Biodiversity and Conservation Science

Impact of Silvicultural Practices on Biodiversity in Forests Used for Timber Production in Western Australia

A Summary of New Concepts and Knowledge Since 2011

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Summary of key points

- Knowledge and understanding of the effects of timber harvesting, silviculture and other forest management activities on the biodiversity of Western Australian forests has advanced considerably during the past decade, supported by a significant output of scientific publications.
- A second round of integrated biodiversity monitoring using the Forestcheck protocol has been implemented at the original 48 sites in the jarrah forest and two rounds of sampling have been carried out at 16 additional sites across two other Jarrah Ecosystems. Results from the second five years of the project have been analysed and submitted for publication in a peer-reviewed journal. Overall, species groups were resilient to the disturbances imposed, noting that limited inferences could be made about many mammal species due to the low detection rates.
- Retained legacy elements including habitat trees and logs make an important contribution to conservation at the operational scale for a wide range of species. There has been considerable research undertaken on this topic since the last review. Coarse woody debris is important as habitat for cryptograms, macrofungi, invertebrates, cryptograms and some epiphytic plants. Large logs in moderate to advanced stages of decay are of particular importance to these organisms and for some vertebrates and should be retained to the greatest extent possible during silvicultural operations. The retention of standing habitat trees in harvested areas is widely recognised as having significant value for preservation of biodiversity in harvested forests and prescribed burning operations should consider how fire may affect this element. Forty-two vertebrate species are known to use tree hollows in south-west forests (Abbott and Whitford 2002). Twenty-nine are considered highly dependent on hollows for breeding, including 11 mammals, 17 birds and one reptile. Similarly, the retention of mid-storey flora provides for habitat important for some species.
- Heterogeneity and connectivity provided by informal reserves, fauna habitat zones and temporary exclusion areas is important for conservation at the landscape scale and assists in ameliorating the impact and persistence of disturbance effects arising from harvesting and silviculture through buffering of microclimate, re-colonisation via proximity to source populations or essential habitat elements.
- Silvicultural practices are undertaken at the operational scale, but the effects on biodiversity are also influenced by a range of factors relevant at the whole of forest scale. Important issues that have emerged or continued during the past decade include a drying and warming climatic trends, chronic drought episodes, wildfires, cats and foxes as predators in south-west forests, and the widespread decline of some mammals across a range of land tenures including conservation reserves and state forest.
- Within the last 10 years two medium sized mammals dependent on forests have been elevated to *Critically Endangered; the* woylie and ngwayir. Three species

were added to the list – *Galaxiella nigrostriata* (black-striped minnow) as endangered, *Lepidogalaxias salamandroides* (salamander fish) as endangered, and *Westralunio carteri* (Carter's freshwater mussel) as vulnerable. In the same period, two species were removed from the threatened and specially protected fauna list (*Morelia spilota imbricata* (carpet python) and *Aspidites ramsayi* (Woma).

- Fox control has a substantially greater influence on terrestrial vertebrate species abundance, and to some extent species richness, than does forest structure. This finding demonstrates that maintaining areas of mature forest in the landscape is, on its own, insufficient to ensure conservation of terrestrial vertebrates. Some mammal recoveries have not been sustained in the presence of a broad-scale program aimed at reducing the impact of the introduced red fox. There is a continuing effort to understand the role of cats in mammal declines in south-west forests and into methods for their control. While cat predation is considered a putative major factor in recent declines of some mammal species, the drivers of these declines require further investigation. Disease, habitat fragmentation, and occurrence of habitat elements are also implicated for some species.
- Tree decline syndromes and major outbreaks of insect pests that reduce forest canopy density at the landscape scale warrant consideration in planning for silvicultural operations because they may result in retained areas of mature forest being temporarily less suitable for habitat and foraging by some birds and animals. A number of tree decline syndromes affecting wandoo, flooded gum and marri have emerged in the past decade posing a potential threat to forest structure, species composition and ecological processes. Causal factors are not always understood but disease, insect attack, fragmentation and climate change are implicated and undoubtedly interacting.
- The FMP 2014-23 allows for seed to be collected from the same or adjacent Land Management Unit and use of mixed seed sources where climate change or other factors require it. Early approaches focussed on local provenancing for seed collections based on assumptions that plants have local adaptation to their site. More recently considerations have developed several provenance strategies based on maximising genetic diversity and capturing adaptive potential. Genetic studies of trees and understorey plants in southwestern forest region suggest that provenances for seed collection can be considered at a regional scale as these widespread and common species show low population structure. Provenancing strategies that maximise genetic diversity are appropriate for species with lor population genetic structure. For species with genetically defined subspecific entities, such as *A. saligna* and *A. microbotrya*, seed should only be used within the natural range of the subspecific entities. The identification of adaptive variation associated with climate gradients in jarrah and marri suggests that a climate adjusted provenancing approach can be considered as a climate adaptation strategy for these dominant tree species.

- Fire significantly affects the ecology of Western Australian forests, both as planned fire used as a management tool, and unplanned bushfire. Research in Jarrah forests over the past decades has resulted in new fire behaviour models for dry eucalypt forests now used across Australia. These models correspond with previous findings that show the usefulness of managing fuels for reducing fuel hazards, rate of fire spread, spotting and intensity of wildfire. The Western Australian approach to wildfire risk management through prescribed burning has been well documented in a series of papers and book chapters and recently developed into the DBCA Bushfire Risk Management Framework. This framework includes management zoning which varies with proximity settlements and infrastructure versus the broader landscape. Economic analysis of this approach shows that prescribed burning close to settlements is more effective and more costly, supporting a mixed strategy balances economic efficiency and risk mitigation.
- Results from several long-term studies examining interactions between fire regimes and responses of plant community richness, shrub populations, cryptogams and birds continue to demonstrate the resilience of jarrah forest ecosystems to contemporary fire regimes. Recent research points to possible impacts of changing fire season (i.e. winter–early-spring burning) on seedling regeneration. Likewise, conceptual models, and field evidence point to the potential for climate change both making forests susceptible to increasing fire frequency, and becoming less resilient to shorter fire intervals.
- The southwestern region has experienced a distinct shift in climate since the mid-1970s, characterised by a chronic warming of +0.15°C per decade, and a chronic reduction in early winter rainfall of 14% (1975-2004 compared with the mid-1900s-1974), and overall winter rainfall declining 30-50% from 1969 to 2012. In addition to these chronic patterns, extreme climatic events have also occurred recently, with 2006 and 2010 experiencing acute drought, and early 2011 experiencing heatwave events. Studies are showing that vegetation communities have also shifted over time with a decrease in rainfall. Sudden forest die-off associated with acute drought and heatwave events have also been recorded in vulnerable, shallow soils with limited water holding capacity and in xeric areas. Climate projections for the southwestern region indicate a continued reduction in winter rainfall and warming in the coming decades, with implications for hydrology and ecology. Although a general shift in biodiversity reflective of a new rainfall regime is expected, the most immediate effect would be on stream biota and riparian zone vegetation, as well as biota on sites with shallower soils.

- The chronic downward trend in rainfall in the region has contributed to significant declines in groundwater levels and streamflows in the forest estate. In addition, past forest management has led to dense regrowth stands that utilise more water than old growth stands which has exacerbated the decline in groundwater levels and runoff. Increasingly, ecological thinning in a highly targeted and nuanced way is being considered to restore diverse stand structure, to improve the health of remaining trees, and alleviate stress on riparian zones. In one experimental catchment, thinning led to a prolonged increase in streamflow and a significant slowing in the rate of groundwater decline for more than 15 years post thinning

Overview

Silviculture is concerned with the theory and practice of managing the establishment, composition, growth, health and quality of forests to achieve specified management objectives (Stoneman *et al.* 2005). In the context of Western Australian forests, silviculture can include: selection of trees for retention or removal; managing the level of disturbance to understorey and intermediate-storey vegetation, and soil; and the planned application of fire to consume fine fuels and woody debris to reduce hazard and create receptive seedbed. Timber harvesting is distinct from silviculture and involves the felling of trees and extraction of logs to a landing area for loading and transport to a processing facility. Timber harvesting that is well planned and implemented can contribute to the achievement of silvicultural objectives.

Action 129 of the 2014-23 FMP states “The Department will initiate an 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”

The purpose of this action is to ensure that management strategies adopted for the next FMP that will apply from 2024 onwards are developed using the best available and most current concepts and knowledge relating to the ecology and management of forests. The past decade has seen publication of important findings from research undertaken in Western Australia and elsewhere, and the emergence of new issues that require management approaches that expand on those adopted for the Forest Management Plan (FMP) 2014-23. Notably, research into the implications of climate change for forest health and biodiversity has expanded rapidly during the past decade, as has understanding of forest ecosystems to burning and wildfires and genetic provenancing for replanting and restoration.

The FMP 2014-23 recognised three scales of management for forests, including for conservation of biodiversity, defined as follows:

- *whole of forest*: all land categories that are subject to the FMP,
- *landscape*: a mosaic where the mix of local ecosystems and landforms is repeated in a similar form over a kilometres-wide area. Several attributes including geology, soil types, vegetation types, local flora and fauna, climate

and natural disturbance regimes tend to be similar or repeated across the whole area. It could be a sub-catchment, catchment, or a forest block or Land Management Unit. Landscape scale is usually tens of thousands to a few thousand hectares,
- *operational*: a discrete area of forest to which one or more operations have been or are planned to be applied.

The need for a hierarchy of management scales recognises that different factors and biodiversity elements (species, populations, communities, ecosystems) function at different spatial scales (Mori, 2011; Mori *et al.*, 2017). There is also a requirement to integrate management actions across different spatial scales (Gustafson *et al.* 2012; Lindenmayer *et al.*, 2012) and land tenures (Fitzsimons and Wescott, 2008). Formal reserves are not enough, and biodiversity conservation must also be provided for in landscapes managed for sustainable utilisation of natural resources. This will be increasingly the case as climate-change causes shifts in the geographic occurrence of ecosystems (Hannah, 2010).

This document reviews concepts and knowledge relevant to the conservation of biodiversity in forests used for timber production which include jarrah (*Eucalyptus marginata*), karri (*Eucalyptus diversicolor*) and wandoo (*Eucalyptus wandoo*) within the FMP area of south-western Australia. The focus of this document is on the operational scale as this is where the potential effects of silviculture are most evident. This document updates that provided for the last review of the silvicultural guidelines by Burrows *et al.* (2011) by drawing on scientific literature relevant to Western Australia's forests that has become available over the last decade.

Much of the Department's research effort in forests has been directed towards Forestcheck, an integrated monitoring project established in 2001 to inform forest managers about changes and trends in key elements of forest biodiversity associated with the dominant harvesting practices (Abbott and Burrows 2004). Forestcheck is designed to provide information relevant to several regional level indicators of ecological sustainable forest management and samples a wide range of organisms at multiple sites covering multiple Jarrah Forest ecosystems. Monitoring has focused on the effects of timber harvesting and associated silvicultural treatment in the jarrah forest including regeneration release through gap creation, regeneration establishment using shelterwood, and selective harvesting. In recent years, the site network and data have also proved valuable for examining effects of prescribed fire and wildfires (e.g., McCaw and Tunsell, 2021; Ward *et al.*, 2020). Forty-eight sampling grids, each 2 ha in size, were established across four of the jarrah forest ecosystems mapped for the Western Australian Regional Forest Agreement and sampled for a range of biotic elements between 2001 and 2006. These were published as a series of papers on various taxonomic elements. These papers examined the response of vascular plants, cryptogams, fungi, vertebrate and macro-invertebrate fauna to harvesting and silvicultural treatment, including the planned use of fire, together with a synthesis of the findings and their implications for forest management by McCaw *et al.* (2011). During the 2014-23 FMP period, the same sites were resampled between 2007 and 2012 and an additional 16 sites in two additional Jarrah Forest Ecosystems, were sampled in 2013-15 and 2019-21. The same methods were used to examine biotic responses to a fire chrono-sequence in the North-west Jarrah Forest Ecosystem between 2003/4 and 2020/21, albeit not for all the elements monitored for the main FORESTCHECK project. Several additional reports and papers have been produced since 2011, and a paper analysing data collected across biotic groups for both rounds of the initial 48 grids has been submitted for peer-reviewed publication.

Conservation of biodiversity at the operational scale

Retained habitat elements

Retained trees and other legacy elements from the pre-harvest stand are widely recognised as making an important contribution to the conservation of biodiversity in forests managed for timber production (Franklin *et al.* 2000; Gustafson *et al.* 2010; Lindenmayer and Franklin 2002; Lindenmayer *et al.* 2012). Legacy elements include standing dead trees, long-lived woody shrubs and mid-storey trees, logs and fallen branches on the forest floor, and stumps. Retained trees and other legacy elements are important because they provide habitat and nesting sites for vertebrates, invertebrates, substrates for cryptogams (mosses, lichens, liverworts) and fungi, and sites suitable for colonisation by epiphytic plants. The distribution and abundance of some forest dependent or conservation-listed species may be constrained by the amount of suitable habitat in legacy elements. Lindenmayer *et al.* (2012) emphasise the need to retain these elements long term through:

> *"An approach to forest management based on the long-term retention of structures and organisms, such as live and dead trees and small areas of intact forest, at the time of harvest. These structures and organisms are not removed in future forest management operations and hence undergo natural processes of growth and decay. The aim is to achieve a significant level of continuity in forest structure, composition, and complexity that promotes maintenance of biodiversity and ecological functions at different spatial scales. Approaches and levels of retention, which take account of natural disturbance dynamics, differ depending on local context but the practice is appropriate for all types of silvicultural systems and forests "*

The importance of legacy elements is emphasised by a tendency for long recruitment and replacement times. They may therefore be naturally rare or uncommon, and prone to modification or removal during timber harvesting and post-harvest silvicultural treatment, including fire and during pre-burn felling of hazardous trees.

Retention forestry or variable retention are terms used to describe forest management approaches that aim to be ecologically sustainable and that explicitly involve the provision for continuity in structural, functional, and compositional elements from the preharvest to the postharvest forest (e.g., Lindenmayer *et al.* 2012). Retention approaches have been applied in forests available for timber harvesting across much of the world for over 30 years and have been shown to deliver better biodiversity conservation outcomes than more traditional approaches (e.g., Fedrowitz *et al.* 2014). In Australia, practices consistent with the retention approach have been applied in some of the forests of Victoria (e.g., Lindenmayer *et al* 2019) and Tasmania (e.g., Scott *et al.* 2019). While not formally termed as retention forestry, the management of the native forests in the southwest of Western Australia are consistent with its principles and is among the world leaders in extent of retention of legacy elements for biodiversity (Gustaffson *et al.* 2012).

Retained forest patches

A global review of the roles of retained forest patches on biodiversity conservation, and specifically the role of forest edges (‘forest influence’) by Baker *et al.* (2013) concluded that retained forest habitat enables species to persist in harvested areas through buffering of microclimate, and/or assist re-colonisation via proximity to source populations or essential habitat elements. They noted that the important factors and mechanisms that underlie the ability of organisms to re-establish in regrowth areas include qualities of retained elements, dispersal capacity, suitability of habitat conditions, and interspecific interactions, all of which may vary with distance from intact mature forest, so a one size fits all approach, in terms of areas of retained forest and distance from retained forest will not suite all biodiversity elements.

Fauna Habitat Zones (FHZs) were introduced in the 2004-13 FMP to provide a rotating source of fauna reliant on mature forest attributes to help recolonise disturbed areas after timber harvesting. The FHZ network was refined for the 2014-23 plan, resulting in a reweighting of the allocation of area to those forest ecosystems with lower levels of reservation, a slightly greater area of mature forest in FHZs and a higher proportion of mature forest in FHZs, a lesser area of regrowth forest and a lesser total area in FHZs, a greater range of size of FHZs in recognition of the characteristics of the landscape in which they are located, and the inclusion of some larger FHZs in areas of known fauna values.

Habitat trees

The retention of trees in harvested areas is widely recognised as having significant value for preservation of biodiversity in harvested forests. Forty-two vertebrate species are known to use tree hollows in south-west forests (Abbott and Whitford 2002). Twenty-nine are considered highly dependent on hollows for breeding, including 11 mammals, 17 birds and one reptile. A meta-analysis by Fedrowitz *et al.* (2014) concluded that positive effects of retention cuts on richness of forest species increased with proportion of retained trees and time since harvest, but there were not enough data to analyse possible threshold effects, that is, levels at which effects on biodiversity diminish. The current retention rate for primary habitat trees is 5 trees ha^{-1} with provision for retention of an additional 6 to 8 potential habitat trees ha^{-1} if suitable trees exist (SFM Guideline No. 1, 2004) based on estimates of use by ringtail and brushtail possum. Primary habitat trees are selected according to obvious signs of use by fauna, presence of visible hollows or broken branch stubs, mature to senescent crown condition, and stem diameter ≥70 cm (refs). Tall trees are likely to remain standing for a considerable period following harvesting operations in the area are preferred.

Retention of large mature trees also poses significant safety issues at the time of harvesting and during re-planting and planned burn operations. The lack of a market for marri (*Corymbia calophylla*) since 2001 has resulted in increased retention of mature marri, which have a relatively high probability of bearing hollows suited to a wide range of hollow dependent fauna. Habitat tree retention in karri forest is also now undertaken routinely, including 2 primary habitat trees and 2 secondary trees per hectare (FPC Karri forest management plan, March 2020).

Burrows *et al.* (2013) examined survival and canopy characteristics of retained habitat trees in karri forest after timber harvesting and rough-heaped regeneration burning. Ninety two percent of retained habitat trees survived the rough-heaping and regeneration burning. There was a significant decline in the canopy condition of karri ($p < 0.001$) and marri ($p = 0.017$) trees (but not jarrah or blackbutt) to a more intermediate crown senescence, increasing their probability (immediate or longer-term) of hollow occurrence. If these habitat trees will survive a typical karri harvest rotation of 100 years, it was suggested that their presence will enhance the structural complexity of the regenerating stand and provide greater numbers of mature habitat elements, such as tree hollows.

Lindenmayer *et al.* (2015) examined the effect of tree retention on bird communities in *Eucalyptus regnans* forests in the Central Highlands of Victoria, finding no advantage of setting aside a single large island of retained trees versus several small islands within a given harvest unit for bird species richness nor the occurrence of individual bird species.

The relationship between tree attributes and the occurrence and size of hollows has been studied in detail for jarrah and marri (Whitford 2002, Whitford and Williams 2002 and Whitford *et al.*, 2015). Hollow occurrence increases with tree age, tree size, and increasing proportion of dead wood in the crown. Marri tends to contain a greater proportion of hollows with characteristics considered desirable for hollow-dependent fauna, while hollows are more common in jarrah, but most are small. Whitford and Stoneman (2004) developed a conceptual framework to determine the number of hollow-bearing trees that need to be retained at the stand scale to provide for the requirements of hollow dependent fauna. They applied this framework to data available for the jarrah forest to estimate the number of potentially usable hollows present per ha in a sample of five trees selected at random using the habitat tree specification in SFM Guideline No. 1, 2004.

The common brushtail possum (*Trichosurus vulpecula*) was identified by means of a strategic risk assessment as the best of eight candidates (6 birds, 2 mammals) to provide early indication of any critical reduction in the long-term supply of large hollows at small spatial scales (Abbott and Whitford 2002). The western ringtail possum (*Pseudocheirus occidentalis*) is also recognised as one of the most sensitive vertebrates to timber harvesting in the jarrah forest (Wayne *et al.* 2001). A study of these two possum species identified the trees and their attributes used and selected for as diurnal refuges (Wayne 2005). Tree diameter, crown senescence, canopy connectivity, tree species and signs of possum are all significant predictors of tree use. Dead standing trees were clearly identified as preferred habitat for diurnal refuge use. The importance of canopy connectivity has direct implications for the consideration of adjacent trees when selecting the most appropriate habitat trees to retain in cutover stands.

The value of retaining primary habitat trees in jarrah forest harvest treatments in mitigating the impacts of timber harvesting on brush tail possums has been demonstrated through the Kingston Study (Morris *et al.* 2001, Wayne unpublished data). This finding relates to silviculture implemented under Guideline 1/95 with a retention rate of 3 trees ha^{-1}. Brushtail possum abundance was less affected by gap creation timber harvesting than by shelterwood harvesting, indicating that the total spatial extent of disturbance is an important factor in determining the responses of hollow-dependent species. Limitation of the maximum size of gaps (<10 ha) can also be viewed as precautionary in limiting the impacts of timber harvesting on possums and other arboreal mammals.

Mid-storey trees and shrubs

Trees and shrubs that form a mid-storey also provide important legacy elements that are potentially long-lived (>>100 years) and capable of persisting through significant disturbance events including bushfires, severe storms and timber harvesting. Characteristic mid-storey species include grasstrees (*Xanthorrhoea* and *Kingia*), sheoaks (*Allocasuarina fraseriana, A. decussata*), some *Hakea* (*H. oleifolia*), persoonia (*P. elliptica*, *P. longifolia*), woody pear (*X. occidentale*) and peppermint (*Agonis flexuosa*). These elements can contribute to biodiversity conservation at the operational scale in several ways:

Balga grasstrees (*Xanthorrhoea*) provide refuge sites for the ringtail possum (Wayne *et al.*, 2001). This may be of particular significance when there is competition with the more aggressive brushtail possum for a limited supply of other refuge sites in hollow trees. Balga are also likely to provide roost sites for bats (Webala, 2010) and foraging and nest sites for Mardo (Swinburn *et al.* 2007);

Foliage, flowers and fruit of mid-storey trees are important food sources for many animals and birds (e.g., cockatoos, Honeyeater, Spinebill, Pardalote: Abbott, 1985); and

Rough outer bark of *Agonis ecussata* and *A. flexuosa* and other mid-storey trees may be colonised by epiphtytic ferns, lichens and mosses, and provide sites where these organisms have a greater likelihood of persisting between bushfires.

Specific actions to protect large trees and groups of balga and mature individuals of other mid-storey species were introduced in SFM Guideline No. 1 (2004). Since this time, awareness of the contribution that mid-storey species make to biodiversity conservation at the operational scale has increased as their role in providing resources and substrates for other organisms has become better understood.

Woody debris

Woody debris is an important legacy element in Western Australian forests. The potentially large dimensions of logs and stumps derived from mature trees, together with high wood density and durability and low rates of decomposition in southwestern Australia (Brown *et al.* 1996), mean that this material can persist for many decades on the forest floor.

Coarse woody debris (CWD) in the jarrah forest was examined in detail as part of the Forestcheck monitoring project (McCaw 2011; Whitford and McCaw, 2019; McCaw and Tunsell, 2021). The volume of woody debris is highly variable across sites, ranging from 26 to 407 m^3 ha^{-1} with a mean of 140 m^3 ha^{-1} on recently harvested stands and 77 tonnes m^3 ha^{-1} on stands that have never been harvested). The 'old harvest' category harvested more than 40 years prior had an intermediate value (89 m3 ha−1) (Whitford and McCaw, 2019). Debris volume increases with both the intensity of harvest and the number of times the stand has been harvested. A substantial proportion of CWD on the recently harvested stands (34%) is derived from harvesting with most of this occurring in the smaller diameter classes (10 to 50 cm). Harvesting also increases the volume of debris in low to moderate decay classes (classes 2 to 5) and may decrease the number of large highly decayed logs.

The amount of CWD in jarrah forest is large in comparison with other open eucalypt forests, emphasising the significance of debris as a legacy element in the Western Australian context. Average debris loads on Forestcheck grids that have never been harvested, or not harvested for at least four decades, is about a third greater than the mean value (50 t ha^{-1}) proposed for open eucalypt forests by Woldendorp and Keenan (2005). In Jarrah Forest harvested between 1988-2002 the debris load is almost twice as great as the mean for open eucalypt forests.

Coarse woody debris plays an important role in the conservation of jarrah forest biodiversity. One-half of all cryptogams recorded on Forestcheck monitoring grids utilised CWD as a substrate, and 40% of them depended on it entirely (Cranfield *et al.* 2011). Coarse woody debris has also been shown to provide substrates for a wide range of macrofungi (Robinson *et al.* in press) and invertebrates (Farr *et al.* 2011). Danti (2008) investigated saproxylic (wood dependent) invertebrates in jarrah forest, comparing assemblages, trophic guilds and dependency groups between uncut stands and stands cut to gap release and shelterwood. Twelve years after treatment, invertebrate assemblages on harvested sites were not significantly different to unharvested sites although some differences in patterns of usage of woody debris were evident between control and treatment sites. Studies in other forest ecosystems indicate differences in volume and condition of woody debris can affect fungal (Norden *et al.* 2004; Gates, 2009) and invertebrate assemblages (e.g., Grove 2002, Grove and Meggs 2003; Grodsky *et al.* 2018; Boggs *et al.,* 2020). Loss of large diameter logs in harvesting may also affect availability of hollows suited to ground dwelling vertebrates such as chuditch, numbat (Seidlitz *et al.* 2021) and a variety of reptiles.

Amounts of woody debris present in karri forest are even larger than in jarrah forest (Smith and Neal 1993), although further work is required to characterise size class distribution and decay condition in relation to stand age and management history.

Large karri logs and stumps of mature trees have been identified as important colonisation sites for *Asplenium aethiopicum* (Priority 4) in regrowth karri forest (McCaw 2006). This appears linked to the development of deep moss beds on partially decayed wood, and the ability of these moss beds to retain and attract moisture during the annual dry season. Small diameter logs (<30 cm) lacking surface decay do not appear suitable as colonisation sites. This example serves to illustrate a broader point about the dependence of some organisms on substrates associated with woody debris from large mature trees that have persisted to reach an advanced stage of decay.

Fire has an important influence on the condition and persistence of CWD. The amount of CWD is increased by prescribed fires but decreased by wildfires (Whitford and McCaw 2019). Post-harvest burning may deliberately aim to consume CWD for the purpose of reducing fuel loads and creating a mineral ashbed. Woody fuel consumption is proportional to fireline intensity (Hollis *et al.* 2011a). Low intensity fires (<500 kW m^{-1}) typically consume between 40 and 60% of CWD fuel >25 mm diameter, increasing to >80% consumption for intense fires (>10000 kW m^{-1}). Woody fuel consumption is also affected by decay condition, fuel arrangement and seasonal conditions but the influence of these factors has proven difficult to quantify and appears of secondary importance to fire behaviour (Hollis *et al.* 2011b). Most silvicultural burning is of low to moderate intensity. Woody fuel consumption can be artificially increased by rough heaping and windrowing where high levels of fuel consumption and ashbed creation are sought. Large logs in advanced stages of decay that are required as legacy elements should be excluded from heaping operations.

Key findings from Forestcheck and other projects investigating responses to harvesting

Soil disturbance and understorey vegetation

Soil disturbance during timber harvesting and associated silvicultural operations can affect a range of soil properties including density, porosity and strength, which influence plant growth, nutrient cycling and soil biota. Impacts of harvesting depend on soil type, areal extent of disturbance, the intensity of the harvest in terms of tonnes per ha harvested, soil moisture conditions at the time of the harvest, and the type of machinery used in the harvest operation (Whitford and Mellican 2011). Studies of soil disturbance on Forestcheck monitoring grids found that surface soils on sites that had never been harvested had a mean fine earth bulk density of 0.71 g cm^{-3}. Timber harvesting increased the bulk density of surface soils by a mean of 0.15 g cm^{-3}. Compaction was greatest on log landings and primary and secondary extraction tracks where fine earth bulk density was increased by 0.27 g cm^{-3} compared to never harvested forest. Compaction on the general harvested area (0.13 g cm^{-3}), which excluded extraction tracks, was approximately half that of log landings and extraction tracks. More than 50 years may be needed for biological processes to reverse the increase in bulk density of soil caused during harvesting (Abbott and Williams 2011). These levels of soil compaction are consistent with increases observed as a result of timber harvesting in a range of other forests. Methods to mitigate soil compaction on vulnerable soils are available, including cording of extraction tracks, restricting extraction to a minimum number of tracks and reusing old extraction tracks (Whitford *et al.* 2012).

Soil disturbance can directly affect the composition and density of understorey plants (Burrows *et al.* 2002). However, studies of vascular plant composition and abundance at Forestcheck monitoring grids (Ward *et al.* 2011; 2020) have not detected reductions in the abundance of some plant groups (perennial herbs, sedges, grasses and woody shrubs) following timber harvesting to the extent reported for the Kingston Project by Burrows *et al.* (2002b). Ward *et al.* (2011) found no significant difference in mean species richness and abundance of understorey plants between harvested grids and unharvested reference grids, but harvesting had a distinct influence on plant community composition. Unharvested reference grids had more species of small and medium shrubs compared to harvested treatments. *Allocasuarina fraseriana* (a midstory tree) and *Kennedia coccinea* (a vine) were more common on harvested grids, while *Xanthorrhoea preisii* (balga) were significantly less common in harvested treatments compared to reference forest. This finding, however, needs to be considered in the context that Forestcheck monitoring grids represent examples of silvicultural practice in the period 1988 to 2002 prior to the introduction of specific measures to protect midstorey trees and shrubs.

Invertebrates

Overall, there were no significant differences in observed species richness between gap release, shelterwood and unharvested reference forest within each forest ecosystem after the first (2001-2006) or second (2007-2012) sampling rounds (Farr *et al.* 2011; Robinson *et al.* in review; Farr and Wills in review). Collection method influenced the direction and magnitude of changes in estimated richness following timber harvesting and post-harvest burning in the first round of sampling, indicating that multiple collection methods are needed to assess invertebrate response to disturbance. Silviculture and time since silviculture had no detectable effect on macroinvertebrate assemblages over two rounds of monitoring (Robinson *et al.* in review, Farr and Wills in review). For both rounds combined more invertebrates were restricted to harvested forest (758) than the total taxa restricted to reference forest (650). Only 40.2% of invertebrates were recorded in both sampling rounds. These results suggest significant patchiness in the distribution of invertebrate species and the likelihood of significant short-range endemism that may be more at risk from harvesting than the community/richness data indicate.

Cryptogams

Timber harvesting impacted significantly on species richness of lichens, which decreased with intensity of harvest and community composition of the cryptogam community (Cranfield *et al.* 2011). The total number of lichens was lowest on gap release grids and intermediate on shelterwood/selective cut grids relative to the unharvested reference grids. However, by c. 10y after disturbance, these differences had moderated, and no statistical differences were evident. A second round of monitoring revealed a treatment by round interaction whereby species richness was significantly lower in reference grids compared to harvested grids, suggesting a complex response to silviculture (Robinson *et al.* in review). A number of lichen species appear to be associated with mature trees, providing further justification for retention of habitat trees in harvested forest. Many cryptogams were strongly associated with coarse woody debris and Cranfield *et al.* (2011) recommended that management of CWD should aim to maintain woody debris in varying stages of decay with a size class distribution that includes large logs.

Macrofungi

Overall mean species richness and abundance were similar for unharvested reference forest, shelterwood and gap release (Robinson and Williams, 2011 Robinson *et al.*, in review). In the first round of monitoring, composition of species assemblages contributing to macrofungal communities differed significantly between harvested and non-harvested forest, while in the second round, assemblages differed only between unharvested and gap release. In the first round in all treatments, the overall mean number of species per grid recorded fruiting on soil was 2-4 times higher than that recorded on litter or wood. Sixty-nine species were restricted to reference forest while 35 were restricted to shelterwood/selective cut and 61 to gap release treatment. This suggests that a large number of fungi depend on some form of disturbance, or a particular stage of forest development, to either colonise a site or to develop sporophores.

Birds

There was little evidence of any substantial effect of logging treatments on avian community structure or on individual bird species (Abbott *et al.* 2011; Robinson *et al.* in review). Differences in assemblages between treatments can be viewed within the context of high temporal variation in assemblages for all ecosystems monitored (Robinson *et al.* in submission). Species accumulated (in terms of numbers of grids) at similar rates in gap release, shelterwood and selective cut, coupe buffer and external reference forests (which had either never been logged or had been harvested more than 40 years previously). In terms of individuals, species accumulated faster in the gap release forests. After 2 rounds, the number of species represented as singletons was greatest on the never logged (11), then coupe buffer (8) and then gap release (4) grids (Robinson *et al.* in review). Dominance diversity curves also showed only minor differences between silvicultural treatments (Abbott *et al.*, 2011). These results are consistent with previous studies, which indicate that most bird species in jarrah forest have a high threshold level of tolerance to disturbance. It is likely that the rapid regeneration of dominant tree species after logging and associated fire, the patchiness of logging and burning at the landscape scale, the high degree of connectivity of logged and burnt forests with forests not recently logged or burnt, and the retention of habitat trees in the most heavily-logged (gap release) forests together dampen local-scale impacts and conserve the avifauna in relation to the home range and normal movements of its constituent bird species.

Terrestrial vertebrates

Forestcheck showed that several terrestrial vertebrate community attributes (species accumulations by grids and number of individuals, dominance diversity plots, overall community structure and overall abundance) differed little between unharvested reference grids and grids in forest harvested by shelterwood or gap release (Wayne *et al.* 2011a). However, unharvested reference grids had significantly lower species richness than shelterwood grids and a significantly different community structure. These differences resulted from a greater prevalence within shelterwood of some reptile species such as *Egernia napoleonis*, *Menetia greyii*, *Ctenotus labillardieri*, and *Ramphotyphlops australis*. These reptiles likely benefit from the larger amounts of coarse woody debris in harvested grids and the intermediate state of forest structure and diversity available in shelterwoods (e.g., moderately open forest structure; increased ectothermic opportunities such as basking sites and the nature, diversity and distribution of micro-habitats). Brushtail possum and woylie (*Bettongia penicillata*) were the most abundant terrestrial mammals recorded in the study, and neither differed greatly in abundance between the harvested and unharvested forest. The statistical power was only sufficient to detect differences in species richness and abundance between treatments that were greater than 23% and 37%, respectively. Relative to other taxa the effort required to generate these data was large. Fox control had the strongest effect on terrestrial vertebrates, with baited areas supporting significantly more individuals (three–fold increase) than unbaited areas. Never logged forest, a subset (8/15 grids) of the external reference treatment, had the lowest overall abundance, due largely to a confounding with fox control.

The Kingston study involving a replicated before-after-control-impact (BACI) repeated measures design conducted over 16 years found no evidence that woylie abundance, survivorship and recruitment were adversely affected by silvicultural practices in the jarrah forest (Wayne *et al.* 2016). However, with the species having undergone a substantial and rapid decline across its range (~90% 1999-2006 Wayne *et al.* 2013) and having been reclassified as *Critically Endangered* (IUCN Red List; Wayne *et al.* 2008), ongoing monitoring and evaluation are necessary to ensure that timber harvesting activities remain benign in the face of a changing climate, possible increased mortality from introduced predators, disease, and further declines in the abundance of this critically endangered marsupial.

Changes in conservation status of threatened species

Within the FMP area, the number of fauna species listed as threatened or specially protected increased from 112 in 2013 to 120 in 2017, which included four species being listed as conservation dependent when this category was introduced in 2017. Within the last 10 years two medium sized mammals dependent on forests have been elevated to *Critically Endangered; the* woylie and ngwayir. Three species were added to the list – *Galaxiella nigrostriatal* (black-striped minnow) as endangered, *Lepidogalaxias salamandroides* (salamander fish) as endangered, and *Westralunio carteri* (Carter’s freshwater mussel) as vulnerable. In the same period, two species were removed from the threatened and specially protected fauna list (*Morelia spilota imbricata* (carpet python) and *Aspidites ramsayi* (Woma).

Key findings from other studies

Frogs and reptiles

Yeatman *et al.* (2016) found that riparian habitats were particularly important for frog species and it was these species that accounted for the greater abundance of ground-dwelling vertebrates in this habitat. Riparian habitat was less important for other groups and the more floristically rich midslope and ridge habitats, which had a greater abundance of leaf litter, fallen logs and rock cover, were favoured by mammal and reptile species. Their paper concluded that the conservation of riparian sites, without the protection of other habitats, would overlook a substantial proportion of the biodiversity in the landscape. Christie *et al.* (2013) found that provision of woody debris sites encouraged recolonisation of Napoleon's skink (*Egernia napoleonis)* in Jarrah Forest bauxite restoration sites, and this may also be the case in harvested Jarrah Forest. Analyses of reptile habitat associations in the Jarrah Forest by Triska *et al.* (2017) could only robustly determine associations for the commonest species due to low detection rates, although it was clear that many individual species show preference for particular habitats in the Jarrah Forest including different densities of leaf litter, coarse woody debris, fuel age and differing densities of trees and vegetation at different storeys. Their study suggests that implementing management activities that maintain habitat heterogeneity and complexity will be the most effective strategy for conserving the most reptile species. Bryant *et al.* (2012) showed that tree hollows are important for pythons, especially over winter in coastal tuart and Banksia woodlands (Yalgorup National Park and Leschenault Peninsula Conservation Park), on the Swan Coastal Plain.

Birds

A series of papers published between 2002 and 2007 (Craig 2002, Craig 2004, Craig and Roberts 2005, Craig 2007) has provided information about the response of forest birds to timber harvesting as part of the Kingston Project. Unlogged forest patches were shown to be important in providing both foraging and nesting opportunities for some species (Craig 2002), leading to the recommendation that temporary exclusion areas be retained until the adjacent logged forest matures sufficiently to support viable populations of vulnerable species (Craig 2004). Changes in the density of the bird community were found to be limited and probably short-term in nature, and un-related to the intensity of disturbance by harvesting and silvicultural treatment (Craig 2007).

In another study, following thinning of Jarrah Forest in 1983, which reduced the canopy cover by half, and removed all *Banksia grandis*, the bird community showed few immediate changes (Abbott and Van Heurck 1985). No species occurred significantly less frequently after harvesting, and the number of species present were similar in unlogged and logged forest; that is, most bird species appeared to be adaptable to high levels of disturbance (Abbott and Van Heurk 1985). Kabay (2009) concurs and suggests that in their study of the Wungong Thinning Trial, there was no effect of commercial logging (with no burning) in their study. However, non-commercial thinning and commercial logging followed by burning had, on average, a negative effect on birds (Kabay, 2009). Ongoing monitoring of bird populations shows that the species composition of bird communities in logged and unlogged forest at Kingston has not yet converged after a decade after post-harvest burning (Abbott *et al.* 2003, 2009).

Bird populations continue to be monitored in karri forest at Gray Block following clearfell harvesting and regeneration burning in 1984/85 (Abbott *et al.* 2009). After 21 years, species richness and total abundance of birds remained greater in the unlogged mature forest than in the regenerated forest. Ordination analysis showed that recovery of bird populations was continuing in the regenerated forest, with the avifaunal composition in 2006 being more similar to that of the unlogged forest than in previous years.

Based on the data from a large citizen science monitoring program, Williams *et al.* (2016) found a statistically significant decline in roost occupancy rate and a non-significant decline in the mean size of roosting flocks of the endangered Carnaby's Black Cockatoo (*Calyptorhynchus latirostris*), with an estimated overall trend of 14% decline per annum in the number of roosting birds. Williams *et al.* (2017) produced population models for the Carnaby's Black Cockatoo, which synthesized detailed demographic and food resource data to model future population size and extinction risk. They found that assuming no changes in the extent or quality of breeding habitat, and current breeding or survival rates, the most important factor currently limiting population growth for Carnaby's cockatoo is adult survival rate, whereas population size is limited by recurring bottlenecks in food availability resulting from a trend of resource depletion combined with large variability in annual seed production.

Johnstone *et al.* (2013a), described the characteristics of nest trees and nest hollows used by Forest Red-tailed Black Cockatoo (*Calyptorhynchus banksii naso*) (FRTBC). They found most were in very large Marri (*Corymbia calophylla*). Mean values of nest trees included 89 cm DBHOB and 20m overall height. The rate of fall or loss of nest trees was c. 16.6% per decade. Johnstone *et al.* (2013a) argued the importance of conserving the large nesting trees as well as the control of exotic nest competitors, including the European Honey Bee. The Whitford *et al.* (2015) response to this paper included the need to demonstrate whether FRTBC nest trees were clustered in the landscape and that most nest hollows occur in intermediate-sized trees. Johnstone *et al.* (2013b) described the breeding, diet and feeding behaviour of the FRTBC, including that most breeding coincided with the fruiting of their principal feed trees: marri and jarrah. Mastrantonis *et al.* (2019) found breeding frequency was strongly linked to the availability of fruit from these tree species and rainfall. Breeding was also influenced by heatwaves, forest productivity and climate change more broadly. The ecology and feeding on rehabilitated mine sites of all three black cockatoo species (FRTBC, Carnaby's cockatoo (*Calyptorhynchus latirostris*), and Baudin's cockatoo (*Calyptorhynchus baudinii*) in SWWA have also been reported (Lee *et al.* 2013a & b, Doherty *et al.* 2016).

Black cockatoo feeding ecology has also been recently reported in other habitats such as banksia woodlands on the Swan Coastal plan (e.g., Johnston *et al* 2016). Fire effects on food supply of black cockatoos in banksia woodlands have also been described (Valentine *et al.* 2014), including that higher numbers of Carnaby's cockatoos were predicted to be supported in vegetation aged between 14–30 years since fire, peaking in vegetation aged 20–25 years. A subsequent study identified that low intensity fire did not disrupt fruiting, but high-intensity fire significantly decreased seed availability for at least four years (Densmore and Clingan 2019). Saunders *et al* (2014) reported on a long-term study on the use of tree hollows by Carnaby's cockatoo and their rate of loss in the wheatbelt.

Bats

Bat activity in jarrah forest at Kingston block has been studied by Webala *et al.* (2010, 2011). The southern forest bat (*Vespadelus regulus*) is highly reliant on hollows in large trees in mature forest including riparian buffers adjacent to timber harvesting. Gould's long-eared bat (*Nyctophilus gouldi*) uses a broader range of roost types in a broader range of forest structures, with an apparent bias towards recently harvested sites (<25 years). Active and foraging bats use mature jarrah forest significantly more than regrowth forest (<30 y old), principally due to reduced under-canopy clutter. Bat activity along forest tracks was even greater and not sensitive to adjacent forest structure. Therefore, tracks provided greater access within regrowth forests for foraging bats than would otherwise be available due to insufficient crown separation in younger regrowth forests. These findings provide further support for the retention of mature trees within harvested areas, and for maintenance of landscape connectivity.

Burgar *et al.* (2015) also showed that bats were highly reliant on mature forest stands for roosting and have not been found to roost in <40-year-old restored mine sites. Foraging and habitat use by bats in restored minesites in the northern jarrah forest was highly dependent on tree density, canopy height, and midstory cover and again highlighted the importance of mature forest structure (Burgar *et al.* 2017).

Studies in dry sclerophyll forests in south-eastern Australia found a positive effect of low-intensity burning on echolocating bat activity, particularly in unlogged forest but that activity and richness was lower in 12–17-year-old regrowth forest (Law *et al* 2019). Thinning regrowth forests or plantations below 1100 stems per hectare were recommended for improving bat foraging (Blakey *et al.* 2016). A study in a climate refuge found the effect of logging history (unlogged vs 16-30 years post-logging regrowth) on apparent survival was minor, mixed and species specific (Law *et al.* 2018). The study also found no effect of logging history on abundance or body condition.

Mammals

Some mammal recoveries have not been sustained in the presence of a broad-scale threat abatement program aimed at reducing the impact of the introduced red fox. Since the mid-1990s, populations of at least seven native mammal species or genera (dunnarts, bush rat, brush tailed phascogale, quenda, ngwayir, woylie and western brush wallaby) have successively declined at similarly rapid rates and magnitudes (80–100%) in the forest habitats of Upper Warren area (Wayne *et al.* 2017). In some cases, post decline recoveries have occurred but not been sustained. For example, the woylie and ngwayir have undergone 80% declines in the four years to 2021 in the Kingston area (Wayne *et al.* unpublished). While cat predation is considered a putative major factor in the declines of many of these species the drivers of these declines require further investigation (Wayne *et al.* 2017).

While successfully delivering substantial conservation gains, it is evident that introduced predator control does not always deliver sustained recovery everywhere, all the time. While it is not yet clear *if* a population might decline after a period of release (e.g., increases due to fox baiting or translocation), Duncan *et al.* (2020) demonstrated that it is possible to predict *when* it might occur. The time taken for erupting populations to reach a peak before declining was related negatively to the intrinsic rate of population growth and positively to body mass, such that larger-bodied species with slow rates of population growth had a longer period of population increase before declining. Therefore, managers of recovering or translocated populations can anticipate this in their conservation planning.

Substantial population changes, such as the elevation to *Critically Endangered* of forest dependent species such as the woylie and western ringtail possum, means that the context for the conservation and management of the species and its habitat has changed from when some of the work assessing potential sensitivities of the species was done. For instance, the responses, threats and risks of a population may be profoundly different between being abundant and stable, declining, and small populations (e.g., Caughley and Gunn 1996). While timber harvesting in the jarrah forest was not a risk while the woylie population was declining (Wayne *et al.* 2016), it is less clear how the subsequent small post-decline populations may respond to timber harvesting and other disturbances and threats such as fire and introduced predators. Therefore, where substantial changes in populations have occurred, and to some extent other aspects of the ecology and environment in which they live (e.g., climate change, increased population fragmentation, etc) any consideration of fauna responses to disturbance or threats should be cognisant of the changing context and dynamics. In other words, context is important and extrapolation beyond the context in which knowledge and learnings have been made comes with risk: what may be so in one context may not necessarily apply in another.

Woylie (Bettongia penicillata)

The cause(s) of the catastrophic declines of the woylie remain unproven. However, based on the available evidence, the leading hypothesis is that disease may be making woylies more vulnerable to predation (Wayne *et al.* 2015). Predation by cats accounted for about two-thirds of the observed mortalities during the woylie declines in the jarrah forests of the Upper Warren region (Wayne *et al.* 2011b, 2013) and the wandoo woodlands in the wheatbelt (Marlow *et al.* 2015b). While a substantial amount of work has investigated the potential role of parasites and disease (Ash *et al.* 2017; Botero *et al.* 2013, Godfrey *et al* 2018; Hing *et al.* 2017a & b; Kaewmongkol *et al* 2011, Northover *et al.* 2015, 2017, 2018, 2019a,b,c,d; Pacioni *et al.* 2013, 2015; Rong *et al*

2012, Skogvold *et al.* 2017; Thompson *et al* 2010; Thompson *et al* 2013, 2014), there is no unequivocal evidence that it has been a major causal factor. However, currently the strongest associative evidence indicates that blood parasites in the genus *Trypanosoma* may be involved (Godfrey *et al* 2018).

Yeatman *et al.* (2016) found that the distribution and abundance of woylies over time was related to the degree of fragmentation by roads and proximity to agriculture. In particular, sites furthest from agriculture supported a greater abundance of woylies and had slower rates of population decline. Sites with fewer roads had a greater abundance of woylies generally and a greater rate of increase in abundance after the implementation of invasive predator control. The results of this study suggest that disturbance is less important at peak population densities, but during times of environmental and population change, sites less dissected by roads and agriculture better support woylie populations.

Habitat fragmentation from land clearing has also resulted in genetic isolation, loss and differentiation in woylie populations (Pacioni *et al.* 2011, 2015). While spatial and temporal differences in woylie diet have been observed (Zosky *et al.* 2018), there is no clear indication that food resource limitations have been associated with the recent catastrophic declines (Zosky 2011).

Western Ringtail Possum (*Pseudocheirus occidentalis*)

The ngwayir, or western ringtail possum was elevated to *Critically Endangered* in 2016 following >95% declines in the largest population at the time (in the jarrah forests of the Upper Warren region) but also ongoing declines on the Swan Coastal Plain (Wayne *et al.* 2017; Woinarski *et al.* 2014).

The last decade has seen numerous papers published on ngwayir from studies conducted in urban areas on the Swan Coastal Plain and south coastal areas in and around Albany. Little has been published regarding the inland populations in forests, except the reporting of the population declines and estimates of population sizes and distribution (Barrett 2016; Wayne *et al.* 2017a & b, 2019; Teale and Potts 2020). Total species population estimates were estimated to be around 20,000 individuals in 2019 (Teale and Potts 2020). However, there have been significant populations changes recently, including an approximate 80% decline of detection rates of ngwayir in the greater Kingston area within the Upper Warren in the four years to 2021 (Wayne unpublished data).

More broadly, several papers have reported on survey methodology (e.g., Finlayson *et al.* 2010; Thompson and Thompson 2011; Barrett 2016, Teale and Potts 2020; Seidlitz *et al.* 2021). Sheoak and marri-eucalypt woodlands near the south coast have been shown to be important habitat and a higher diversity of plant species have been found in their diet (Bader *et al.* 2019; Mathieson *et al* 2020). Roads and waterways can have a significant effect on ngwayir movements, home ranges (Yakochi *et al.* 2015) and genetics (Yakochi *et al.* 2016). And the presence of the ngwayir was not related to remnant vegetation within the immediate surrounds, nor the distance from remnant habitats within the City of Albany (Busschots *et al.* 2021).

Studies relevant to consideration of the impacts of climate and climate change on ngwayir have included a physiological study of their tolerance to heat, which suggests that they should physiologically tolerate the climate of habitat further inland than their current distribution and based on their heat tolerance alone that they could withstand moderate impacts of climate change in the south-west of Western Australia (Cooper *et al.* 2020). However, this study did not consider the climatic effects on other aspects of the biology and ecology of the species such as water balance, diet, breeding or the interaction with other factors such as predation and disturbances such as fire. Species distribution modelling using bioclimatic variables predicted a reduction of up to 60% in the range of the ngwayir and its habitat, as a result of local climate change scenarios for 2050. Reductions in the distribution of important tree species for ngwayir (jarrah marri and peppermint) were also predicted (Molloy *et al.* 2014).

Two population-level studies on the genetics of the ngwayir are currently in preparation for publication (Spencer *et al.* in prep, White *et al.* in prep). Both indicate significant differences in the genetic characteristics across the species' current range. At least eight genetic subregions were identified, four within the west coast management zone (including inland forest populations in the Leschenault water catchment area), two within the southern forest management zone and two within the south coast management zone (White *et al.* in prep). More samples are needed to investigate three genetic outliers – Lower Blackwood River, Two Peoples Bay area and around Pemberton.

Numbats

The largest of the two remaining indigenous numbat population is in the jarrah forests and wandoo woodlands of Upper Warren region. A study there found evidence of numbat activity at 83% of sites across the area. While there were no strong effects detected from forest management activities (prescribed fuel reduction burns, timber harvesting, increased intensity of fox baiting) on numbat habitat use/occupancy, the number of logs was important (Seidlitz 2021). Numbat habitat use was positively related to the number of logs, and log numbers were higher at timber-harvested sites. The study demonstrated that the numbat is a habitat generalist and that there was no preference by numbats for wandoo over jarrah forest habitats. Recent estimates of the numbat population in the Upper Warren are around 2,000 (Seidlitz 2021, Thorn *et al.* in review), which is substantially greater than previous unsubstantiated estimates of 200-500.

Common brushtail possum

Recent analyses of Western Shield data (1996 to 2017) identified that populations of koomal (brushtail possum) have declined significantly at 17 of the 30 sites analysed (Gwinn and Drew, 2018), many of which are in the forest management plan area. Most sites experienced declines in the period 2008 to 2017, with some experiencing significant declines from 2013 to 2017. These findings are consistent with earlier reports that koomal numbers had substantially declined across the northern jarrah forest based on researchers such as Jennifer Cruz revisiting sites in the 2000s that had been surveyed as part of Operation Foxglove (de Tores 2020). The drivers of these population changes remain unknown but there is a project proposal that aims to investigate the matter (Drew *et al.* unpublished).

Chuditch

Significant declines have been recorded at several Western Shield monitoring sites, including some in the forest regions (including Balban, Bindoon, Moopinup, Noggerup, Centaur) since 2011 (Gwinn and Drew 2018; Drew 2021). In restored minesites in the jarrah forest, chuditch were shown to use burrows associated with surface rocks, where preferred shelter sites in hollow logs and stumps were less available. The addition of more logs was recommended for restoration sites given their preference (McGregor *et al.* 2014). Little other research has been recently completed on chuditch in the southwest forests. While not in the forests, chuditch were shown to respond positively to cat control in south coast reserves (Comer *et al.* 2020). Several papers have reported on aspects relating to chuditch translocations across their former range (e.g., Cannella and Henry 2017; Jensen *et al* 2021; Moseby *et al.* 2021; West *et al.* 2020).

Quokka

Survey methodology for quokka in the southern forests has been improved (Bain *et al.* 2014), which has enabled further ecological studies. A habitat preference study (Bain *et al.,* 2015) found that predictors within habitat suitability models were different between southern and northern forest populations. In the southern forests occupancy patterns were influenced by complex vegetation structure, low levels of woody debris and habitat patchiness. Populations were also highly fragmented and potentially isolated, despite there being continuous native vegetation cover. Therefore, perceptions of habitat fragmentation need to include processes such as fire regimes and feral animals that affect the availability and connectivity of habitat and have the potential to adversely affect population viability.

The most important variables for post fire recolonisation are retention of vertical vegetation structure and having multiple unburnt patches across >20% of the total area (Bain *et al* 2016). Prescribed burns with high surface moisture, low soil dryness and slow fire rates of spread were conducive to these outcomes. Intense wildfire resulted in complete loss of vegetation structure and a lack of unburnt patches, which contributed to these areas remaining uncolonized for extended periods. Burning with high moisture differentials, maximising the effectiveness of edaphic barriers to fire, retaining unburnt vegetation and maintaining vegetation structure were found to be important elements of fire regimes in this region (Bain *et al* 2016).

The O'Sullivan wildfire of 2015 burnt 98,000 ha of mostly forested habitats near Northcliffe, including areas occupied by a significant portion of the mainland quokka population. A subsequent post-fire study (Bain *et al.* 2016, Bain 2020) found that the fire resulted in the loss of 77% of known subpopulations of quokka within the fire-affected area and about 84% of the individuals. Five years after the fire the abundance of quokkas in the fire-affected area had increased to approximately 46 % of pre-fire numbers. It is estimated that the quokka population will take a total of 12 years to reach pre-fire levels provided significant effort to protect recovering populations occurs (Bain 2020).

Quenda

Overall, the relative abundance of quenda has declined over time at most Western Shield monitoring sites (including some forest sites such as Centaur, Julimar and Moopinup) in recent years, however data has yet to be modelled to determine if this trend is significant (Drew, 2021). The loss of digging mammals, such as quenda, represents a critical loss in ecosystem functioning, given the contributions they make during foraging to soil turnover, increasing soil moisture, reducing hydrophobicity, increasing potassium, and increasing seedling growth (Valentine *et al.* 2013, 2017, 2018).

Flora

Analyses by Luxton *et al.* (2021) show that, while Jarrah Forest Ecosystem types are adequately represented in the conservation estate, the conservation estate may not as well represent finer scale flora communities based on full floristic surveys. This suggests that some flora communities may be affected by harvesting while not being adequately represented in the conservation estate.

Mattiske (2010) indicated that understorey species richness was found to be independent of thinning treatments in the Wungong Catchment Trial. In addition, as part of the Wungong demonstration plots, Mattiske (2010) preliminary investigations found that plots with the light thinning treatments had the lowest species diversity, with no significant difference being recorded between the notched and felled treatments. However, it was noted that further temporal studies will be required to determine if any changes occur to understorey species richness because of the different silvicultural treatments.

Conservation of biodiversity at the landscape scale

Biodiversity patterning

While silvicultural practices are undertaken at the operational scale, the effects on biodiversity are also influenced by a range of factors relevant at the whole of forest scale. Knowledge about biodiversity in the south-west forests and effects of silviculture is partly dependant on adequacy of the underlying data on biodiversity distribution. Chapman and McCaw (2017) quantified the relative effort for biodiversity surveys across the public forest estate in the south-west of Western Australia. The results indicated that the western, and particularly the south-western, parts of the study area were relatively well surveyed while eastern parts were relatively poorly surveyed. This is likely to reflect greater habitat loss and fragmentation of vegetation on the eastern margins of the forest estate where it adjoins the extensively cleared Western Australian wheatbelt. There was also an emphasis on monitoring biodiversity in forest habitats closer to the main population centres of the south-west.

Forest structural heterogeneity and connectivity

The network of formal and informal reserves, fauna habitat zones and temporary exclusion areas contribute to heterogeneity and connectivity at the landscape scale. This provides opportunity for movement of individuals and populations, and for dispersal of propagules. Some fauna species have a preference for particular structural elements that are not provided in the early developmental stages following timber harvesting.

For some vertebrates, including the brushtail and ringtail possum, the impacts of timber harvesting can extend to adjoining areas of mature forest in temporary exclusion areas and informal reserves. The abundance of brushtail possums in temporary exclusion areas and informal reserves declined following timber harvesting at Kingston, albeit to a lesser extent than in cut-over stands. However, ongoing population monitoring by trapping and spotlight surveys has confirmed that brushtail possum populations can be sustained in abundance (Wayne *et al.* unpublished data).

At the landscape scale, a key finding of Forestcheck monitoring is that fox control has a substantially greater influence on terrestrial vertebrate species abundance, and to some extent species richness, than does forest structure (Wayne *et al.* 2011). This finding clearly demonstrates that maintaining areas of mature forest in the landscape is, on its own, insufficient to ensure conservation of terrestrial vertebrates.

Pest outbreaks and tree decline in the context of silviculture

Major outbreaks of insect pests that reduce forest canopy density at the landscape scale warrant consideration in planning for silvicultural operations because they may result in retained areas of mature forest being temporarily less suitable for habitat and foraging by some animals. Jarrah leafminer (*Perthida glyhopa*) and Gum leaf skeletoniser (*Uraba lugens*) periodically cause extensive defoliation in jarrah forest, and more than 250 000 ha of forest in the Warren and South West Regions was defoliated by *U. lugens* in the late spring and summer of 2010/11 (Wills and Farr 2017). Both insects are native to Western Australia and broadscale defoliation events are likely to be within the historic range of variability with which the biota has evolved. Outbreaks of *U. lugens* are understood to be related to fluctuations in longer term antecedent and preceding autumn rainfall drought. Outbreaks are limited in regional extent to normally wetter areas of forest by the balance of rainfall and evapotranspiration (Wills and Farr 2017). However, the potential cumulative effects of severe defoliation in combination with other disturbance events including timber harvesting and fire are not well understood. Should major insect outbreaks become more frequent in the future due changing climate, then these cumulative effects would warrant investigation and adaptive management response. During silvicultural operations, retaining trees that exhibit resistance to defoliation by pest insects provides a means of increasing resilience and lessening the impact of outbreaks on other organisms.

A number of tree decline syndromes affecting wandoo, flooded gum and marri have emerged in the past decade (Hooper and Sivasithamparam 2005, Hooper 2009). In *E. wandoo*, previous studies have implicated a range of drivers over time, including climatic changes (Brouwers *et al.* 2013), defoliating insects (Curry 1981), and canker fungi in association with wood-boring beetle larvae (Brown *et al*. 1990). Hooper (2009) suggested that unusually high vapour pressure deficit (VPD; the atmospheric demand for moisture) was associated with E. wandoo decline and that high autumn VPD was strongly implicated as a stress trigger mechanism for borer escalation. There is strong evidence that cankers were causing foliage loss in the declining canopies (Hooper and Sivasithamparam 2005). In 2002 and 2008, large-scale surveys of *E. wandoo* health suggested that recent decreases in annual rainfall and increasing temperatures were affecting the health of *E. wandoo* (Brouwers *et al.* 2013).

Eucalyptus rudis (flooded gum) has experienced cycles of decline across much of its range for many decades (Yeomans 1999; Clay and Majer 2001; Serpentine-Jarrahdale Landcare 2007; Edwards 2010). Although a range of threatening processes exist, including clearing, fragmentation, climate change, introduced soil-borne plant pathogens, increased psyllid, and other insect infestations, little is known about the key underlying causal factors and their interactions, and what actions to take to mitigate the decline. Although treatments trialled previously include tree injections, nutrient implants, and revegetation (Serpentine-Jarrahdale Landcare 2007), few have been consistently successful. More work is needed to understand drivers of decline, investigate the mechanisms underpinning the primary and secondary drivers of decline, and develop intervention actions.

Corymbia calophylla (marri) has been affected by two main pathogens in the last few decades, which affect growth, reproductive effort, and survival, *Quambalaria coyrecup* (a canker), and *Quambalaria pitereka* (a shoot blight), and the impact of changing climate (Paap *et al.* 2017). Canker incidence was significantly higher in wetter and cooler areas of the marri distribution, and in areas with high proportions of non-native vegetation area surrounding the studied stands of trees (Paap *et al.* 2017). Canker incidence was significantly greater on trees present at anthropogenically disturbed sites (along roadsides and in paddocks) than on forest trees (Paap *et al.* 2016).

These decline syndromes pose a potential threat to forest structure, species composition and ecological processes. Typically, tree decline is most advanced in remnant vegetation in extensively disturbed landscapes. Where timber harvesting and silvicultural treatment take place in forest blocks that are isolated in an agricultural landscape, or have an extensive interface with cleared land, the condition of remnant native vegetation patches and corridors on lands adjoining State Forest should be taken into account in planning the extent and timing of operations.

Conservation of plant genetic resources and climate appropriate provenancing

For most tree and understorey species regeneration is achieved with seed from retained and surrounding trees and returned topsoil, resulting in the conservation of local genetic resources. This maintains local genetic resources that are presumed to be locally adapted and best suited to local regeneration sites. Some regeneration is carried out by artificial seeding or planted nursery stock (Bradshaw 2015) and current silvicultural guidelines provide recommendations for sourcing seed for regeneration in this case. The FMP 2014-23 allows for seed to be collected from the same or adjacent Land Management Unit and use of mixed seed sources where climate change or other factors require it.

Genetic studies provide a basis for understanding diversity to guide conservation of genetic resource and inform seed collection strategies. Early approaches focussed on local provenancing for seed collections based on assumptions that plants have local adaptation to their site. More recently other provenance strategies have been developed based on maximising genetic diversity and capturing adaptive potential. Admixture and composite provenancing strategies mix seed from multiple populations to maximise diversity (Breed et al. 2013), and climate adjusted provenancing (a form of assisted gene migration, Aitken and Whitlock 2013) uses seed collected from along a climate gradient in the direction of projected climate change to capture genetic adaptations to climate to increase adaptive potential at the regeneration site (Prober et al. 2015). Approaches to seed collections have recently been reviewed in the Florabank Guidelines (Harrison *et al.* 2021). Forest management in Canada uses assisted gene migration as a climate adaptation strategy.

Genetic studies of species in south-west forest have generally shown high genetic diversity and low genetic structure in both dominant tree species and understorey species. For tree species genetic analysis had been undertaken for jarrah (Wheeler *et al.* 2003; Wheeler and Byrne 2006; O'Brien 2007; O'Brien *et al.* 2007; Filipe et al. in review), karri (Coates and Sokolowski 1989, Mazanec *et al.* 1993), tuart (Coates et al 2002), marri (Sampson *et al.* 2018; Ahrens et al. 2019a) and wandoo (Dalmaris *et al.* 2015). These show low population structure in the forest area, although jarrah shows genetic differentiation between populations on the Swan Coastal Plain and the Darling Plateau. Similarly, studies in several common understorey species of the jarrah forest show high diversity and low genetic structure in *Kennedia coccinea* (Bradbury et al 2016), *Bossiaea ornata* (Bradbury *et al.* 2016b) and *Allocasaurina humilis* (Llorens *et al.* 2016). Patterns of genetic differentiation were stronger in *Banksia sessilis* among Darling Plateau, coastal north, and coastal southern areas (Nistelberger *et al.* 2020). Studies of *Acacia saligna* and *Acacia microbotrya* show genetically delineated subspecific entities that require treatment as different taxa.

Provenance trials assessing quantitative genetic traits in dominant tree species in southwestern Australia are limited but have provided some evidence of local adaptation. For example, reciprocal transplant trials planted >30 years ago showed increased survival over 18 months for local provenances of jarrah, and increased emergence for local provenances of marri, although there was no effect for she-oak and regeneration site location and degree of disturbance was shown to have a much more significant impact on performance than provenance (O’Brien and Krauss 2010). However, it must be noted that this response reflects establishment conditions from 30 years ago rather than current climatic conditions that have changed significantly since then. Assessment of quantitative and heritable ecologically important traits in different provenances grown at common sites also allows assessment of environmental adaptation. Cool-wet provenances have shown greater growth and resistance to leaf blight (*Q. pitereka*) in common garden experiments of marri (Ahrens et al. 2019b), supporting similar earlier findings for jarrah (O'Brien et al 2007) and karri

(Mazanec et al. 1993). However, cool-wet provenances of jarrah have lower overall survival than warm-dry provenances (O'Brien et al. 2007) and recent heatwave experiments have shown cool-wet provenances of marri have more limited plasticity and greater damage in response to water deficit than warm-dry provenances (Challis et al. 2021). Assessment of functional traits in marri associated with leaf morphology, leaf function, wood density and water use efficiency showed significant differences between populations for all traits with moderate narrowsense heritability for five traits (Ahrens et al. 2020). There were differences between current and future predictions for traits, and some traits showed independent association with different climate factors.

Analysis of the impact of heatwaves on populations of marri from cool and warm environments showed greater damage under moderate heatwaves for populations from cool environments compared to those from warm environments (Ahrens et al., 2021). Exposure to a second heatwave resulted in greater tolerance for high temperature with lower leaf temperatures, implying that adaptation and plasticity may provide some capacity for response to fluctuating heat waves in this species.

Analysis of the interaction between climate and seed germination in jarrah and marri has shown variation across the geographic distribution within species and also different responses between the species (Filipe unpublished). Jarrah has a lower optimal germination temperature and a narrower range for germination compared to marri that has a higher optimal temperature and a wider range. This implies that the impacts of changing climate on seed germination will be evident earlier in jarrah than marri, and this effect is likely to be greater in the northern part of the distribution.

The development of more advanced genomic approaches provides greater coverage of the genome and allows for genomic assessment of adaptation to climate. Such studies have been undertaken for jarrah (Filipe et al. in review) and marri (Ahrens et al. 2019), and show genetic patterns correlated with climatic variables, particularly precipitation and temperature variables. Analysis in marri showed stronger adaptive signals to temperature variables than precipitation variables, and genes associated with adaptive variants include functions important in stress response. Analysis in jarrah showed association with both temperature and precipitation variables.

Genetic studies of trees and understorey plants in southwestern forest region suggest that provenances for seed collection can be considered at a regional scale as these widespread and common species show low population structure. Provenancing strategies that maximise genetic diversity are appropriate for species with lor population genetic structure. For species with genetically defined subspecific entities, such as *A. saligna* and *A. microbotrya*, seed should only be used within the natural range of the subspecific entities. The identification of adaptive variation associated with climate gradients in jarrah and marri suggests that a climate adjusted provenancing approach can be considered as a climate adaptation strategy for these dominant tree species.

Fire

Fire significantly affects the ecology of Western Australian forests, both as planned fire used as a management tool, and unplanned bushfire. Abbott and Burrows (2003) reviewed knowledge of fire in ecosystems of south-west Western Australia in a book that remains the most current comprehensive synthesis, although several important new works have developed knowledge in specific areas. The most relevant include: new fire behaviour models for dry eucalypt forests; a series of studies examining biodiversity outcomes after varying fire regimes; the capacity for silviculture practices to alter fire effects, and; a broader understanding how climate change may impact fire risk and interactions between fire and native species.

Project Vesta is a CSIRO-DBCA (DEC) collaboration that investigated the behaviour and spread of high intensity bushfires in temperate Australian dry eucalypt forests, developed predominately through a series of experimental burns in Jarrah Forest (Gould *et al.* 2008, 2011) The project generated a detailed understanding how fuel structural attributes and age affected fire behaviour. A key outcome was the pair of Dry Eucalypt Forest Fire Models (Cheney *et al*. 2012), which predict rate of spread from line ignitions. The study documents significant positive correlations between rates of fire spread and fuel hazard scores over the fuel ages examined, which ranged from 2 to 22 years. Relationships between fuel age, bark hazard and the density of firebrands (i.e., spotting) were also demonstrated. These results support using fuel treatments to reset fuel hazard scores and thereby reduce the rate of spread, amount of spotting and intensity of subsequent wildfire. Reconstructions of the Waroona fire that occurred January 2016 further demonstrated a relationship between long-unburnt jarrah forest, extreme fire behaviour and an ember shower that destroyed the town of Yarloop and killed two people (McCaw *et al.* 2016, Peace *et al.* 2017).

These results provide detail on the mechanisms underpinning previous findings that the annual frequency and extent of wildfire in the Warren region over a 50-year period decreased when fuel management practices increased the fraction of the forested landscape to <6 years since fire (Boer *et al*. 2009). The Western Australian approach to wildfire risk management through prescribed burning has been described in a series of papers and book chapters (Burrows and McCaw 2013; McCaw 2013; McCaw and Burrows 2020) and subsequently developed into a risk-based framework based on potential wildfire intensity under 95th percentile weather conditions (Howard *et al*. 2020). This framework identifies a suggested fire return interval and fraction of landscape with fuels under a fire intensity threshold for major fuel types (including dry and wet Eucalypt forests) and four fire management zones. These zones are defined on the basis of distance from settlements and critical infrastructure. Studies elsewhere (e.g., Gibbons *et al*. 2012) examining factors associated with house losses in wildfires show the benefits of concentrating fuel management activities closer to assets requiring protection. Florec *et al*. (2020) assessed costs and benefits of undertaking prescribed burning with varying proximity to urban interfaces, finding that prescribed burning close to settlements is most effective but generates a considerable expense that supports a mixed strategy to balance economic efficiency and risk mitigation in Western Australia.

Three major longer term studies examining interactions between fire regimes and species responses reported findings in the past decade. Burrows *et al*. (2019) analyse whether plant community richness changes relative to varying fire frequency and season over a 30-year experiment replicated across ‘dry’ and ‘moist’ jarrah forest sites. While they describe compositional drift, the study found no species were lost as a result of the fire treatments, and neither low to high fire frequency nor autumn to late spring treatments affected the number of understory species present. In a different study, Pekin *et al*. (2012) found a similar result, noting also that frequently burnt plots did have lower shrub richness and abundance.

A series of studies comparing an experimental application of mosaic burning within a Jarrah – heathland landscape (Burrows et al. 2021) examined persistence of a fire-sensitive shrub, *Banksia quercifolia* (Burrows and Middleton 2016), cryptogams (Wills *et al*. 2018; Ward *et al*. 2017), and birds (Wills *et al*. 2020). These studies complement a previous series examining fire regime effects on community composition across a range of sites with varying fire intervals in Western Australian forest ecosystems include Burrows (2008), Burrows *et al*. (2008) and Wittkuhn *et al*. (2011). Collectively, these papers demonstrate the resilience of jarrah forest ecosystems to contemporary fire regimes and identify biological indicators that can guide managers in implementing fire regimes that will be ecologically sustainable in the long run.

In addition to these studies of broad fire regime effects, studies have examined influence of varying wildfire intensity on tree survival (Etchells *et al*. 2020; McCaw and Middleton 2015) community composition (Wardell-Johnson *et al*. 2017), and of fire season on seed and seedling survival and establishment (Miller *et al*. 2021; Tangney *et al*. 2020). Research examining fire regime interactions with southwest forest species include studies of quokkas (Bain *et al*. 2016) and understorey shrubs and small trees (Chia *et al*. 2015; Burrows 2013; Nield *et al*. 2016). Bradshaw *et al*. (2018) sought to review the of impacts of management fire regimes on native species persistence in SW forests broadly. However, this work speculates on the impacts of a 6-year fire interval on species persistence when fire intervals across southwest forests in fact average 13.5 years (total area of fire in the DBCA estate averages 7.4% per year [DEC, DPAW Annual reports – 2010/2011 to 2019/2020]; 100/7.4 = 13.5 year mean interval). The review also discusses the impact of these intervals in relation to the needs of species from the much drier wheatbelt region where typical return intervals are longer still.Research on interactions between fire intensity and thinning found bole and crown damage in regenerating karri and jarrah stands was less likely when prescribed fire was applied to unthinned stands, although stem diameter was the greatest determinant of bole damage post-fire (Bishop 2015).While the impacts of climate change on fire likelihood have not been explicitly studied in Western Australia’s forests, a number of strong modelled and conceptual inferences have been published. For instance, a study of tall wet eucalypt forests across Australia, including Karri forest in the SW Furlaud *et al*. (2021) identified the importance of climatic constraints on fire weather and the availability of fuels to burn, suggesting ongoing drying and warming will make these forests susceptible to increasing fire frequency. Similarly, examining areas impacted by drought-induced forest die-off in the Northern Jarrah Forest, Ruthrof *et al*. (2016) predicted that rate of fire spread could be 30% greater due to a combination of increased fuel and altered microclimate conditions. A key conceptual advance arising from Western Australian fire research is the fire interval squeeze model (Enright *et al*. 2015), which identifies three climate change processes that combine to tightly constrain plant persistence in fire prone ecosystems: increased frequency of fire due to changed weather and drought conditions; decreased fecundity due to poor conditions for growth and seed production, and; decreased seedling survival and establishment rates in the post fire environment. Burrows and Middleton (2016) document some support for the second process in *Banksia quercifolia*. This species lives around the edges of wetlands and damp areas within the jarrah forest mosaic. The issue of increasing drying of peat and organic soil areas, makes these Banksias, and the broad peat community also more vulnerable to burning.

Since the last silvicultural guidelines review, Fire Management Information Notes (FMINs) have been written or updated for *Geocrinia* frogs, the quokka, mallefowl, ground parrot, geophytic plants, organic soils, the Tingle forest, granite outcrops, and the southern Forest and shrubland mosaic. These tools provide advice to fire managers on the knowledge of the responses and requirements of sensitive species or groups to fire and varying fire regime.

Introduced Predators

The European red fox (Vulpes vulpes) and cat (Felis catus) are considered the principal driver in most of Australia’s mammal extinctions and ongoing declines since settlement by Europeans (e.g. Abbott et al. 2014; Woinarski et al. 2014; Doherty et al. 2017; Radford et al. 2018; Woinarski et al. 2019). Effective mitigation of the impact of introduced predators is, therefore, critical to the conservation of much of native terrestrial vertebrate fauna in the southwest forests as it is elsewhere across Australia.
Toxic meat baits have been the most extensive and effective broadscale method for reducing the densities and impacts of the introduced red fox (Vulpes vulpes) on vulnerable Australian native fauna (Marlow et al. 2015a; Orell 2004; Reddiex et al. 2006; Robley et al. 2014; Saunders and McLeod 2007)). The toxin used (sodium fluoroacetate, FCH2CO2Na, branded ‘1080’) is particularly effective for targeting introduced vertebrates in southwestern Australia where the native fauna has a naturally evolved tolerance (e.g. Twigg et al. 2003). While broadscale control of feral cats has been more challenging than fox control, baiting is still recognised as the most effective method currently available (Lohr and Algar 2020; Woinarski et al. 2019). However, experimental trials of the Eradicat bait (designed to target feral cats) indicate that the current operational protocols for its use in the southern jarrah forest will be ineffective, with 0.1% of baits being eaten by feral cats by no more than 12% of the cats that visited bait locations (Wayne et al. In review). While locating baits closer to surface water features and on roads improves baiting opportunities, the gains are not considered sufficient to be an effective control method in this environment (Wayne et al. in prep). Eradicat baiting trials in karri forest associated with timber harvesting activities (Bain et al. 2021) also had a low rate of bait removal by cats. In both studies, bait interference by non-target species was a major factor in reducing the opportunities for cats to take a bait. In the karri study however, there was a substantial reduction in cat and fox activity associated with the baiting in the treatment site but not the control site. While other factors may account for these reductions (e.g., introduced predators being attracted elsewhere in the landscape), it is also possible that the reduction may have occurred indirectly through secondary poisoning. More well-designed baiting

trials are needed to verify whether reductions in introduced predators using Eradicat in karri harvest sites can be repeated and sustained. In both studies, bait interference by non-target species was a major factor in reducing the opportunities for cats to take a bait.

A paper by Read *et al.* (2016) explored novel alternative ideas for reducing the impact of cats on vulnerable prey. This includes using the natural advantages in the southwest, including the native fauna being more tolerant to sodium fluoroacetate (1080) than the introduced predators, and the opportunity for secondary poisoning of cats that predate on native fauna that have 1080 in their system. For instance, promoting populations of poisonous plants (e.g., *Gastrolobium*) or invertebrates that enable natural trophic pathways to sustain sublethal dosing of Trojan species could both protect vulnerable native prey and reduce the feral cat population. Denser ground vegetation, such as thickets of *Gastrolobium* and some melaleucas, also provide improved physical defences for native species preyed upon by introduced predators.

Field trials are currently underway to assess the effectiveness of Felixer grooming traps at reducing cat densities by more than 60% at a meso-spatial scale (~14,000 ha) in the southern jarrah forests, for the purposes of determining whether this may be an effective tool for vulnerable fauna conservation, particularly in high-value areas (A. Wayne pers. comm.).

Climate change

The southwestern region has experienced a distinct shift in climate since the mid-1970s, characterised by a chronic warming of +0.15^{o}C per decade, and a chronic reduction in early winter rainfall of 14% (1975-2004 compared with the mid-1900s-1974) (Hughes *et al.* 2003; Bates *et al.* 2008), and overall winter rainfall declining 30-50% from 1969 to 2012 (IOCI 2012). In addition to these chronic patterns, extreme climatic events have also occurred recently, with 2006 and 2010 experiencing acute drought, and early 2011 experiencing heatwave events (Ruthrof *et al.* 2018).

In response to a changing climate, a general decline trend in net primary production has been reported for southwestern Australia (Brouwers and Coops 2015). The rate of decline for the period 2000-2011 was an estimated -0.38 $Mg.C.yr^{-1}$, for the southwest region (37,042 km^2) which is likely to continue given climate change projections (Brouwers and Coops 2015). For the northern part of the southwest forest estate over a 100 km x 160 km area, and using Landsat imagery, Wallace *et al.* (2009) showed that the drier forests of the Intermediate Rainfall Zone showed widespread cover decline between 1989-2007. At a catchment scale, vegetation communities have also shifted over time with a decrease in rainfall, as shown in Mattiske (2012), who re-monitored Havel (1975) vegetation plots in the 31 Mile Brook Catchment. This type of study provided insights into how ecosystems will change with a drying trend. Mattiske (2012) noted decreases in certain tree species, especially those that prefer seasonally moist soils (e.g., *E. patens*, *Banksia littoralis* and *E. megacarpa*), and there seems to be a xeric shift within the proportion of some of the key tree species. Understorey species supported this pattern, with species preferring moister soils tending to decrease in abundance (*Babingtonia camphorosmae* and *Hypocalymma angustifolium*).

As well as general trends in vegetation change, sudden forest die-off associated with acute drought and heatwave events have also been recorded (Matusick *et al.* 2013; Ruthrof et al. 2015; Steel *et al.* 2019) in vulnerable, shallow soils with limited water holding capacity and in xeric areas (Brouwers *et al.* 2013; Andrew *et al.* 2015). Over

16,000ha of the Northern Jarrah Forest is estimated to have experienced die-off to some degree in 2011 following drought and heatwave events (Matusick *et al.* 2013). At the same time, other forest and woodland types in southwestern Australia, such as *E. gomphocephala* (Matusick *et al.* 2012), *Banksia attenuata*, and *B. menziesii* (Bader *et al.* 2014; Challis *et al.* 2016) also experienced die-off, as well as other vegetation types (Ruthrof *et al.* 2018; 2021). Forest die-off events such as the one documented in the Northern Jarrah Forest can have a broad range of flow-on effects such as increases in fine fuels and changes in potential fire behaviour (Ruthrof *et al.* 2016), changes in carbon dynamics (Walden *et al.* 2019), altered faunal habitat with open areas having greater temperature extremes (Dundas *et al.* 2021), outbreaks of wood boring insects (Seaton *et al.* 2015) and shifts in soil microbial communities (Hopkins *et al.* 2018).

Climate projections for the southwestern region indicate a continued reduction in winter rainfall and warming in the coming decades (Andrys *et al.* 2017), with implications for hydrology and ecology. The area of *E. marginata* forest predicted to fall below 600 mm yr^{-1} rainfall by 2030 increases from 1.3% for a low severity scenario to 5.1% for a high severity scenario, which equates to 73,000 ha of forest below the threshold limit for the current distribution of Jarrah Forest (Maher *et al.* 2010). The area of Karri Forest predicted to fall below 900 mm annual rainfall by 2030 increases from 0.1% for the low severity scenario to 6.1% for the high severity scenario, which equates to an additional 9,800 ha of forest below the threshold limit for current distribution of Karri Forest (Maher *et al.* 2010). Earlier bioclimatic work by Gentilli (1948), who defined the Jarrah Forest-sustaining bioclimatic threshold to be rainfall of 800 mm yr^{-1} of, suggested that a difference from the mean of just 165 mm rainfall per annum would be significant enough to drive changes in the forest distribution across the southwest. Although a general shift in biodiversity reflective of a new rainfall regime is expected, the most immediate effect would be on stream biota and riparian zone vegetation, as well as biota on sites with shallower soils (Bradshaw 2015).

Hydrology and ecological thinning

The chronic downward trend in rainfall in the region has contributed to significant declines in groundwater levels and streamflows in the forest estate (Petrone *et al.* 2010; Hughes *et al.* 2012; Liu *et al.* 2019). In addition, past forest management has led to dense regrowth stands that utilise more water than old growth stands which has exacerbated the decline in groundwater levels and runoff (MacFarlane *et al.* 2010, Macfarlane *et al.*,2018). The jarrah forest is becoming increasingly susceptible to drought and heat stress (Matusick *et al.*, 2013; Ruthrof *et al.*, 2021). To restore diverse stand structure, to improve the health of remaining trees, and alleviate stress on riparian zones, ecological thinning in a highly targeted and nuanced way has been proposed. Ecological thinning has numerous impacts on hydrology that may promote a more resilient and biodiverse forest. These processes include decreased interception of rainfall, stand-level evapotranspiration, competition for water and water stress, as well as increased soil moisture, groundwater recharge, and streamflow (Ruprecht *et al.*, 1991; Molina & del Campo, 2012; Schenk *et al.*, 2020).

To examine the impact of silviculture and the conversion of forest to agriculture on hydrological processes more than 20 research catchments were established throughout the jarrah forest in the 1970s and ‘80s (Bari and Ruprect, 2003). This involved the establishment of weirs for monitoring streamflow as well as numerous groundwater wells. Surprisingly, there has been no long-term monitoring of the largest component of the water balance, evapotranspiration. With a focus then on forestry and water yields experimental thinning was conducted just south of Dwellingup at the research catchment Yarragil 4L in 1983 and more recently in 2019 and at catchments Yarragil 4X and Yarragil 6C in 2001. In Yarragil 4X mechanical thinning comprised a reduction in basal area from 33 m^2/ha to 24 m^2/ha, in 6C basal area was reduced from 32 m^2/ha to 17 m^2/ha while in 4L basal areas were modified from 35 m^2/ha to 11 m^2/ha in 1983 and 25 m^2/ha to 12 m^2/ha in 2019. Despite the modest thinning at Yarragil 4X in 2001, groundwater levels continued to decline at a rate of ~3.5 m/decade whereas at Yarragil 4L, thinning lead to a prolonged increase in streamflow and a significant slowing in the rate of groundwater decline for more than 15 years post thinning (Stoneman, 1993; Kinal & Stoneman, 2011). The data logging infrastructure was upgraded at the Yarragil catchments in 2020, along with automated groundwater logging in 2021. While the streams all flowed in 2021 on the back of high winter rainfall it is too early to assess the changes to streamflow and groundwater levels in response to the recent thinning at Yarragil 4L.

Kinal and Stoneman (2012) showed that groundwater had disconnected from the stream zone at 4X leading to a significant shift in the runoff generation mechanism and reduction in annual stream flows. Catchments in the northern and southern jarrah forests which developed saturated zones around streams from higher groundwater levels tended to have moderately higher salinity, more sustained flows and an amplified contribution from fresher shallow flows during higher rainfall years (Grigg and Kinal 2020). In the Dwellingup research catchments, a declining groundwater contribution to streamflow is evidenced by freshening streamflow. There are risks that thinning conducted in the wrong areas may bring saline groundwater closer to the surface and increase the risk of stream salinization (Ruprecht & Schofield 1991).

Soil depth and its properties may also be critical controls on the success and/or impacts of thinning. Geophysics surveys at drought impacted and unimpacted sites by DBCA have shown that the drought impacted sites had bedrock within 8 m of the surface whereas the unimpacted sites had deep pallid-zone clays to at least 30 m (unpublished). The lateritic soils in the Jarrah Forest tend to have high infiltration rates (Ruprecht & Schofield, 1993). The lateritic soils have also been described as containing microporosity at a range of scales up to ~1 m^2 which promoted deep and rapid infiltration (Ruprecht and Schofield 1993). Wu *et al.* (2021) suggested that the decay of tree roots following thinning further increased preferential water flow. The soils of the forest therefore have the potential to store sufficient winter rainfall through to the end of summer if the soils are sufficiently deep. Therefore, detailed maps of the depth to bedrock, derived from airborne geophysics, may be a key component in identifying areas for which thinning could lead to increases in resilience to drought. Other potential impacts to soil hydraulic properties by thinning have not yet been studied in detail, such as the role of the thinning methodology on soil compaction, trends and changes to soil water repellence, and soil temperatures.

Aquatic ecosystems

Aquatic invertebrates and water physico-chemistry were monitored at 51 sites throughout the south-west forests between 2005 and 2011 and reported on by Pennifold and Pinder (2011). Generally, these sites are downstream of, rather than within, areas subject to timber harvesting and planned burning, as the aim is to monitor broader effectiveness of forest management rather than local impacts. The sampling protocol used is based on the Australian River Assessment Scheme (AusRivAS) and a variety of biotic measures are used to assess the degree of disturbance. Of the 51 sites, 16 had an average rating of 'significantly impaired' (AusRivAS B band) and eight were classed as 'severely impaired' (C band). A few sites were rated as 'extremely impaired' (D band) in some years but no site received an average D banding across the sampling period. All of the severely impaired sites were in jarrah forest and were either saline, had reduced flows or local disturbance. Sites with an overall rating of significantly or severely impaired were mostly in the northern Jarrah Forest (north of Dwellingup) and in the drier eastern forests. The level of impairment was not directly related to the percentage of the catchment subject to timber harvesting or burning. Most cases of impairment could be attributed to low rainfall or limitations of the AusRivAS model. These results suggest that current harvesting and planned burning regimes are sufficient to protect water quality and invertebrate biodiversity in forest streams. Twenty of these sites, rated as being in reference condition for much of the 2005-2011 period and spread across the south-west forests and both State Forest and the conservation estate, were resampled in 2013 and 2016. Results suggested these sites had not declined in condition relative to the 2005-2011 period. These same data were used to analyse compositional patterning in the south-west forests and representation of stream invertebrates in the conservation estate by Pennifold *et al.* (2017). Proportional protection of ecological environments (scaled by riverine invertebrate taxa) was found to vary between 20% and 30%, being higher in southern parts where more land has been allocated to reserves and less in northern and inland parts, noting that the more eastern parts of the forest were not as well sampled by the project. Surveys have shown that the few large swamps in the Jarrah Forest retain significant aquatic invertebrate diversity, though these are all within the conservation estate (Cale 2020; Cale and Pinder 2020; Pinder *et al.*, 2004).

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