prioritised for thinning. The critical question is: What stocking level or basal area or LAI should a stand be thinned to? In a warming and drying climate, stand-level LAI, productivity, and carrying capacity are all expected to decline. Thinning prescriptions that link projected future LAI to DMDs may be a useful approach to guide the future silvicultural operations. There may be some scope to use historical thinning experiments and trials in jarrah and karri forests to help develop an empirical framework for ecological thinning prescriptions.

How is ecological thinning done?

Most ecological thinning prescriptions involve a stand-wide reduction in basal area. The thinning typically proceeds from the smallest trees towards larger trees (i.e., thinning from below) until the basal area target has been met. Large trees are typically excluded from culling as they are the most likely future habitat trees and store the greatest amount of carbon. In some ecological thinning treatments, a diameter cap for trees to be thinned is established to prevent the loss of large trees that may be current or future habitat trees. In others, underrepresented species may be retained to maintain diversity of the tree flora.

The intensity of ecological thinning varies widely. Some prescriptions remove as little as 18% of the overstorey basal area (e.g. in Turkish oak forests to increase water yield (Gökbulak *et al*. 2016)), while others may remove as much as 68% (e.g. in dry conifer forests in Pacific Northwest USA to restore pre-European structures and fire regimes (Dodson *et al*. 2008)). Other treatments thin to a target stem density. For example, in redwood forests of northern California, two separate restoration-focused thinning treatments reduced stand density to 185 trees per hectare (tph) or 371 tph *(*O'Hara *et al*. 2010). These treatments are often guided by DMDs that provide an indicative stem density for a given mean stand diameter at breast height (DBH) under various levels of stocking. It is important to recognise when comparing published studies on thinning for ecological outcomes that there are a wide range of thinning prescriptions that are generically referred to as ecological thinning. Often these treatments vary dramatically in the number of trees removed.

Ecological thinning prescriptions also vary in the spatial arrangement of treatments within a stand. Some prescriptions apply a uniform reduction in basal area across an area, while others aggregate the thinning to create small gaps in the forest. Silviculturists working in temperate northern hemisphere forests have proposed using variable-density thinning to generate both horizontal and vertical structural diversity within a stand (e.g. O'Hara *et al*. 2010; Puettmann *et al*. 2016). Variable-density thinning involves applying a range of thinning intensities across a stand. These may be applied randomly by the person marking the stand for thinning (e.g. O'Hara *et al*. 2010) or varied based on variability in local stand structure and composition. It is worth noting that there may be a range of operational limitations on thinning prescriptions. This may be due to safety concerns. For example, hand-felling is often considered too risky except for the smallest trees. However, most harvesting machinery may have a lower limit on the size of trees that can be handled and a minimum width of forest that it must harvest to move around within the stand given the dimensions of the machine.

Potential concerns with ecological thinning

Ecological thinning has many potential benefits. However, like any silvicultural prescriptions it has potential drawbacks as well. Here we highlight a few of these in the context of managing for forest health in the forests of south-west WA.

Thinning operations leave biomass from trees on the ground. Depending on the type of thinning this may include leaves, branches, or whole trees. In fire-prone ecosystems such as those of south-west WA, excess biomass that is produced by thinning represents fuel loads and structures that may increase fire intensity if the stand was to burn. However, the increase in fuel loads from thinning will likely be localised and relatively small within the broader landscape given the scale of thinning that might reasonably be expected to occur. In addition, given the priority to thin in regrowth stands dominated by small trees, most of the residue will be relatively small and will break down relatively quickly (and this can be aided by on-site residue management at the time of thinning). While there may be a short-term increase in fuel loads in localised patches, over the long-term the fuel loads would decrease. The combustion of coarse woody material in close proximity to retained trees can cause can significant bole damage which, following successive fires, can lead to hollow-butting and tree collapse (Burrows 1987).

Historically, large-scale forest management activities have focused heavily on ensuring that adequate regeneration occurs after harvesting. If most forest management activities in the next FMP (2024-2033) are focused on ecological thinning, then regeneration of new areas of forest will be wholly dependent on natural regeneration after disturbances (primarily fire). While this is not a problem if seed crops are abundant and predictable and regeneration conditions are suitable, in a changing climate neither of those conditions may occur. The next FMP (2024-2033) should explicitly address the need to ensure that suitable natural regeneration is occurring within the landscape and develop contingency plans to supplement regeneration if it is not.

Harvesting trees in forests typically requires heavy machinery. This can lead to soil disturbances that may reduce the productive capacity of the soil through compaction and erosion. Where thinning intensities are relatively light, repeated entries may be required to maintain reasonable stocking levels. This risks increasing the soil damage. Operational plans to manage soil impacts should be monitored and adjusted if significant impacts are identified. This might include earlier thinnings that require lighter machinery that has less potential to impact the forest soils and limiting operations to dry soil conditions.

Thinning opens up dense stands. This has the combined effect of increasing airflow through the stand and removing neighbouring trees that might have provided some structural support in stands dominated by relatively slender trees. Consequently, the risk of damage to stands from strong winds will typically increase in the years after thinning. We are not aware of any published data on post-thinning windthrow in the south-west forests, but note that the unpublished disturbance history data from DBCA-managed forests notes that windthrow in jarrah and karri forests is minor and typically associated with localised 'mini-tornadoes'.

Thinning activities may damage retained trees and increase their risk of secondary damage or mortality. For example, where the base of a tree is damaged by harvesting machinery it may create a wound that is more vulnerable to fire-induced damage or pest and pathogen attack. While there is little evidence of this in eucalypt forests, Maloney *et al*. (2008) working in conifer forests, found relatively minor impacts of thinning on root rot. However, they noted that if the thinning increased the mortality rate of larger trees, it might undermine restoration goals.

Many thinning prescriptions are designed create heterogeneity within a stand. However, if one or a few thinning prescriptions are applied broadly across a landscape, they may have the unintended consequence of homogenising the forest at the larger spatial scale. This is particularly prevalent in forested landscapes dominated by relatively small number of canopy tree species, such as the jarrah and karri forests of the south-west. As such, it would be beneficial to develop a diverse set of thinning prescriptions that vary in intensity and within-stand spatial variability. This would provide a more heterogeneous landscape, which would support a resilience-based adaptation strategy, and be an important foundation for a program of adaptive management based on stand responses to the different thinning prescriptions.

Finally, thinning is a silvicultural prescription that kills trees. While there may be a sound scientific basis for a program of active management that includes thinning forests to improve forest health, a legacy of mistrust between different stakeholder groups may undermine the ability to implement such activities and engage the relevant communities.

Overview of ecological responses to thinning in south-west forests

Thinning has been conducted in the forests of south-west WA for decades. While it may not have been explicitly conducted for ecological outcomes, there are certainly lessons that have been learned in this process. Here we summarise what has been learned about the ecological and environmental outcomes of thinning in these forested landscapes.

Effects of thinning on biodiversity

The FORESTCHECK program has been monitoring the effects of silvicultural operations relevant to the forest management objectives espoused in the current FMP (2014-2023), and natural variability, on a wide range of organisms, communities, and processes in jarrah forests since 1999 (Abbott and Burrows 2004). It has shown that forest taxonomic groups are generally resilient to contemporary silvicultural treatments (Bradshaw 2015a and 2015b), bushfires (e.g. Abbott and Williams 2011; McCaw *et al*. 2011; Ward *et al*. 2011) and increases in coarse woody debris. There have also been some negative outcomes including increases in soil bulk density, decreases in grasstree abundance and lichen species richness, and changes in macrofungi composition. Retained legacy elements such as habitat trees, coarse woody debris and fauna habitat zones have made an important contribution to species conservation for a wide range of species. Ecological thinning and associated burning must be undertaken in a manner that maximises the preservation of these habitat elements.

Effects on pests and diseases

Dense stands of small trees are more vulnerable to extreme climatic events and fires. However, they are also more vulnerable to diseases and pathogens. The small crowns of the trees relative to total tree size limits the available photosynthate that can be used to produce chemical defences. The relatively small root systems make the trees particularly vulnerable to pathogens such as *Phytophthora cinnamomi* that attack the root system. Ecological thinning can increase the vigour of individuals within a stand by increasing the size of the tree crowns relative to total tree biomass. This allows for more photosynthate to be directed towards plant defence and replacement of fine roots and leaves. While this does not prevent infection by diseases and pathogens, more vigorous trees are better able to defend themselves against such infections and reduce the impacts if they do become infected.

In the south-west forests of WA there are several key pathogens that can have significant impacts. *Phytophthora cinnamomi*, a water mould that thrives in wet, warm conditions, has been a concern since the 1960s (Podger *et al*. 1965). If areas become temporarily waterlogged, harvest activities may risk spreading the pathogen. The endemic fungi *Armillaria luteobubalina* is a widespread collar and root rot that impacts jarrah and karri (Shearer and Tippett 1988). More recently, a canker caused by *Quambalaria coyrecup* has been found in marri; it is generally more prevalent in wetter and cooler areas of marri's range (Paap *et al*. 2017). The canker was found more often on trees growing along disturbed road edges.

Reducing basal area and stem density via thinning may reduce competition, stress and reduce susceptibility to pathogens. However, this needs to be investigated in terms of other pathogens and weighed up against the potential to spread pathogens whilst undertaking thinning. A study by Batini (2012) where tree crown health was monitored after thinning in the Cobiac catchment in 2008, and following a severe drought in 2010, showed that thinning increased crown health of remaining trees, regardless of *Phytophthora cinnamomi* status.

Effects on site and landscape water balance

There have been many studies in south-west WA, across Australia and internationally examining the effect of forest practices in general and thinning and clear felling in particular, on streamflow and groundwater levels. A summary of findings in WA was given by Macfarlane *et al*. (2010) who showed that sapwood area is a much better determinant of transpiration by trees, and small diameter trees, having larger sapwood area per unit basal area than larger trees, consume significantly more water than larger ones. In a study of patches of regrowth and mature jarrah forest, the regrowth patch, with two-thirds of the basal area of the mature patch, had 30% greater LAI, nearly twice the sapwood area, and double the transpiration of the mature patch. From this, thinning smaller, younger trees has a greater impact on reducing forest water consumption than culling older larger trees. If thinning for water yield and soil moisture recovery is to be adopted, thinning smaller trees will yield a greater moisture return than a similar area of older larger trees. This approach would also have the effect of restoring a size distribution more similar to virgin uncut forest than may exist in un-thinned regrowth stands.

The absolute limit to streamflow increase from forest thinning can be determined from several experiments showing that complete clearing for agriculture, which yielded 20% to 30% of rainfall increase in streamflow with 50%-90% removal of forest; this was equivalent to a four-fold to 15-fold increase in streamflow, although the greatest proportional increase was in lower rainfall areas, the greatest quantum of increase was in the higher rainfall areas (Bari and Ruprecht 2003). However, these increases always occurred with a rise in salinity which would render the streams unsuitable for water supply, and would potentially be detrimental to aquatic systems dependent on fresh water. For ecological thinning of forest which, by definition, is aimed at preserving or improving the structure of the forest, a much more refined approach is needed. Thinning of forest has been shown to increase soil moisture and groundwater levels, and may raise streamflow levels by up to 18% of rainfall depending on treatment (Bari and Ruprecht 2003) but this does not always occur (Kinal and Stoneman 2011). Forest thinning, as opposed to clearing for agriculture referred to above, has not resulted in an increase in stream salinity.

Effects on fire behaviour

Large, high-intensity bushfires are a threat to many values, including human communities and forest health. In a fire-prone environment, managing fuel build-up by prescribed burning has been and will continue to be, an important bushfire mitigation activity. Reducing fuel build-up and fuel hazard reduces the intensity of bushfires, making them less damaging and easier and safer to suppress (Cheney *et al*. 2012; Burrows and McCaw 2013). Ecological thinning can have several effects on potential fire behaviour: i) it can reduce the potential for sustained crown fire by reducing canopy connectivity (e.g. Stocks *et al*. 2004), ii) it can increase surface fire intensity by adding a substantial amount of dead fuels to the forest floor, and iii) it can alter micrometeorological conditions within the stand (e.g., increased temperatures and reduced humidity at the forest floor, greater wind movement through more open stand). The quantum increase in fuels and fuel hazard resulting from thinning will depend on forest type, thinning intensity and the treatment/utilisation of the residue. In jarrah forests, overall fuel hazard can be ameliorated to some extent by prescribed burning to reduce total fuel load in advance of, and soon after, thinning operations. In forests dominated by young karri, which are more sensitive to fire damage, if residue removal is done effectively, post-thinning prescribed burns may be avoidable.

ToR3: Consider the DBCA draft proposed approach to ecological thinning (*DBCA's Explanatory Note on ecological thinning*) and recommend practical changes or refinements necessary to deliver improved forest health outcomes at the local, stand and landscape levels.

ToR4: Review current silvicultural guidelines and procedures and recommend adjustments and improvements necessary to prioritise enhanced forest health within an ESFM context.

In the view of the Panel, ToR3 and ToR4 request similar information. The primary distinction between them is that ToR3 places this in the context of the DBCA Explanatory Note on Ecological Thinning whereas ToR4 does so in the context of existing silvicultural guidelines and procedures (i.e., the current FMP (2014-2023)). We focus primarily on the former because of the recent policy shift away from a production-centred forest management paradigm towards one focused on forest health. It should be noted that the current FMP includes two guidelines relevant to the current discussion:

Guiding principle 10 – Promote ecosystem health and vitality through silvicultural management.

Guiding principle 13 – Silvicultural treatment of native forest may be used to maintain or enhance the flow of water to surface and ground water reserves.

However, it is the understanding of the Panel that there has been little thinning within the current FMP that was specifically aimed at meeting these Guiding Principles. It will be the aim of the next FMP (2024-2033) to apply these principles broadly to the State forests. Nonetheless, the extensive experience of thinning, particularly of karri forests, in the current FMP (2014-2023) provides useful insights into the operational realities of extensive thinning in the forests of the south-west. Here we address the specific details of the DBCA's Explanatory Note on Ecological Thinning (Appendix 1), make some suggestions for refining them for the different forest types, and discuss various issues that should be considered in managing for forest health at multiple scales within an EFSM context.

The DBCA Explanatory Note on ecological thinning

The Explanatory Note (Appendix 1) provides a useful overview of the motivation for ecological thinning in the south-west forests and a strategic-level framework for implementation. It suggests the types of forest within the next FMP (2024-2033) area that should be prioritised for ecological thinning and some broad guidelines for how it might be applied. The Explanatory Note is also useful in noting a number of experiments in which some of these ideas have been trialled and a summary of some of the outcomes. Overall, the panel felt that it was a useful and accessible guide to the DBCA's proposed approach to ecological thinning in the next FMP. However, there were several issues that the Explanatory Note raises that we felt should be highlighted and expanded.

Definition of ecological thinning

The Explanatory Note defines ecological thinning as, "*an operation where trees are selectively removed from a forest to reduce current and future moistures stress on the site for an extended period*." This is a relatively narrow definition of ecological thinning that focuses on a single specific benefit that thinning might provide. While the document notes that there are other ancillary benefits, such as reducing ladder fuels and increasing fire resilience, it ignores the possibility that thinning might be done for reasons unrelated to moisture stress. We discussed a number of these in detail in the earlier section reviewing the current scientific literature on thinning for ecological outcomes. Some obvious reasons to thin include accelerating the development of habitat trees, increasing the resistance of trees to fire-induced mortality, and increasing tree vigour to reduce threats from pests and pathogens. While these benefits may be realised in a program that is focused on using thinning to reduce moisture stress, it would be reasonable to consider using thinning specifically for these goals on sites that may not be a priority for managing moisture stress, but might, for example, benefit from more habitat trees in the coming decades. By taking a broader view of ecological thinning and its intended purpose, the DBCA would increase the range of potential sites that might be available for ecological thinning within the landscape (i.e., not limit ecological thinning to only those stands that are experiencing acute moisture stress).

Silvicultural guidelines for ecological thinning

The Explanatory Note provides a number of guidelines for the implementation of ecological thinning, but these are quite general and will require substantial refinement. As noted in our review of thinning for ecological values above, there are many thinning prescriptions that have been used to enhance ecological values. Most of the thinning experiments from the south-west forests that are cited in the Explanatory Note used a standard prescription that involved thinning from below to a uniform target residual basal area. This has both operational, commercial, and aesthetic appeals. It is simple to implement, produces trees of consistent size and wood quality, and is generally considered to be visually attractive. However, the relatively uniform spacing amongst retained trees means that most of the trees will begin to compete for space and light at approximately the same time in the future. If the thinning is not intense enough, this may lead to declining vigour at the stand level within a decade or two and require subsequent thinnings. If the thinning is too intense, future stagnation may be avoided, but the thinning operation may not be socially acceptable. In addition, intense thinnings may lead to a regeneration response, which will require attention of its own. Given these issues, developing thinning prescriptions that are spatially variable within the stand would be worth exploring. There is precedent for this approach in restoration-focused silvicultural practices in North America (as noted earlier).

One of the silvicultural guidelines in the Explanatory Note proposes thinning to a level that will maintain the leaf area index (LAI) within an acceptable range for at least 20 years. The length of this period may vary across sites and forest types, but the goal is to maintain a reduced LAI for a prolonged period. This raises the concern that to reduce LAI for several decades will require a very intense thinning. Several of the thinning experiments described in the Explanatory Note had silvicultural prescriptions that reduced stand basal area by 60-70% or more. While there may be hydrological or ecological merit to this intensity of thinning, it may not be socially acceptable. However, lighter thinnings may not lead to a reduction in moisture stress or the reduction may be short-lived as the retained trees quickly refill the space. If the reduction is transient, then multiple entries will be required. This may create issues with soil compaction and understorey damage associated with the harvesting machinery (Burrows *et al*. 2002; Whitford and Mellican 2011).

The silvicultural guidelines note that thinning in regrowth stands will typically commence when the stands are 20-25 years old. This is likely associated with the time that stocking levels lead to declines in growth and vigour. There may be advantages to thinning much earlier. For example, thinning in much younger stands could be done with lighter machinery, which will reduce the risk of soil compaction and disturbance. In regrowth forests dominated by the more fire-sensitive karri, earlier thinning could reduce fuel loads that accumulate from self-thinning and self-pruning, which may lessen the risk of fire damage. Historically, forest managers have avoided thinning to very low densities because of the loss of stem quality associated with large branches. In an ecological thinning regime, that may be less of a restriction and provide greater latitude in the development of new silvicultural prescriptions. However, managing stands at very low densities from early on may also lead to greater accumulation of vegetation on the forest floor, which may create higher fuel loads. Because of the strong re-sprouting ability of jarrah, thinning will need to be followed up with coppice control, otherwise the LAI will quickly re-establish to pre-thinning levels. Experimental thinning trials would facilitate an assessment of the relative risks and benefits associated with these issues.

Ecological thinning in practice

The overarching historical silvicultural approach is that if a tree is to be removed it should achieve one of three principal objectives: 1) promote growth of the retained trees, 2) open up the overstorey to allow ground coppice to develop into saplings, or 3), reduce overstorey competition and allow seedlings to establish and grow more rapidly (Bradshaw 1987).

Ecological values will be enhanced by having a relatively small-scale mosaic of diverse forest structural conditions. In the past, coupes and fire management cells have often been larger than 1,000 ha. This has led to a degree of homogenisation of the forest in terms of structure, composition, and age over large areas. Such large blocks of relatively uniform forest structures are substantially different to the forests that existed prior to European colonisation. This has reduced forest resilience to changing climatic conditions and disturbance regimes. Shifting forest management practices to apply diverse thinning prescriptions to create a fine-scale mosaic of different forest structures would move the landscape towards pre-European forest structures and the ecological processes that accompanied them. In principle this would increase resilience at the landscape scale. Furthermore, the current practice of retaining habitat trees (5 per ha plus secondary habitat trees) should be extended to retention of habitat precincts, that include not only habitat trees but also areas around them with other trees so that the animals that nest within the main habitat tree have a minimum range for forage and nesting. Any machinery operations will need to minimise soil disturbance and compaction, and damage to the understorey and to retained trees. The process will also require residue management to limit fuel accumulation that may result in excessive fire risk or fire damage to retained trees.

The primary objective of ecological thinning is to provide retained trees with greater access to resources, which will make them more resistant to environmental stressors. Ecological thinning may also be a tool for increasing environmental water availability, including water for mesic habitats in the forest landscape such as riparian ecosystems, peat swamps and other wetlands. The hydrological relationship between upland forests and these lower lying mesic ecosystems is poorly understood. There are a range of studies detailing the efficacy of thinning on the growth of retained trees, and on streamflow and groundwater, but there are no data on the effects of thinning of upslope forest on riparian ecosystems and wetland habitats. It is possible that ecological thinning could have little impact on water availability to these habitats, depending on the rainfall zone, or that any effect it has could be relatively short-lived (e.g., 12-15 years, Bari and Ruprecht 2003).

Ecological thinning by forest type

Jarrah forest

The jarrah forests are commonly divided into the northern and southern forests (forests north or south of the Preston River). While there are biophysical differences between the northern and southern jarrah forests, the forest hydrology, including the relationship between rainfall deficit (evaporation minus rainfall) and leaf area index (LAI), is similar (Croton *et al.* 2015) and current silvicultural prescriptions (Bradshaw 2015a and 2015b) apply to both. For these reasons, and for the purpose of this review, the jarrah forest is treated as a single entity.

At the landscape and regional scales, the jarrah forest is a heterogeneous mosaic of patches of different ages and stand structures (Fig. 5) due its complex history of past disturbances and land-use. At the stand scale, many forests are relatively homogeneous in structure and composition. Since the 1980s, the aim of silviculture in the jarrah forests has been to apply the treatment most appropriate to each patch within the forest structural mosaic (Bradshaw 1987). This has resulted in a large total area that has large patches of heavily stocked even-aged regrowth (Table 1; Fig. 1). Individual trees in these stands have relatively small crowns and root mass and therefore have limited access to water and limited ability to increase their access to water. In jarrah forests self-thinning occurs extremely slowly. Even though some trees accumulate wood faster, there is little differentiation in height and the smaller trees are tolerant enough of shade that they are able to survive while growing very slowly. Several studies have measured mortality rates at ≤0.2% yr^{-1} (Burrows *et al*. 2010; Bhandari *et al*. 2021). While overstocked young jarrah forests may eventually self-thin and attain a mixed size structure similar to that at the time of European colonisation, this process may take hundreds of years. In a drying climate these stands will be particularly vulnerable to dieback and mortality due to drought-induced stress.

While all jarrah forests would likely benefit from silvicultural measures that reduce water stress, it is unlikely that forest managers will have sufficient resources to treat all areas that require treatment in a timely manner. Developing tools that can identify areas to prioritise for ecological thinning should be an urgent priority given the proposed focus of the next FMP (2024-2033) on ecological thinning. Croton *et al*. (2014) proposed a framework based on the different rainfall zones of the northern jarrah forests. This suggested a stream flow target of 100 mm/yr for the High Rainfall Zone (HRZ; >1100 mm/yr), 10 mm/yr for the Intermediate Rainfall Zone (IMZ; 900-1100 mm/yr) and 1 mm/yr for the Low Rainfall Zone (LRZ; <900 mm/yr). This would require maintaining basal areas of 18-21 m^2 ha^{-1}, 15-18 m^2 ha^{-1}, and 9-15 m^2 ha^{-1} for the HRZ, IRZ and LRZ, respectively (Croton *et al*. 2014). However, this approach does not address issues such as the temporal dynamics of runoff, persistence of water within the different soils, or the influence of bushfires, landform, or climate variability on water yields. Further work in this area is urgently needed.

As a general principle, treatment should aim to reduce water stress in more mesic parts of the forest landscape, such as riparian ecosystems, and seasonal wetlands, by thinning overstocked forests upslope of these ecosystems. These 'mesic' ecosystems comprise 10-15% of the jarrah forest and they are distinctly different from surrounding upland ecosystems because of unique soil, vegetation structure and floristics, and habitat characteristics that are strongly influenced by the presence of water. As can be seen in Fig. 5, the dendritic nature of riparian zones provides corridors and landscape connectivity, which is important for many fauna species, but especially for those that exist as metapopulations, such as the vulnerable quokka (*Setonix brachyurus*). However, the specific mechanisms (and their interactions) that drive water balance in these ecosystems are poorly known for most areas. The development of an adaptive management framework for all thinning prescriptions in the next FMP (2024-2033) will be central to better understanding these relationships and developing predictive models to estimate the potential impact of ecological thinning on water status of different parts of the landscape.

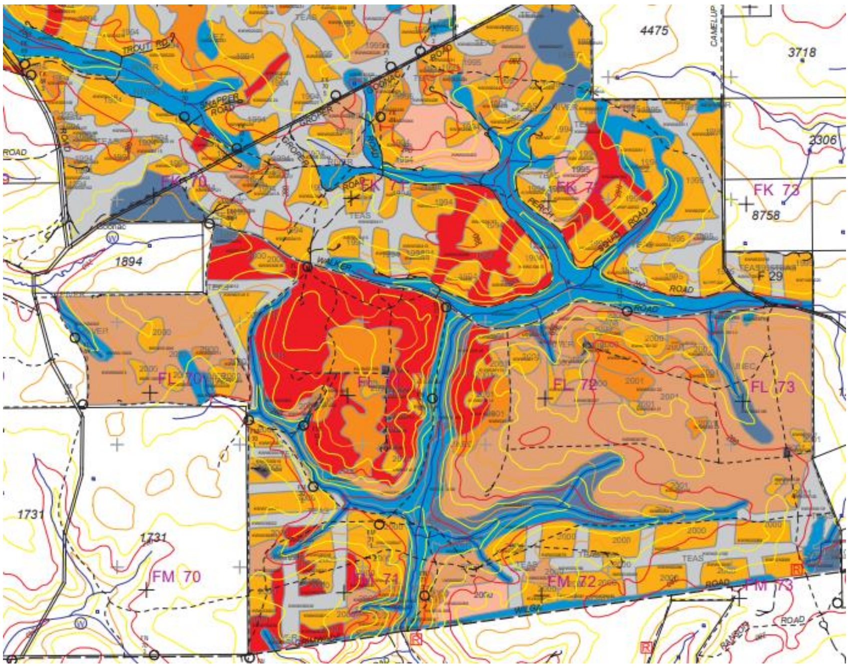

Figure 5: An example of a northern jarrah forest landscape showing patches of regrowth resulting from past logging and the dendritic nature of creek lines and riparian zones (dark blue) excluded from logging as part of the informal reserve system. Riparian zones are important habitat, refugia and wildlife corridors but are vulnerable to degradation in a drying climate. Other colours represent various silvicultural objectives (source: DBCA).

Ecological thinning operations should prioritise stands and catchments that are most vulnerable to drought stress and 'lock-up', being a function of stand age, density and soil depth/volume. Because stands vary in their stocking and size structure, no single thinning prescription will be suitable for all jarrah forests. While the DBCA Explanatory Note on Ecological Thinning provides several sensible guidelines for developing silvicultural prescriptions, forest managers should be encouraged to explore a range of different thinning prescriptions and work to tailor them to local conditions. This might include standard prescriptions such as thinning from below to a uniform residual basal area target. But it should also consider crown thinning (i.e., reducing the density around specific retained trees throughout a stand, but leaving the matrix of dense trees intact) and variable-density thinning (i.e., varying the intensity of thinning across the stand area such that some areas are thinned to low densities, some to moderate densities, and others left unthinned). Thinning should avoid damaging grass trees (*Xanthorrhoea* spp.) and mid-canopy or understorey tree species such as *Banksia* spp., *Allocasuarina* spp., and *Persoonia* spp., although there may be a case for thinning dense groves of *Banksia grandis* that have developed in gaps created by logging. Thinning should be focused low in the landscape adjacent to, but not in, riparian zones and wetlands, and move upslope. In these situations, it will be important to implement operational techniques that minimise risk of disease spread within the area being treated. Management should focus on dense even-aged regrowth stands in the higher rainfall zones where the chances of improving the local water balance is most likely.

There are several ways in which trees can be culled in a thinning operation including by notching (poisoning), hand culling (chainsaw falling or ring-barking), or machine falling. Each method has advantages and disadvantages. Notching is the least expensive and creates the least disturbance to the soil and the understorey. It also results in less coarse woody debris as fuel on the forest floor. Because the trees are killed, there is no need to treat coppice. However, dead standing trees near fire boundaries can be a safety hazard and will create problems for fire managers during prescribed burning and bushfire suppression, so some culled trees may need to be felled. There are concerns about the effects of herbicides on humans and the environment, so the appropriate chemicals need to be used, training and safeguards for safe use need to be in place, and a range of operational constraints regarding the appropriate weather conditions for application need to be met to ensure success. Notching, or poisoning trees may be perceived as unacceptable by some stakeholders, so this will need to be managed.

Ring-barking trees is more labour intensive than notching. However, while the outcome is similar, ring-barking is more likely to result in coppice growth, particularly in small trees. Chainsaw-falling also causes minimal soil and understorey disturbance but significantly adds to the fuel load on the forest floor, and is labour intensive. Chainsaw-falling often requires follow-up coppice control with herbicide. If the coppice is not treated, the benefits of thinning on local water balance may be lost within five years (Kinal and Stoneman 2011). Thinning using machines such as feller-bunchers fitted with an herbicide applicator to prevent stumps coppicing is most effective if the thinning residue is to be utilised. However, large harvesting machinery presents a greater risk of damage to soil, the understorey, and to retained trees. In addition, feller bunchers often have limits on the minimum stem size that they can handle, which may limit their utility in dense stands of small trees.

Thinning will generate considerable residue, either standing or on the forest floor. There are benefits to commercial utilisation of the residue, including off-setting the cost of thinning, reducing post-thinning fuel loads in the forest, and the potential for long-term carbon storage in durable manufactured wood products. There may be some fuel reduction benefits in directing permitted firewood collectors to stands that have been thinned to waste by felling. However, commercialising the operation could be perceived as the driver of ecological thinning rather than a by-product, so may undermine public acceptance and support for a program of ecological thinning.

Following a thinning operation, the retained trees will grow relatively quickly in the initial stages following thinning – up to double the growth rate of trees in unthinned stands (Stoneman *et al*. 1997). Thinned stands will need to be monitored and follow-up thinning operations will likely be necessary to prevent stands growing into drought-induced 'lock-up' as the leaf area recovers with tree and crown growth. Thinning is not a panacea for chronic decline in streamflow and groundwater because of reduced rainfall and dense regrowth stands. Rather, it represents a risk-based approach to reducing the potential impact of a drying climate on forest and riparian zone condition.

Karri

In the forests of south-west WA, there is a distinct difference between the jarrah/marri forests and karri forests in their growth habits. Karri typically reproduces in high numbers after stand-replacing fires. It grows relatively quickly and self-thinning occurs over the course of stand development leading to natural reductions in stand density as the dominant trees increase in size. Because young, even-aged karri self-thin relatively well, silvicultural interventions such as ecological thinning are a lower priority in these forests. However, there is some variability in how well karri self-thins. Monitoring and assessing stocking levels and growth dynamics in karri might identify stands that would benefit from thinning. Thinning might also be applied to accelerate growth to increase fire resilience and the development of habitat characteristics such as hollows. Thinning may also improve moisture availability to important riparian communities and species. Because karri is more sensitive to fire than jarrah, a strategy to manage the fuel hazard associated with thinning would need to be developed in parallel with the thinning prescriptions.

Wandoo

It is likely that little silvicultural intervention will be required in this forest type. There may be a requirement to only thin areas of regrowth forest where this will enhance the moisture availability to important riparian ecological communities. Where wandoo is associated with jarrah forest in areas identified as climate vulnerable landscapes, regardless of whether or not it is regrowth, it may need active management to reduce the stocking levels in the stand as the climate dries.

Post-mining rehabilitation

Mining has been undertaken on the Darling Range since the mid-1960s. This was conferred via State Agreements with the various mining companies. By far the largest area affected is by bauxite mining with Alcoa and South32 being the major companies involved. Bauxite mining involves the complete removal of all vegetation growing over the ore body and, following mining, the subsequent establishment of a highly engineered forest designed according to the completion criteria in effect at the time. These completion criteria have changed several times since mining started in the region. In addition, they vary depending on the type of mining, and the State Agreement and associated regulations in each case. Planning, removal of vegetation and over-burden, and mining, typically takes four to six years, and is followed by re-establishment of forest cover and subsequent management.

Early rehabilitation design from the 1960s to mid-1980s focussed on several key criteria, which have since been revised. These involved planting species resistant to *Phytophthora cinnamomi*, a soil-borne fungal pathogen that causes dieback in trees and understorey plants. In addition to concerns about tree mortality, forest managers were also concerned that rising water tables might increase the salinity of streams flowing to water supply reservoirs, and increase turbidity caused by erosion and rapid flowing surface waters.

Most of the trees planted to rehabilitate mining sites before 1988 were eucalypts from the eastern states or pine species that are resistant to dieback. There are 3,760 ha of these plantings in the south-west forests (**Error! Reference source not found.**). The standard protocol for planting was at 4 x 4m spacing. Given the variety of exotic species that were planted and differences in growth rates and self-thinning rates, there is considerable variability in current stocking levels. In some cases, these stands are now significantly overstocked and growth has stagnated; in others the stands have differentiated well and dominant trees have established a vigorous forest canopy. The overstocked stands are at risk of increased dieback and disease, fire- and drought-induced mortality, and growth stagnation without further intervention to reduce stand density. In the next FMP (2024-2033) stands dominated by non-native tree species should be converted to native forests.

Since the late 1980s mined sites have been regenerated with a mix of local tree species with the goal of producing jarrah/marri forest with native mid-storey and understorey species that approximates natural forest. There are now 20,780 ha (**Error! Reference source not found.**) of forest in this state. The intensity of seeding of canopy tree species has been reduced over time. Initially stands were seeded at a rate intended to yield ~3,000 jarrah seedlings per hectare; however, current practice aims to yield ~1,000 per hectare (with about 70% jarrah and 30% marri). Alcoa currently has a proposal to expand their mining envelope within the life of the next FMP. The planning for this, and expectation of agreement, has assumed that completion criteria for hand back to the State would be as per current prescription. This may be reassessed given the new priorities for State Forest management.

Through the operation of past FMPs and under the mining State Agreements, the post-mining rehabilitated forest has, since 1988, been established according to the completion criteria requirements. Thinning has been investigated at experimental and demonstration scales as part of responsible stewardship of these stands but thinning of older established stands is not a requirement of past or current completion criteria.

Of the 20,780 ha of jarrah/marri on rehabilitated mine sites, several thousand hectares are older than, or are approaching, 30 years old, and are densely stocked, even-aged stands that would benefit from thinning to improve moisture balance and stand health. This would be expected to accelerate these jarrah/marri forests towards a more natural forest structure than leaving them to develop without intervention. Because the trees in these stands were grown at high density and have good timber form, they may have some commercial value that could offset the costs associated with thinning to restore the mining sites.

The alternative: no active silvicultural management

This report has largely focused on what a coordinated program of thinning focused on improving forest health might look like. It is worth considering the alternative in which no silvicultural management occurs and the forests of the south-west are left to develop on their own. In reality this scenario applies for large parts of the forest estate that are protected in parks and reserves. However, the densely stocked even-aged regrowth forests that account for tens of thousands of hectares are largely limited to the State forests and are the primary focus of forest management activities that will increase stand-level resistance and landscape-scale resilience to climate change. Because of their relatively high water use and a weak capacity to self-thin, even-aged regrowth jarrah stands will eventually stagnate and stop growing. Individual trees in these dense stands will have small crowns. This will limit their photosynthetic capacity and thus their ability to produce new roots and leaves, defensive compounds, and reproductive organs.

Because jarrah is quite tolerant to competition, these dense stands of small trees can persist for many decades, prolonging the period that they are exposed to the risk of extreme climatic conditions and fires. The risk of dieback and death in these dense stands will vary within any given landscape. Stands on shallow or stony soils may be more vulnerable and require a less extreme climatic event to induce mortality. Stands in high rainfall zones, on deeper soils or in parts of the landscape with better access to water may be less vulnerable and require a more extreme climatic event to induce mortality. The slow growth in stem diameter and tree height of stagnating stands prolongs their exposure to a range of threats while they are at a vulnerable size. As the climate warms, the probability of intense multi-year dry spells or prolonged droughts increases, as does the probability of bushfires and pathogen infection. The combination of a prolonged period of vulnerability and an increased frequency of stressful or lethal events will greatly increase the likelihood of significant mortality in the stand and potentially across many stands simultaneously. The increased probability of stand- and landscape-scale mortality will reduce recruitment of large trees within the landscape. This will pose a threat to fauna that depend on large trees for hollows and it will reduce the capacity of the forests to capture and sequester carbon.

Eliminating active forest management from the forests of the south-west could have many and profound undesirable social and economic consequences across the region. Consideration of those is out of the scope of this report. However, in the context of forest health the absence of silvicultural management will almost certainly set large areas of these forests along a trajectory of diminishing stand-level health and landscape-scale resilience at a time when climatic stressors and natural disturbances are becoming more frequent and more intense.

While out of scope of this report, it is important to mention the need for on-going fire management to maintain forest health and to mitigate the damaging impacts of bushfires to the environment and to human communities. Maintaining an effective prescribed burning program at the appropriate temporal and spatial scales is critical to mitigating the bushfire threat and for maintaining healthy forests (Burrows and McCaw 2013).

ToR5: Provide recommendations on silvicultural research and integrated monitoring programs to inform progressive adaptive management and evaluation of ecological thinning outcomes.

Ecological thinning to restore natural patterns and processes in south-west native forests would be a new approach to managing a large proportion of the public forest estate. While thinning has been used in the past, particularly in the karri forest, the scale and variety of thinning prescriptions in jarrah regrowth has been quite limited. The proposed ecological thinning as an element of forest management in these forests raises important questions that require further investigation. Here we highlight key areas that would benefit from further assessment, noting that in some instances the data may already exist, in others new data may need to be collected, and in yet others, new experiments may need to be developed and implemented.

1. Density management guidelines to highlight when stands are overstocked and provide guidance on thinning prescriptions that could be applied. Preliminary density management diagrams for jarrah exist (Martin Rayner, DBCA, pers. comm.) but would benefit from further development. Density management diagrams for karri and marri do not exist and would need to be developed from existing inventory data and supplemented with new data.

2. Thinning prescriptions in south-west forests typically involve thinning the stand from below uniformly across the stand to a target residual basal area. However, there is a wide range of potential thinning prescriptions that may be better suited to achieve ecological- and restoration-focused outcomes. These include variable density thinning and crown thinning. We recommend that a program of experimental thinnings applied at operational scales be implemented in each of the major forest types, with a comprehensive data collection and analysis designed to test which thinning prescription, including no intervention, best meets the design objectives. This will provide the basis for adaptive implementation of thinnings in the future as we better understand the consequences of the different thinning treatments at the stand level. We have not explicitly defined what "operational scales" are. We expect that this would be on the order of 5-50 ha, but acknowledge that it must reflect the desired spatial scales of the outcomes and will depend many factors including on the size of management units, the machinery and costs involved, and the stand conditions.

3. To assess the outcomes of ecological thinnings, whether experimental or operational, requires clear definitions of the desired values and metrics to quantify them. We recommend that a program of monitoring that incorporates these definitions and metrics be developed and applied across the forest estate. The FORESTCHECK system is an existing monitoring program that is well suited to doing this. We would encourage that any monitoring be applied to the full forest estate, including parks and reserves, to ensure that the outcomes of treatments can be compared to untreated forests in different land management tenures.

4. Most ecological and silvicultural research focuses on changes at the stand scale. However, the proposed policy shift to eliminate native forest logging and limiting harvesting to ecological thinning and mining will have important ecological consequences at the landscape scale. It is unlikely that the consequences of ecological thinning applied at the stand scale will scale up directly to the landscape scale. We recommend that a detailed modelling exercise that assesses the costs and benefits of ecological thinning at the landscape scale be undertaken to better understand any potential impacts and to provide guidance on how, where, and when different ecological thinning prescriptions might be implemented over the coming decades.

Forest monitoring – FORESTCHECK 2.0

The FORESTCHECK ecological monitoring program commenced around 1999 to provide information on the impact of a range of silvicultural practices on jarrah forest condition (McCaw *et al*. 2011). This program has generated a significant amount of data useful for a range of applications, well beyond understanding the impacts of silviculture (Abbott and Williams 2011). The FORESTCHECK sample grids incorporate many environmental aspects that govern ecological condition including soil condition and nutrients, soil surface debris, microbes and fungi, plants, invertebrates, vertebrates, and forest structural components. Analysis of these data have found that, in the main, the ecology of the forest is not significantly different between different silvicultural treatments, and further there are not major differences between areas that have never been logged and areas logged more than 40 years prior to measurement. The biggest impact determined from these monitoring sites appears to have been that of soil compaction due to machinery movement within the forest, and the impact of timber harvesting on grass trees and some fungi and cryptogam species. We note that forest managers have responded to the soil damage and grass tree findings by implementing mitigation measures.

A shortcoming of FORESTCHECK in the context of the new forest management objectives, would appear to be the lack of temporal consistency between sites; that is, the sites were designed to monitor impact of silvicultural treatments and the design and location of sites covered a matrix of treatment type and time since the treatment. With the changed focus on monitoring forest condition under climate change, and the efficacy of proposed ecological thinning interventions, it would be preferable to assess the sites as near to simultaneously as possible given limited resources. The Panel recognises that there are significant resources and specialist expertise required to carry out the broad suite of measurements included in FORESTCHECK.

The panel recommends that FORESTCHECK be re-purposed to align with the new forest management objectives and be expanded beyond the jarrah forest into karri forests. This could mean reducing the number of taxonomic groups being monitored and focussing on keystone and / or surrogate species. Monitoring sites should be established in drought-prone ecosystems at risk in a drying climate, such as riparian ecosytems and wetlands in thinned and unthinned catchments. We also recommend the program be reviewed for possible measurement enhancement, incorporation of new and emerging technologies such as environmental DNA, and geographical spread. It is especially important that sufficient sites be included in the conservation estate, which has been excluded from intervention, with the exception of fire management and introduced predator control. With intelligent re-design, and rationalisation of other monitoring programs in place in the south-west forest region, FORESTCHECK 2.0 could be a vital tool for monitoring and reporting on the effects of a range of anthropogenic and natural disturbances, including fire, ecological thinning, Western Shield baiting and climate change.

Thinning for hydrological response

Given the variation in responses to past thinning experiments, and particularly as many of those undertaken in WA were performed over 20 years ago, with the climate continuing to warm and dry, the Panel suggests it is imperative to complement the current experimental resource with further catchment experiments, designed to enhance ecological health and resilience. This will require investment in new infrastructure.

As mentioned above, these should be accompanied by new fit for purpose FORESTCHECK sites, within and downslope of areas subject to treatment, so that the ecological responses can be quantified. If these are carried out early in the life of the FMP then by 2033 we would expect systematic evaluations could be made to modify the treatments and improve the outcomes.

As discussed, there are ecosystems particularly at risk due to a drying climate, such as riparian zones and peat swamps, so consideration should be given to thinning stands upslope of these ecosystems with a view to enhancing water flows to these areas. There are no data on whether this will be effective, so trails will need to be undertaken in an adaptive management framework. It is important that sufficient monitoring take place to establish the most feasible thinning policy in this case, such that the level of thinning, the location of thinning is confirmed and the impact on riparian ecosystems as well as groundwater and stream flows are quantified. Given the lengthy time for hydrological responses to be manifest, such experiments should be implemented within the early period of the FMP, to ensure enough time, at least six years, for data collection before and after treatment and appropriate analysis to ensure the results are ready for preparation of the next FMP.

Fire management

DBCA have in place a landscape scale prescribed burning program to mitigate the impacts of forest fires on human communities and forest health. Ecological thinning will reduce the potential for crown fires in heavily stocked regrowth stands, but unless residue is removed, it will generate additional fuel on the forest floor. Prescribed burning operations will need to be integrated with ecological thinning to ensure the best fuel hazard reduction outcomes. Large trees are more fire resilient than small ones, so thinning to promote tree growth will increase the fire resilience of the stand, enabling low intensity prescribed burns to be undertaken sooner and with reduced risk of tree death and damage.

Mining rehabilitation

Stands of exotic trees from the rehabilitation prior to 1988 should be thinned or harvested and replaced with a natural mix of species from the northern jarrah/marri forest.

The early stands of mining rehabilitation post-1988 include dense stands of jarrah/marri mixed forest. Significant areas of these forests are now in a dense even-aged condition that will approach "lock-up" shortly unless thinned. These stands, having been established at high density, have produced stands of well-formed trees, and consistent with circular economy principles, thinning costs could be offset by utilisation of the residue rather than wasting it.

Conclusions

A history of timber harvesting and mining in south-west forests has left a legacy of tens of thousands of hectares of densely stocked young, even-aged regrowth forests. These forests use considerably more water than older mixed-age forests and in a drying climate may be particularly vulnerable to physiological stress and stand- and landscape-scale dieback. Reduced growth and increased fuel loads associated with dieback may make these regrowth stands particularly vulnerable to catastrophic mortality in bushfires and prolong the amount of time required to develop important habitat features such as tree hollows. In addition, the increased water use of regrowth stands may reduce water available to flora and fauna within the stand or landscape that are associated with riparian zones or aquatic ecosystems. While anthropogenic activities over many decades have contributed to the current situation, a complete cessation of management activity will likely lead to declines in forest health and resilience. Instead, we recommend an active program of forest management that is focused on creating more heterogeneity within stands and restoring forests to structures that are more typical of pre-European colonisation forests. This should increase their resilience to a drying climate and to changing fire regimes. Ecological thinning is a central component of such a program. We suggest developing empirical guidelines for assessing when regrowth forests are overstocked and at high risk of stagnation and dieback. This will help to prioritise ecological thinning within and amongst landscapes. We expect that jarrah forests will be more likely to require management intervention as they are more prone to overstocking and stagnation. Karri forest are better able to self-thin and are therefore less prone to stagnation, so are a lower priority for thinning than jarrah forests. The area requiring treatment is large, so a risk-based framework is needed to prioritise areas for treatment. FORESTCHECK should be re-purposed to monitor forests in a drying climate. Ecological thinning will be costly and will generate significant residue at the stand-scale. Developing mechanisms to utilise or minimise the residues may help to offset some of the costs and help reduce some of the potential fuel management issues.

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Appendix 1: 'Ecological' thinning explanatory note (DBCA 2022)

'Ecological' thinning – why it's needed, what it is, where and how it might be undertaken

Introduction

Government forest policy settings for the next Forest Management Plan (FMP 2024-2033) include a requirement that active forest management be undertaken to maintain forest health. Timber supplied from native forests will be restricted to that generated during 'ecological' thinning and clearing in advance of mining operations. This note outlines the 'ecological' thinning concept, the selection of areas to be thinned, and how these forest thinning operations might be implemented to achieve enhanced resilience of forest ecosystems to climate change.

Why is 'ecological' thinning needed?

Native forests on DBCA-managed lands in the south-west extend from Lancelin in the north to Denmark in the south, comprising over 1.89 million hectares of jarrah, wandoo and karri forest ecosystems. Since the 1970s, weather patterns across this broad geographic range have shifted to produce markedly drier, warmer landscapes. These trends are forecast to continue in future decades, with climate projections to 2030, 2050 and 2070 suggesting further significant increases in average temperature, ongoing reductions in annual rainfall, shifts in seasonality of rainfall, and increasing frequency of heatwaves, drought events and conditions conducive to catastrophic bushfires.

The decreased rainfall has been accompanied by significant increases in depth to groundwater in jarrah and karri forest catchments, with evidence of perennial streams drying out in the Northern Jarrah Forest. Within this long-term (chronic) drying pattern predisposing landscapes to droughts, short-term (acute) heatwave events have driven tree mortality and collapse of forest structure in vulnerable parts of the Northern Jarrah Forest. Furthermore, trends in vegetation cover recorded by satellite remote sensing since the 1970s suggest the Eastern Jarrah Forest, including wandoo forest, has been progressively declining in cover and adapting to a drier climate.

In many forest landscapes, the ongoing declines in rainfall and groundwater levels will create an imbalance between the demand and availability of water to maintain the existing forest structure and density of vegetation. Note that it is not only the changing climate increasing moisture stress in the forest, but stress in certain catchments also originates from an altered forest structure, which has shifted to being dominated by many small stems because of historical harvesting. The magnitude and extent of moisture stress experienced by the vegetation will vary and, in many cases, lead to rapid or progressive 'drying out' and adjustment of these forest ecosystems. The associated decline in forest structure, composition and function will have major consequences for biodiversity conservation in these ecosystems. However, the rate and intensity of change can be actively managed by reducing vegetation density to buffer the forest ecosystem from the effects of a drying and warming climate.

Thinning has been applied in parts of the jarrah, wandoo, and karri forests for many decades to increase water yields in catchments (e.g., Mundaring catchment; Wungong and Manjimup catchments), promote timber growth and future yield in areas available for timber production, enhance visual amenity alongside tourist routes or recreation nodes (e.g., Big Brook Dam), or to mitigate bushfire risk through reducing vegetation ('fuel loads') adjacent to critical infrastructure or community assets.

Importantly, thinning has been demonstrated to reduce moisture stress in forest stands and increase resilience to drought and heatwave events (e.g., catchment experiments in Wungong and Yarragil).

What is 'ecological' thinning?

In south-west native forests, 'ecological' thinning can be defined as an operation where trees are selectively removed from a forest to reduce current and future moisture stress on the site for an extended period. The number of trees removed (and hence number retained) will vary depending on the dominant forest type (jarrah, karri or wandoo), condition of the forest (age, number and structure of trees in an area) and the characteristics of the site (e.g., soil types, soil depth, current and future climate).

'Ecological' thinning is a subset of active forest management. Active forest management requires multiple sustained actions to maintain forest health and ecosystem function, including management of:

- vegetation structure and density for hydrological and bushfire risk mitigation outcomes (using thinning and / or prescribed burning);
- invasive weeds (including 'exotic' tree species such as pines);
- *Phytophthora* dieback and other plant diseases, including *Armillaria*, marri cankers and potential incursions by Myrtle rust;
- invasive pest species (vertebrate and invertebrate control); and
- protection from adverse impacts of human use and infrastructure.

A defining feature of 'ecological' thinning at the stand or patch scale is the primary objective to increase resilience of the forest to climate change impacts and maintain forest ecosystem health. This remains nested within the landscape-scale objective of maintaining biodiversity conservation outcomes over the long-term.

An ancillary benefit of ecological thinning programs can be bushfire risk mitigation through reducing the quantity and vertical arrangement of vegetation (fuel) available to bushfires. Current research being undertaken in other jurisdictions is highlighting the importance of ensuring prescribed burning occurs in combination with ecological thinning to enhance ecosystem resilience and reduce bushfire severity. However, application of mechanical fuel reduction thinning at the stand or patch scale could only be considered ecological thinning if it is undertaken consistent within a broader landscape objective of maintaining biodiversity conservation outcomes.

Where might 'ecological' thinning take place?

The nature, location and extent of ecological thinning will be determined through the process to develop FMP 2024-2033, noting that proposed ecological thinning will need to ensure the value of the land to Aboriginal culture and heritage is protected. Ecological thinning could not be undertaken in the 30 per cent of DBCA-managed lands in the south-west that are already covered by an area management plan, unless the plan specifically provides for such operations.

Candidate tenure and purpose

Forests within the CAR (Comprehensive, Adequate and Representative) reserve system – in national parks, nature reserves, informal reserves on State forests – will not be considered for ecological thinning at this time. This includes all old-growth forests.

While the impacts of climate change on vegetation will accrue across tenures, a strategic, staged approach when implementing ecological thinning is necessary to demonstrate the biodiversity benefits before thinning would be extended to targeted areas within parts of the CAR reserve system. Notable exceptions may be considered on a case-by-case basis where thinning would demonstrably enhance protection of threatened groundwater-dependent or other species.

Candidate areas for ecological thinning will therefore be considered within State forests and timber reserves outside of existing and proposed reserves under the current *Forest Management Plan 2014-2023* (FMP 2014-2023).

Candidate forest structures

Forests ‘at risk’ and predisposed to large areas of tree and vegetation mortality during drought events will typically have high stocking densities (many stems per hectare) and a predominantly even-aged structure. Within areas available for timber production under the FMP 2014-2023 these would include:

- Densely stocked, uniformly even-aged stands of minesite rehabilitation. These stands are dominated by exotic species (in areas rehabilitated during 1966-1987) or jarrah/marri (since 1988). The total area of rehabilitation to December 2019 is 23,000 hectares, dispersed within the broader mixed-mature forest landscape in cells or pods averaging 30-40 hectares. Silvicultural treatments including thinning to increase streamflow and water yield have been investigated over the last two decades, and an operational-scale thinning trial is underway in a 32-year-old stand in Turner forest block northwest of Dwellingup;

- Densely stocked, predominantly even-aged jarrah-marri regrowth stands, including those regenerated following harvesting since 1970 of mixed-mature forest. These stands are dispersed across the jarrah forest, ranging in size from 5 to 100+ hectares within the mixed forest mosaic. Between 1970 and 1985 around 5,000 hectares of these stands were regenerated, with a further 46,000 hectares dating from 1986 to 2010. An example of this candidate forest structure is the ecological thinning demonstration site in a 31-year-old stand at Munro forest block, east of Balingup;

- Densely stocked, even-aged karri and karri-marri regrowth stands naturally regenerated or planted since the 1930s, mostly since 1967. These stands vary in size from 5 to 200+ hectares. Approximately 1,200 hectares of these stands are thinned each year, from a total area of regrowth karri forest presently available for timber production of 51,000 hectares; and

- Other forests at risk of adverse forest health outcomes under a drying climate, located on vulnerable sites within drying landscapes. These forests have varying structure and composition influenced by previous harvest and regeneration events. Research is ongoing to predict vulnerability of landscapes, informed by evidence from drought collapsed sites, groundwater monitoring, geophysics, remote sensing and historic catchment harvesting experiments. In the Northern Jarrah Forest experiments in sub-catchments of 130 hectares (Yarragil), 360 hectares (Cobiac) and 1,750 hectares (Chandler) indicate that thinning across at least 40 per cent of a catchment has been necessary to provide hydrological benefits. Given the rate and forecast severity of rainfall decline, trade-offs may be necessary between targeting action in areas already demonstrating severe stress (e.g., north-eastern jarrah-wandoo forests) or where resilience may be most improved (e.g., western jarrah forest).

Selection of areas

The process to identify the location, timing, and type of ecological thinning in densely stocked even-aged regrowth stands can be readily informed by their age, site and condition.

The process to identify the broader landscapes at risk and prioritise actions will be informed by such factors as the observed and projected change in rainfall; groundwater trends; depth to bedrock;

vegetation condition, structure, and density; biodiversity at risk (such as threatened species); and potential to inform future adaptive actions.

How might ecological thinning be undertaken?

Thinning to sustain forest health and biodiversity values within progressively drying landscapes will require development of new silvicultural guidelines and operational practices.

Silvicultural guidelines will be refined to:

- Align (where possible) the number and type of trees retained during thinning to an acceptable range of leaf area or similar index. The overall water demand in forest stands is highly correlated to the amount of tree canopy and total leaf area transpiring, and leaf area index (or equivalent indices) can be monitored indirectly through remote sensing at the landscape scale.

- Thin to a level that will maintain the leaf area index within an acceptable range for a period of at least 20 years. This nominal period will vary across sites and forest ecosystems to reflect the rate at which the stands grow and therefore return to a high leaf area index and hence likely moisture-stressed condition.

- Prioritise the removal of young trees. Younger, smaller trees have a comparatively higher proportion of sapwood area compared to larger, mature trees. Dense stands of young trees generally have much higher water demand than older, mature stands. Preferentially retaining the large, mature trees in thinned areas also enhances forest resilience to high intensity bushfires (as large trees are more likely to survive), helps maintain carbon stores (as large trees store the highest proportion of carbon in the stand) and ensures maximum retention of habitat for hollow-dependent fauna, and resources for fauna such as flowers and seeds.

- Minimise the potential for vigorous resprouting of stumps. A rapid flush of leaf growth from resprouting stumps can negate the hydrological benefit from thinning. Maximum benefit will be obtained where the stumps of removed trees are treated with herbicide to prevent resprouting. Where trees are not felled but a reduction in leaf area is desired, ringbarking or girdling of trees is possible, but not a preferred option due to increased likelihood of severe stand damage during subsequent fire events.

- Ensure areas of undisturbed (unthinned) vegetation are retained at the patch and landscape scales to provide additional biodiversity protection.

- Promote retention of nutrients on site by managing the timing of silvicultural fire operations (where necessary) and level of woody debris retained on site.

Thinning in young regrowth stands will generally commence from around 20 - 25 years of age, Operational practices in such stands will benefit from using smaller, specialised harvest machinery to minimize soil disturbance and potential damage to the retained trees and understorey.

Monitoring outcomes and active adaptation

Ecological thinning will be undertaken in landscapes that have multiple threatening processes and pressures impacting biodiversity outcomes. Knowledge gaps and uncertainties in future climate trajectories compounds the challenge of delivering effective outcomes from ecological thinning. A strategic, risk-based program which trials a variety of approaches, supported by integrated monitoring programs, will be necessary to inform options to improve landscape resilience as the cumulative impacts of climate change emerge.

Appendix 2: Terms of Reference for a review of silvicultural practices in native forests of south-west Western Australia

Introduction

The *Forest Management Plan 2014-2023*[2] (FMP 2014-2023) provides the policy framework for management of south-west native forests on lands vested in the Conservation and Parks Commission (CPC). A series of subsidiary documents guide implementation of the statutory plan. This includes silviculture guidelines that provide for the management of native forests for a range of multiple uses (including timber production) within an Ecologically Sustainable Forest Management (ESFM) context.

The FMP 2014-2023 commits to a review of silvicultural practices by a panel of independent experts to inform development of the next *Forest Management Plan 2024-2033* (FMP 2024-2033):

> *"The Department will initiate an independent expert review of silvicultural practices during the second half of the term of this plan. Among other things, the review will have regard to the results from FORESTCHECK and other research monitoring, audits and adaptive management projects."* (Management Activity 129).

Preparation of the FMP *2024–2033* has commenced and a review of silvicultural practices by independent experts (Expert Panel) will assist the Department of Biodiversity, Conservation and Attractions (DBCA) and the CPC refine settings for forest management and future monitoring.

Context

The current suite of silviculture guidelines, procedures and reference manuals has been developed and refined over time to implement silvicultural practices for timber harvest and regeneration in jarrah, karri and wandoo dominant forests. These practices reflect the species characteristics and biology, and are implemented with consideration to the local, landscape, and whole-of-forest scales of management necessary to deliver ESFM.

The primary recommendation from the silvicultural panel that reviewed the guidelines for the current FMP 2014-2023 was to implement forest management to achieve a better water balance in a drying climate (Burrows *et al.* 2011[3]). Over the last decade further research and monitoring of weather patterns, groundwater levels and forest condition has reinforced that the south-west is progressing toward drier, warmer conditions consistent with climate change projections.

In September 2021, the Western Australian Government announced major changes to forest policy including a cessation of large-scale commercial harvesting in south-west forests by December 2023; the end of FMP 2014-2023.

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[2] Conservation Commission of Western Australia, 2013, *Forest Management Plan 2014-2023*, Conservation Commission of Western Australia, Perth.

[3] Burrows, N., Dell, B., Neyland, M., Ruprecht, J. (2011) *Review of silviculture in forests of south-west Western Australia*. Unpublished report prepared for the Department of Environment and Conservation, Western Australia.

Under FMP 2024-2033, "…*timber taken from our native forests will be limited to forest management activities that improve forest health and clearing for approved mining operations, such as Alcoa*". These revised settings represent a re-weighting of silvicultural management objectives to prioritise forest health, recognising the ongoing impacts of a drying and warming climate in the south-west. Active forest management incorporating 'ecological' thinning of densely stocked regrowth stands, minesite rehabilitation and potentially mixed-mature forests in landscapes vulnerable to drought or elevated moisture stress, is proposed as the key silvicultural practice to actively manage forest health.

The purpose of this Expert Panel review is to assist DBCA and the CPC in adapting silvicultural guidance and practices to deliver enhanced forest health and resilience, and to advise on practical approaches to integrate management actions at the local and landscape scales. The 'Definitions' section of this document provides further context.

Scope

The geographic scope of this review is the jarrah, karri and wandoo forests on lands vested in the CPC within the area to be covered by FMP 2024-2033 (see map at Attachment 1). The subset of forest types and structures in which thinning is envisaged includes areas of densely stocked regrowth jarrah and rehabilitation areas following bauxite mining which commenced in the northern jarrah forest in the 1960s; regrowth karri; and areas of mixed-age jarrah and wandoo forest in landscapes vulnerable to climate change impacts.

The scope of silvicultural practices for consideration include, but are not limited to, the application of thinning, associated control of stump coppice and natural regeneration, prescribed fire, salvage of dead or damaged trees from bushfire, drought, disease or pest events, and management of invasive or pest animal and plant species.

Thinning and salvage operations would be undertaken within the broader ESFM framework.

Method

Having due regard to the historic and projected future trends in climate for the south-west of Western Australia, the Montreal criteria as a framework for assessing ESFM, and forest policy settings for the FMP 2024-2033, the Expert Panel will convene for 10 days and will:

1. examine national and international trends on forest practices applicable to enhancing forest health, to identify those relevant and practical for application in south-west jarrah, wandoo and karri forests;
2. undertake field inspection of contemporary silvicultural practices, bushfire or other salvage operations, historic silvicultural experiments and adaptive management trials that inform catchment management and ecological thinning;
3. consider the DBCA draft proposed approach to ecological thinning and recommend practical changes or refinements necessary to deliver improved forest health outcomes at the local, stand and landscape levels;
4. review current silvicultural guidelines and procedures and recommend adjustments and improvements necessary to prioritise enhanced forest health within an ESFM context; and
5. provide recommendations on silvicultural research and integrated monitoring programs to inform progressive adaptive management and evaluation of ecological thinning outcomes.

The Expert Panel will prepare a draft report detailing its recommendations and provide a presentation based on the report to the FMP 2024-2033 Steering Group.

A final written report will be prepared for the Executive Director, Conservation and Ecosystem Management Division (CEM) DBCA.

DBCA will:

1. Provide current silvicultural guidelines and procedures for jarrah, karri and wandoo forests.
2. Provide a summary of relevant climate, silviculture or related issues raised in performance reviews of the FMP 2014-2023.
3. Provide a summary of information arising since commencement of FMP 2014-2023, including impacts of silvicultural practices on biodiversity in south-west forests.
4. Provide briefings and arrange field trips to assist the panel in its deliberations.
5. Publish the final report on the DBCA website.

Timeline

As practicable the Expert Panel will convene in WA for 10 days in early 2022.

An indicative schedule would involve:

Day	Focus
1	Introduction, background presentations / discussions on south-west climate, proposed ecological thinning and FMP 2024-2033 approach
2-4	Review and inspect jarrah and wandoo silviculture practices and trials
5-7	Review and inspect karri silviculture practices and trials
8-10	Report preparation and presentation of recommendations

The panel will provide a draft report and deliver a presentation to the FMP 2024-2033 Steering Group by the end February 2022.

A final written report will be provided to the Executive Director CEM (DBCA) by 15 March 2022.

Members

The panel will comprise four members (one of whom will be nominated as Chairperson) with advanced expertise and practical experience in forest ecology, forest hydrology, eucalypt silviculture, and forest fire management practices.

Definitions

For the purposes of this review the following definitions will apply.

'Biodiversity' means the variability among living organisms and the ecosystems of which those organisms are a part and includes the following:

a) diversity within native species and between native species;

b) diversity of ecosystems; and

c) diversity of other biodiversity components

'Biodiversity components' includes native species, habitats, ecological communities, genes, ecosystems and ecological processes.

Source: *Biodiversity Conservation Act 2016*

'Ecological thinning' in south-west forests is defined as an operation where trees are selectively removed from a forest to reduce current and future moisture stress on the site for an extended period. The number of trees removed (and hence number retained) will vary depending on the dominant forest type (jarrah, karri or wandoo), condition of the forest (age, number and structure of trees in an area) and the characteristics of the site (e.g. soil types, soil depth, current and future climate).

Source: DBCA Explanatory Note 2022[4]

For the purposes of this review *'Ecologically Sustainable Forest Management'* (ESFM) refers to the slightly modified Montreal Criteria of sustainability adopted as the framework within which to identify management actions in the *Forest Management Plan 2014-2023* (FMP 2014-2023). These criteria are:

- conservation of biodiversity;
- maintenance of ecosystem health and vitality;
- conservation and maintenance of soil and water;
- maintenance of forests contribution to the global carbon cycle;
- maintenance of productive capacity;
- maintenance of heritage; and
- maintenance of socio-economic values.

The principles of ESFM are as defined in Section 19(2) of the *Conservation and Land Management Act 1984*.

'Scales of management' are defined as

(i) Whole-of-forest

All land categories that are subject to the FMP 2014-2023 and FMP 2024-2033

(ii) Landscape

A mosaic where the mix of local ecosystems and landforms is represented and repeated in a similar form over an area that may cover several kilometres.

(iii) Local

A discrete area of land that to which one or more disturbance activities have been planned or applied.

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[4] Department of Biodiversity, Conservation and Attractions 2022 *''Ecological'' thinning – why it's needed, what it is, where and how it might be undertaken*. Unpublished Explanatory Note.