Vulnerability of Forests in South-West Western Australia to Timber Harvesting Under the Influence of Climate Change

Expert Panel Report

Department of Environment and Conservation

2009

Department of Environment and Conservation
Our environment, our future

Prepared for the Director Sustainable Forest Management, Department of Environment and Conservation by Deirdre Maher, Lachie McCaw and Colin Yates.

Acknowledgements
The authors would like to acknowledge the support provided by:
1. Pat Collins, Graham Loewenthal and Mark Gibb, Forest Management Branch;
2. Tony Mennen and Erin Newton, Forest Policy and Practices Branch; and
3. Belinda Newman, Science Division.

Reference details
The recommended reference for this publication is: Department of Environment and Conservation 2009, Vulnerability of forests in South-West Western Australia to timber harvesting under the influence of climate change. Expert Panel Report, Department of Environment and Conservation.

Department of Environment and Conservation
17 Dick Perry Avenue
Technology Park, Western Precinct
Kensington, Western Australia 6151
Telephone (08) 9334 0300
Facsimile (08) 9334 0498
Website: www.naturebase.net
Email: info@dec.wa.gov.au

Cover *Eastern jarrah forest near Collie*

Table of Contents

1 Executive summary

This report has been prepared at the request of the Director of Sustainable Forest Management to address the potential implications of climate change for timber harvesting in native forest ecosystems in multiple use State forests in south-west Western Australia (SWWA). The report briefly describes relationships between climate and forest ecosystems in SWWA, the expected magnitude and rate of change of climate for the region, and the potential impacts of climate change on the health and productive capacity of forest ecosystems. The vulnerability of major forest ecosystems in SWWA to climate change is assessed by comparing the extant distribution of each ecosystem under historical mean annual rainfall (period 1961-90) with the distribution expected in 2030 for annual rainfall simulated using CSIRO global climate model projections for low, medium and high severity climate scenarios. The area of jarrah forest predicted to fall below 600 mm annual rainfall by 2030 increases from 1.3% for the low severity scenario to 5.1% for the high severity scenario which equates to an additional 11 200 ha of multiple use State forest and 61 870 ha of conservation reserve below the threshold limit for current distribution of jarrah forest. 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 7160 ha of multiple use State forest and 2630 ha of conservation reserve below the threshold limit for current distribution of karri forest. Spatial patterns of change in distribution are examined for landscape conservation units which identify areas of similar underlying geology, landform, soil and climate at a scale appropriate to management planning and operational practice. The effect of additional water stress resulting from increased evaporation is examined for the jarrah forest ecosystem. Measures identified in the Forest Management Plan 2004-13 and associated guidance documents that may either reduce the likelihood or consequence of risk through enhancing the natural resilience of forests are described, and additional measures that could be applied to further enhance resilience are identified. Vulnerability to climate change is linked to developmental stage at stand, landscape and whole-of-forest scales and will therefore vary in both time and space. Recommendations are made in relation to the need for: additional monitoring of forest health, biodiversity and silvicultural outcomes; review of regeneration practices for mixed karri jarrah marri stands; development of a guidance document for salvage harvesting and post-fire rehabilitation in the event of extensive high intensity bushfires; and further research into the eco-hydrology for major forest tree species.

2 Terms of reference

The Expert Advisory Group will provide a report to the Director of Sustainable Forest Management by 30 June 2009 addressing:

- the likely impact of climate change to 2030 on the forests and associated ecosystems of the south west of Western Australia;
- the factors affecting vulnerability of the forests and associated ecosystems of the south west of Western Australia;
- the identification of areas of vulnerability in relation to climate change in State forest in the area covered by the Forest Management Plan 2004-2013;
- the risks posed by this vulnerability in terms of timber harvesting during the period 2010 – 2013;
- the documentation of measures that are already in place that mitigate any such risks posed by this vulnerability; and
- additional measures that could be taken to mitigate any such risks.

3 Introduction

Evidence for warming of the Earth's climate continues to accumulate with observations of global increases in average air and ocean temperatures, widespread melting of snow and ice, and rising average sea level. It is very likely that most of the increase in global temperatures since the mid 20th century is due to human activities which have elevated concentrations of greenhouse gases in the global atmosphere. Continued greenhouse gas emissions at or above the current rates are very likely to cause further warming and changes to the Earth's climate system (IPCC 2007).

Increasing evidence shows that anthropogenic climate change is causing changes to the phenology, distribution and abundance of plants and animals as well as affecting species interactions and a multitude of ecosystem processes (Parmesan 2006; Fischlin *et al.* 2007; Rosenzweig *et al*. 2008). Reducing or stabilizing greenhouse gas emissions may slow global warming, but past emissions will continue to contribute to unavoidable warming and related changes in climate and impacts on biodiversity for more than a century at least (IPCC 2007). Because of this inevitability, Governments and communities are beginning to address the causes of climate change by reducing greenhouse gas emissions, and at the same time implement strategies to adapt to the unavoidable impacts of climate change.

The native forest ecosystems of south-west Western Australia (SWWA) harbour considerable biodiversity much of which is endemic. Forest ecosystems in the region also provide a number of important services including provision of water and timber, and sequestration and storage of carbon, and have a number of important cultural and recreational values for the people of Western Australia.

Management of forest ecosystems in SWWA is guided by the Forest Management Plan 2004-2013 (FMP) (Conservation Commission 2004). The FMP has adopted the slightly modified, Montreal Criteria of sustainability as the framework within which to identify management actions in line with the principles of ecologically sustainable forest management. The criteria are: the conservation of biodiversity, the maintenance of productive capacity, the maintenance of ecosystem health and vitality, the conservation and maintenance of soil and water, the maintenance of the contribution forests make to the global carbon cycle, the maintenance of heritage, and the maintenance of socio-economic values.

SWWA has experienced a decline in rainfall since the mid 1970s and increases in temperature. These changes can in part be explained by anthropogenic climate change and further declines in rainfall and increases in temperature are projected (Bates *et al*. 2008). Such changes have the potential to significantly affect biodiversity, ecosystem vitality and health, forest productivity, ecosystem services and amenity in SWWA forest ecosystems and forest management planning will need to prepare for the impacts of inevitable climate change.

This report provides a preliminary assessment of the vulnerability of forests in SWWA to timber harvesting under the influence of climate change.

4 Relationship between climate, other environmental factors and forest ecosystems in south-west Western Australia

4.1 Climate and environment of the south-west

In south-west Western Australia (SWWA) open forests with a potential mature height >10 m are mostly restricted to areas where mean annual rainfall exceeds 600 mm. The occurrence of forest vegetation aligns broadly with the Darling Botanical District which includes the Swan Coastal Plain, Jarrah Forest and Warren biogeographic regions (Thackway and Cresswell 1995, Wardell-Johnson *et al*. 1997). Prior to European settlement in 1826 forests occupied about 4.2 million ha of SWWA but clearing for agricultural and urban development has reduced the current area of forest to 2.6 million ha (Conservation Commission of Western Australia 2004). More than 90% of remaining forest is on public land vested in the Conservation Commission of Western Australia and managed by the Department of Environment and Conservation as multiple use State forest and conservation reserve including national park and nature reserve according to the FMP. Forests dominated by jarrah (*Eucalyptus marginata*) occupy 1.6 million ha and are the most commercially important. Other widespread dominant forest trees include marri (*Corymbia calophylla*), karri (*Eucalyptus diversicolor*), wandoo (*Eucalyptus wandoo*) and tuart (*Eucalyptus gomphocephala*) (Bradshaw *et al*. 1997).

The climate of SWWA is Mediterranean with cool moist winters and warm dry summers (Gentilli 1989). Western parts of the jarrah forest along the Darling escarpment receive have historically received mean annual rainfall in excess of 1200 mm due to orographic uplift of moist air masses associated with winter cold fronts approaching from the Indian Ocean. Areas within about 50 km of the south coast also have historically received more than 1000 mm of annual rainfall, with a narrow coastal zone between Northcliffe and Walpole receiving up to 1400 mm per annum. The eastern margin of the forest corresponds broadly with the 600 mm isohyet (Fig. 1) although this boundary is now defined artificially by agricultural clearing. Rainfall is strongly seasonal with more than 80% of the annual total recorded during the six consecutive wettest months (May-October) and mean monthly rainfall below 25 mm during the three driest months (December-February) for all except a narrow zone adjacent to south coast. Summer pan evaporation (December-February) ranges from above 800 mm at the northern extent of the forest to below 400 mm in southern areas experiencing milder temperatures, more cloudy days and greater chance of summer rainfall (Gentilli 1989). Maximum temperatures regularly exceed 35°C during the summer, while winters are cool (<15°C) and nights may be frosty occasionally dropping to -5°C. For much of the year prevailing winds over SWWA are generally easterly and of moderate strength (20-30 km h^{-1}) with southerly sea-breezes extending up to 50 km inland. Strong north-west to westerly winds are associated with winter storms, with development of summer heat troughs and with decaying tropical cyclones below latitude 30°S (McCaw and Hanstrum 2003). Lightning storms occur between October and March in most years providing a potential source of ignition for bushfires across widespread areas of forest.

The forests of SWWA occur on the southwestern margin (latitude 31-35°S) of an extensive plateau of Archean crystalline rocks associated with the Yilgarn craton (Churchward and Dimmock 1989). The plateau surface is undulating with crests ranging from 250-400 m above sea level (a.s.l) and swampy valley floors 50-100 m lower. Isolated summits representing the remnants of an older, higher land surface rise above the general level of the plateau to elevations of 500-600 m a.s.l. The Darling escarpment forms a distinct western boundary between the plateau and the 20-50 km wide Swan Coastal Plain. At the southern end of the escarpment the Blackwood plateau extends westwards at an elevation of 80-150 m a.s.l. on soils derived from sedimentary parent materials which are prone to waterlogging in winter. Other major landforms dominated by forest vegetation include southern swampy plains derived from marine sediments in the Warren region and limestone karst associated with the Leeuwin-Naturaliste ridge.

Vegetation patterns within the forest landscape are determined by topography, moisture availability, soil fertility and soil texture (Havel 1975 a and b, Bell and Heddle 1989, Havel and Mattiske 2000). Vegetation complexes characterised by particular associations of overstorey and understorey species have been mapped at 1:250 000 scale for the majority of the area covered by the FMP except the Swan Coastal Plain. Mapped vegetation complexes provide a systematic basis for examining the likely distribution of dominant plant species, and are also useful for assessing habitat characteristics and the potential occurrence of vertebrate fauna (Christensen and Liddelow 2005). More than 300 vegetation complexes occur within the FMP area. Landscape Conservation Units (LCU) provide a higher order grouping of vegetation complexes with similar underlying geology, landform, soil and climate at a scale appropriate to management planning and operational practice (Mattiske and Havel 2004). Lands managed by DEC within the FMP area occur in 29 LCUs, with some areas on the Swan Coastal Plain and South Coast outside the area covered by the LCU classification.

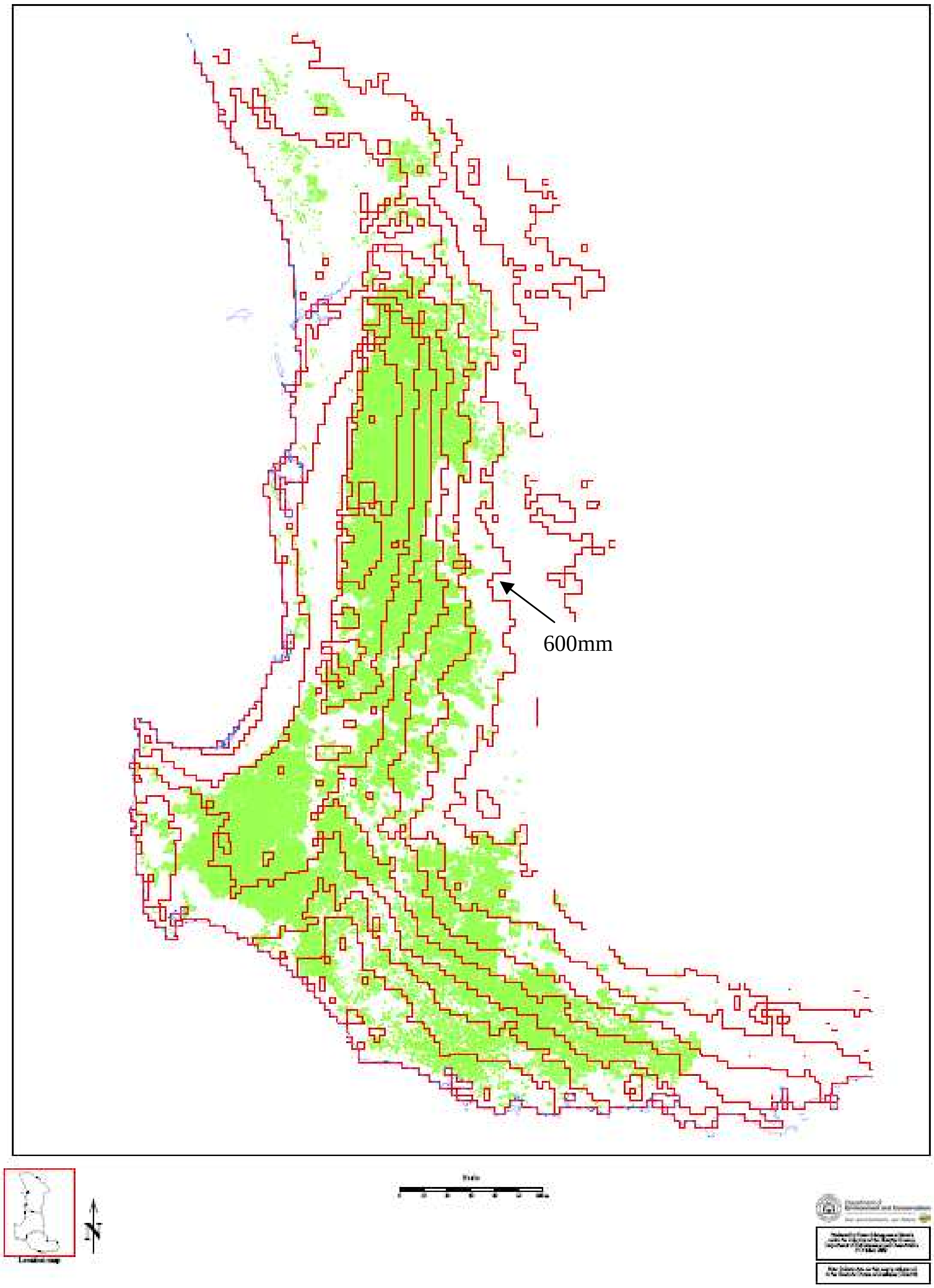

Figure 1 **Jarrah forest distribution on DEC-Managed land showing historical (1961-1990) average annual rainfall.**

Despite the relatively subdued nature of the topography and the prolonged isolation imposed by the aridity of the surrounding landscape the forests of SWWA support a rich biodiversity and represent a significant component of a globally significant hotspot of plant biodiversity and endemism (Myers *et al*. 2000, Hopper and Gioia 2004). Many species of plants and animals are rare or poorly known, and a number have ancient Gondwanan linkages that stretch deep into evolutionary time (Yates *et al*. 2003). While the forests of SWWA are notable for the dominance of a few species across much of the landscape, the associated understorey and intermediate tree strata are species rich and exhibit a high turnover of taxa across short distances in response to variation in site characteristics (Havel 1975 a & b, Havel and Mattiske 2000). Sampling conducted as part of the FORESTCHECK monitoring project (Abbott and Burrows 2004) has also revealed similar patterns of high species turnover for invertebrates.

4.2 Recent (post-1750) distributions of major forest tree species

Jarrah, marri, wandoo, tuart, flooded gum (*E. rudis*), bullich (*E. megacarpa*), yate (*E. cornuta*) and swamp yate (*E. occidentalis*) have recent natural distributions extending well beyond (>50 km) the area covered by the FMP (Table 1). The natural distributions of these species generally extended into lower rainfall areas in the Avon-Wheatbelt that have been extensively cleared for agriculture with the result that distributions have become diffuse and highly fragmented, and in some cases species have vanished almost entirely from parts of the landscape where they once occurred. Eastern limits of distribution of some typical forest species have been investigated in relation to climate and landform (Lange 1960), and outlying populations have been examined in an attempt to understand the reasons for their unusual occurrence (Abbott 1984). Within the broader forest matrix a number of eucalypts also have disjunct distributions associated with particular landform and soil characteristics including the Darling escarpment (eg. wandoo, *E. laeliae*), lateritic breakaways and stony ridges (eg. *E. accedens, E. astringens*), granite outcrops (*E. virginea*), humus podsol soils (*E. ficifolia*), leached infertile sands (*E. staeri*) and fertile loams in tributary valleys of the Warren River (*E. cornuta*). Forest dominant eucalypts largely confined to the FMP area include karri, blackbutt (*E. patens*), and the red, yellow and Rates tingle (*E. jacksonii*, *E. guilfoylei*, *E. brevistylis*). The relative dominance of a limited number of overstorey species in the forests of SWWA has tended to overshadow the high species richness of eucalypts in the Darling Botanical District with estimates of the total number being more than 100 taxa and an additional number of hybrids (Wardell-Johnson *et al*. 1997).

Table 1. **Distribution of characteristic forest eucalypts of SWWA in relation to the area covered by the Forest Management Plan 2004-13.**

Distribution extends >50 km outside FMP area	Distribution largely confined to FMP area except for a limited number of outliers	Distribution entirely confined to FMP area
C. calophylla	*E. diversicolor*	*E. brevistylis*
E. accedens	*E. ficifolia*	*E. guilfoylei*
E. cornuta	*E. patens*	*E. jacksonii*
E. decipiens		*E. laeliae*
E. gomphocephala		
E. marginata		
E. megacarpa		
E. occidentalis		
E. rudis		
E. staeri		
E. virginea		
E. wandoo		

Jarrah typically occurs on infertile soils derived from highly weathered lateritic profiles, which may be weathered to a depth of 30 m or more. Surface horizons are rich in oxides of iron and aluminium and have low concentrations of extractable and total elements (Churchward and Dimmock 1989). Soils can be broadly grouped into sandy gravels, siliceous sands, earths, non-calcareous loams and duplex soils. The relative dominance of one overstorey species across such a large area makes the jarrah forest somewhat unusual amongst open eucalypt forests. Marri and jarrah often occur together on upland sites with the proportion of marri increasing in more mesic southern forests. Other eucalypts commonly associated with jarrah include blackbutt, flooded gum and bullich on fertile moist sites, wandoo on the drier northern and eastern margins of the forest, and Albany blackbutt on infertile leached sands in the south–eastern range of jarrah.

Karri has a relatively continuous distribution throughout wetter parts (>900 mm annual rainfall) of the catchments of southward draining river systems in the Warren IBRA region (Donnelly, Warren, Shannon, Deep, Frankland, Bow, Denmark, Hay). Karri also occurs in the upper reaches of Long Gully which drains into the Blackwood River near Nannup. Within this broad occurrence, the distribution of karri is closely linked to more fertile red earth soils and yellow podsols, with some occurrence on sands in moist sites adjacent to the south coast. At the western end of this range there is a significant outlying population of karri on limestone derived soils at the southern end of the Leeuwin Naturaliste ridge. Outlying populations occur of karri at Rocky Gully, on moist coastal sands south of Albany, at Mt Manypeaks and at the Porongurup Range. Churchill (1968) attributed persistence of these outliers to reliability of summer rainfall or in the case of the Porongurup population to soil moisture storage being supplemented by run-off from adjacent granite outcrops.

4.3 Paleo-climate and paleo-distribution of forest eucalypts in SWWA

Climatic oscillations have long been a feature of SWWA, although essentially modern vegetation types, a Mediterranean-type climate and fire regimes may have existed in parts of SWWA since the mid-Tertiary c. 30 Million years ago (Hopper and Gioia 2004). Elements of rainforest flora including *Nothofagus* and araucarian/podocarp conifers persisted until about 2.6 Mya with pollen records indicating that these taxa co-existed with obvious post-fire opportunists and in landscapes experiencing a frequency of fire not dissimilar to the present day (Atahan *et al*. 2004, Hopper and Gioia 2004). Insights provided by recent reviews of phylogeography are consistent with contraction to, and expansion from, major refugia during mid-Pleistocene climatic oscillations (Byrne 2008). Responses to climate change appear to have involved persistence and resilience rather than large scale migration. There is some knowledge of genetic structuring within populations of dominant forest eucalypts including jarrah (Wheeler and Byrne 2006), karri (Coates and Sokolowski 1989) and wandoo (Dalmaris and Byrne pers. comm.) which provide a basis for interpreting past shifts in distribution and composition of forests in response to climate oscillations.

Pollen studies (palynology) at a number of sites in SWWA suggest that the relative dominance of overstorey eucalypts has varied considerably during the Holocene (Churchill 1968, Newsome and Pickett 1993, Pickett and Newsome 1997, Dodson and Lu 2000, Dortch 2004). Pollen evidence also shows that the distributions of some species, including karri and *E. decipiens*, have changed by tens of kilometres or more over the mid to late Holocene; for example Churchill (1968) found karri pollen in mid Holocene swamp deposits on the western side of Lake Muir, more than 10 km further north east than the extant distribution of karri in this area. Churchill (1968) used data on the ratio of karri/marri pollen to infer periods of relatively wetter and drier climates during the Holocene, although his conclusions have been challenged by Newsome and Pickett (1993). Dortch (2004) used evidence from charcoal and vertebrate sub-fossil remains at Tunnel Cave on the Leeuwin-Naturaliste ridge to argue that post-glacial maximum increases in rainfall around 10 000 years ago led to dense karri forest encroaching on the cave, making it unsuitable for continued persistence of the black flanked rock wallaby (*Petrogale lateralis*); this species now has a widespread distribution in semi-arid Western Australia and in arid Central Australia. These studies clearly illustrate that the composition and distribution of plant and animal communities have been responsive to past oscillations in climate and environmental conditions in SWWA over time scales that are relatively brief in a geological context.

Western Australia has a short record of weather observations with few locations having more than a century of reliable data. Climate proxies such as tree rings and speleotherms are extending the historical climate record and generating useful insights into climate variability in the region. Recent tree ring studies have demonstrated the potential for re-constructing climate variability over periods of several hundred years (Cullen and Grierson 2008) although much more work is need to establish which tree species may provide reliable records, particularly in higher rainfall areas of SWWA, and to create cross-dated master chronologies. The study by Cullen and Grierson (2008) at Lake Tay in the transitional rainfall zone identified that since 1655 AD rainfall had exhibited cycles of relatively dry periods lasting 20-30 years interposed with wetter periods lasting up to 15 years. Speleotherms may provide a climate analogue for coastal areas including the Leeuwin Naturaliste ridge although their potential has yet to be fully demonstrated (Treble 2004).

5 Global climate change: magnitude and rates

The evidence for warming of the Earth's climate continues to accumulate with observations of global increases in average air and ocean temperatures, widespread melting of snow and ice at the poles and on glaciers, and rising average sea level. Global average temperatures have increased 0.74˚C from 1906 to 2007, with the years 1995-2005 ranking among the warmest since instrumental observations of temperature began in 1850 (Rahmstorf *et al*. 2007, Steffen *et al*. 2009).

The IPCC Fourth Assessment Report (2007) concluded that it is *very likely* that most of the increase in global temperatures since the mid 20th century is due to human activities which have elevated concentrations of greenhouse gases in the global atmosphere.

Continued greenhouse gas emissions at or above the current rates are very likely to cause further warming and changes to the Earth's climate system including changes to wind patterns, precipitation patterns and the frequency of extreme events. Reducing or stabilising emissions will slow global warming, but past emissions will continue to contribute to unavoidable warming, changes to the climate system and sea level rise for more than a century (IPCC 2007).

5.1 Recent climate change in South-west Western Australia

Changes in the climate of SWWA, the factors that may have caused the changes, and projections of future climate for the region have been investigated in detail by the Indian Ocean Climate Initiative (IOCI, see Bates *et al*. 2008 for a detailed description of the Initiative's key findings). In summary, over recent decades, the climate of SWWA has been characterised by warming and drying. Since the 1970s, annual mean temperature has increased at a rate of about +0.15℃ per decade with increases occurring in all seasons except summer, where cooling of about −0.1℃ per decade has occurred. Perhaps more significantly, since the mid-1970's there has been a reduction in early winter (May to July) rainfall. The mean totals over the period from 1975 to 2004 are close to 14% less than the means for the period from the mid-1900s to 1974. A major feature of the decline has been the absence of the very high rainfall years which were relatively common throughout much of the previous century. While there has been little decline in late winter (August to October) rainfall, the most recent data shows that winter half-year rainfall is still relatively low (Bates *et al*. 2008). A major impact of this has been a reduction of surface water and stream flow in the region's water catchments with associated declines in levels of groundwater held in unconfined aquifers (IOCI 2005a & b, Kinal 2009).

Investigations of atmospheric circulation patterns using different methods at different spatial scales consistently point to changes in large scale circulation and the frequency of synoptic states being responsible for the observed decline in winter rainfall. At the hemispheric scale there has been a reduction in the strength of the sub-tropical jet stream over Australia and an associated reduction in the likelihood of synoptic disturbances developing over SWWA (Frederiksen & Frederiksen 2007). At the synoptic and local scales there has been a decline in the frequency of synoptic types associated with high rainfall and wet conditions and an increase in the frequency of synoptic types associated with dry conditions (Charles *et al.* 1999ab; Hope *et al*. 2006).

These changes can in part be explained by increases in the atmospheric concentrations of greenhouse gases (Hope 2006), but natural multi-decadal variability (Cai *et al*. 2005) and land clearing (Pitman *et al*. 2004) may also be contributing factors with the relative contributions of each remaining uncertain (Bates *et al*. 2008).

5.2 Projections of future climate in South-west Western Australia

The extended period of dry conditions in SWWA and the apparent link with the enhanced greenhouse effect, is forcing natural resource management agencies to prepare for an uncertain future. Whether the future holds a return to wetter conditions, continuing dry conditions or further drying is of utmost significance for the management of agriculture, biodiversity, forests and water resources (Bates *et al*. 2008; Morgan *et al*. 2008).

Global Climate Models (GCMs) are the principal tool for projecting future climates (GCMs, Randall *et al.* 2007). These are numerical representations of the physical processes and interactions between the Earth's atmosphere, oceans and land-surface. There are many GCMs in operation, each with different assumptions and parameterisations. As a consequence various GCMs display marked differences with respect to future climate projections. Similarly, because society may respond in different ways to climate change, the magnitude of future greenhouse gas emissions is unknown. To this end the IPCC (2000) developed a number of alternative emission scenarios (SRES markers) for use in forecasting. To derive a projection of future climate, a GCM is forced with a change in atmospheric chemistry prescribed by an emission scenario (Mackellar *et al.* 2007).

Projections of future climate generally utilise multiple models forced with multiple emission scenarios to specify the range of uncertainties. However, likelihoods of projected changes in climate attributes are rarely given (but see CSIRO 2007).

Regional projections of climate change for SWWA have been undertaken by IOCI using a range of GCMs and IPCC emission scenarios (Bates *et al*. 2008). Changes are relative to the average climate for the period (1960-1990). *All* models and *all* scenarios indicate increases in temperature and decreases in rainfall for the region by 2030 with the magnitude of the changes increasing later in the century. The magnitude of the projected rainfall changes for the SRES emission scenarios are between -2 and -20% by 2030 and between -5 and -60% by 2070. The projections also show a warming for the winter half-year of between +0.5 and +2.0℃ by 2030 and between +1.0 and +5.5℃ by 2070. For the summer half-year (November to April), increases in temperature are projected to reach between +0.5 and +2.1℃ by 2030 and +1.0 and +6.5℃ by 2070 (Bates *et al.* 2008).

Beyond changes in average climate conditions for the region, increases in the frequency of droughts, elevated maximum temperatures and longer-duration heat waves are also projected (IPCC 2007, CSIRO 2007).

The actual climate trajectory for SWWA will depend on how quickly the world curbs greenhouse gas emissions. Currently and significantly, global emissions are exceeding the IPCC's most pessimistic highest emission scenario (Raupach *et al*. 2007, Steffan *et al*. 2009). CO_2 concentration in 2009 is 385 ppm and increasing at a rate of c. 3.3% per annum. If emissions continue to follow this trajectory projected global average surface warming by the end of the century relative 1980-1999 is expected to be between 2.4 and 6.4℃ with a best estimate of 4℃ (IPCC 2007).

Stabilisation emission scenarios and their resultant global warmings may be more relevant for policy and adaptation than the SRES emission scenarios, since they describe outcomes based on various emissions reduction programs which may be adopted to reduce the magnitude of future climate change (Pittock 2009). The eventual stabilised global warmings from stabilised emission scenarios are reported in IPCC (2007) and can also be found in Pittock (2009). These scenarios outline the magnitude of the mitigation and adaptation challenge. A scenario which aims to limit CO_2 concentrations at between 350 and 400 ppm and eventual global average surface warming above pre-industrial to between 2.0-2.4℃, would require greenhouse gas emissions to peak between 2000 and 2015, with a subsequent reduction in emissions of between 50 and 85% of 2000 levels.

6 Factors affecting the vulnerability of South-west Western Australia forest ecosystems to climate change

Climate exerts a profound effect on broad patterns of forest biodiversity in SWWA,and there is strong evidence that present day patterns and adaptations reflect the effects of past climate oscillations (Main 1996). Projected future climate change driven by anthropogenic greenhouse gas emissions will affect SWWA forest species and ecosystems directly through changes in temperature, rainfall and the frequency of extreme climate events including heat waves and droughts, and indirectly through altering species interactions, fire regimes, stream flow and hydrology, and the nature and intensity of existing biodiversity threats.

However, the precise nature of impacts will be difficult to predict for a number of reasons. Firstly, as discussed above the magnitude and rate of global warming is uncertain; secondly the adaptive capacity and physiological tolerances of species, and thresholds of ecosystem resilience are generally poorly known; and thirdly, because ecosystems are made up of multiple interacting species and processes they can exhibit non-linear dynamics and surprising changes can emerge abruptly.

Unlike the northern hemisphere, observed impacts of climate change on WA biodiversity are very limited and largely restricted to the conspicuous avifauna. All studies are correlative, and consequently, it is not always easy to distinguish climate effects from other human pressures. However, the limited data available indicates that terrestrial species and ecosystems in WA are being affected. Changes in ocean temperatures and climatic conditions along the WA coast have contributed to the southerly extension in the breeding distribution of some tropical seabirds (Dunlop 2001). In SWWA the decline in rainfall is associated with changes to the seasonal movement of bird species, particularly waterbirds (Chambers 2008), and together with groundwater extraction, has lowered water levels in cave streams, threatening aquatic communities (English *et al.* 2003).

In a global context, Mediterranean climate biomes are acknowledged as having very high biodiversity values and being particularly vulnerable to climate change. Recent analysis drawing on downscaled results from 23 atmospheric-ocean general circulation models has suggested that SWWA is likely to be more profoundly impacted than most other Mediterranean biomes, with significant contraction of Mediterranean climate conditions expected due to warming and drying in the transitional rainfall zone of woodlands and shrublands (Klausmeyer and Shaw 2009). Limited climate change impact models predict that the ranges of many species in SWWA will contract and some species may lose all range, but there are many uncertainties (Fitzpatrick *et al*. 2008; Yates *et al*. 2009 ab, Gibson *et al.* in prep.). Some species have persisted *in situ* through multiple sequences of climate change in the Pleistocene and their current distributions may not reflect their climate tolerances (Byrne 2009, Yates *et al*. 2007). If contraction is the primary response of many species, then identifying refuges will be critical. Warmer and drier conditions in SWWA may have a large impact on the region's many narrowly distributed endemic species, because, with the exception of the Stirling Ranges which rise to 1109 m a.s.l., the region is of low relief offering limited scope for altitudinal migration into montane refuges. Many relictual mesothermic lineages are restricted to the coolest and wettest climate zones on the south coast and these climate zones may disappear (Hopper *et al.* 1996). The following sections identify key climate related factors that may affect forest biodiversity in SWWA.

6.1 Climatic water stress

Because rainfall and summer water deficit are strong determinants of the distribution of major forest ecosystems in SWWA (Gentilli 1989, Beard 1991), climate change may have a significant impact on their composition and productivity. Projected warmer temperatures, reduced rainfall and declining groundwater levels for the region will affect the availability of water to plants exposing them to increased risk of climatic water stress. Beyond changes in the mean climate conditions, increases in the frequency of droughts, elevated maximum temperatures and longer-duration heat waves might be expected to further exacerbate water-stress.

Climate induced water stress may directly cause tree mortality through irreversible disruption of water columns (xylem cavitation) in leaves and stems. When trees are subject to water stress they can reduce the risk of xylem cavitation through closing leaf stomata, but this comes at a cost because it prevents CO_2 diffusion into leaves, thereby reducing photosynthesis. In trees that are able to reduce the risk of xylem cavitation through stomatal closure, chronic water stress over long periods may still result in death through carbon starvation (McDowell *et al*. 2008).

The physiological responses of plants to increases in the atmospheric CO_2 concentration may offset declines in rainfall. Elevated CO_2 has been shown to have significant impacts on plant performance, albeit with considerable variation in the responses of different species, functional types and ecosystems (Ainsworth & Long 2005; Körner 2003). One of the reported effects of elevated CO_2 appears to be a reduction in stomatal conductance (Ainsworth & Long 2005; Wand *et al.* 1999), resulting in increased soil moisture beneath plants (Niklaus *et al.* 1998) Model simulations of vegetation distribution through the last glacial maximum and pre-industrial era indicate that, during periods of higher atmospheric CO_2 concentrations, grasses and trees were able to establish with much lower rainfall than was possible under lower CO_2 conditions (Crucifix *et al.* 2005). However, detailed predictions of elevated CO_2 effects on plant performance are difficult because they appear to be taxon specific and strongly interactive with soil type and climate (Körner 2003; Spinnler *et al.* 2002; Bradley & Pregitzer 2007; Fischlin *et al.* 2007).

Plants in SWWA forest ecosystems have a wide array of life-history characteristics, physiological and morphological features for coping with summer water deficit and regulating leaf temperatures (Cowan 1981; Gaff 1981; Pate & Dixon 1981; Florence 1981). Through various combinations of these attributes there is a spectrum of drought tolerances among species and these may allow species to persist as the climate dries and becomes warmer. Inevitably, there will be tolerances and thresholds where plants can no longer persist as the climate dries, but these are poorly understood for most species in SWWA.

Access to water at depth is important for the survival of a number of species in SWWA forest ecosystems. On deep unconsolidated sands found on the Swan Coastal Plain *Banksia* plants form a deep root system which can access sources of soil water stored at depth including groundwater in shallow unconsolidated aquifers (<9m, Zencich *et al*. 2002; Groom 2004). Recent research shows that a number of *Banksia* spp. are more or less dependent on this groundwater to survive the annual summer dry season with both obligate and facultative phreatophytes being prevalent (Groom 2000; Zencich *et al*. 2002; Froend & Drake 2006). Recharge of aquifers is primarily dependent on annual rainfall and declines in groundwater levels have occurred with declining rainfall since the mid 1970's. There are no published *in situ* drought experiments measuring *Banksia* spp. response to separation from the water table, but the co-incidences of excessive groundwater abstraction, low annual rainfall and aquifer recharge, and a short period of high summer temperatures caused extensive death of *Banksia* spp. in woodlands with water stress being the primary cause (Groom *et al*. 2000). Similarly, jarrah has deep vertically descending roots that penetrate fissures in the laterite and access water held deep in the highly weathered pallid zone beneath (Florence 1981). The volume of water available to jarrah at depth in the soil profile may buffer trees against already observed declines in rainfall, stream flow and groundwater levels, but again little is known about the thresholds in these systems. The eventual consequences of continued declining rainfall, stream flow and groundwater for jarrah are unknown.

Regional scale die-offs of forest trees in response to global change-type droughts have been reported for most continents, and from diverse forest types and climatic zones (Allen 2009, Breshears *et al*. 2009). In SWWA, changes in plant species composition of *Banksia* woodland communities on the Swan Coastal Plain have been linked to declining groundwater levels resulting from reduced winter rainfall and groundwater extraction (Heddle 1981, Groom *et al*. 2000). Localised drought deaths of a range of tree species have also been observed on shallow soils around granite outcrops during protracted dry periods in 1993/94 and 2004/05 (McCaw, personal observation) and since 2006 (Batini 2009). Regional scale declines in the condition of *E. gomphocephala* and *E. wandoo* woodlands have been observed, but evidence for decline being a consequence of a drying climate and associated climatic water stress remains equivocal. This is in part because there were no long-term field observations of plant water relations and stress prior to and culminating in the mortality, and also because mortality appears to involve multiple, interacting factors including climatic water stress, pathogens and insect pests, making the determination of a single cause after the event difficult (Barber and Hardy 2006, Wandoo Recovery Group 2006). The inherent drought tolerance of much of the vascular flora of SWWA, including the dominant forest trees, is likely to also mask the effects of changing climate to a greater extent than in some other environments. Determining the drought tolerances of SWWA forest ecosystem species and their ecohydrological domains will be particularly important for understanding their vulnerability to projected warming and drying of the climate.

6.2 Pests and pathogens

Increased water stress and carbon starvation may reduce the resistance of forest trees to insect and disease outbreaks (MacDowell *et al*. 2008). Furthermore changes to climate conditions may also directly affect the population dynamics of forest insects and pathogens, and some massive outbreaks of tree-killing forest insects have been attributed to climate factors (Raffa *et al*. 2008). Perhaps the most dramatic example is the provincial wide die-off of lodgepole pine (*Pinus contorta*) in British Columbia (Konkins & Hopkins 2009). This tree is the preferred host for the mountain pine beetle (*Dendroctonus ponderosae*). At endemic levels the beetle breeds in weakened large-diameter trees. At epidemic levels, it attacks and kills healthy trees over large areas. Extreme cold winter temperatures kill the beetle and play a major role in regulating its abundance. Higher winter temperatures in British Columbia in the last decade have led to increased survival of the mountain-pine beetle. In addition changes to patch dynamics in the forest have led to widespread development of even-aged stands of lodge-pole pine which have come to maturity providing the beetle with ideal habitat. The combination of higher winter temperatures and large areas of contiguous mature forest have resulted in the largest beetle epidemic recorded in the history of British Columbia (Aukema 2008, Raffa *et al.* 2008).

Current knowledge of the risks posed by possible changes in the dynamic between pests/pathogens and SWWA forest ecosystems as a consequence of climate change is in its early stages. The moth *Uraba lugens* (gum leaf skeletoniser) is a well known defoliator of eucalypts in Australian forests. Winter temperatures are an important regulator of whether one (univoltine) or two (bivoltine) generations form each year. Population modeling shows that in the southern jarrah forest the moth is usually univoltine, but following two consecutive warm winters, populations can switch to a bivoltine cycle. Consecutive warm winters are thought to have initiated a severe outbreak of the moth in the southern jarrah forest during 1982-88 causing extensive canopy defoliation to over 300,000 ha of forest (Strelein 1988, Farr 2002). Stress is also considered to reduce the resistance of trees to the moth. Projected warmer and drier conditions for SWWA could mean that populations produce two generations per year more frequently and that trees may be less resistant potentially leading to the increased incidence of outbreaks (Farr 2002). The incidence and extent of damage in karri forest caused by cerambycid borers is higher on dry sites in close proximity to patches of jarrah/marri, and in smaller patches of regenerated karri typical of margins of the current karri forest distribution (Abbott *et al*. 1991, Farr *et al*. 2000). Increased moisture stress resulting from declining rainfall and greater summer evaporation may lead to greater severity of borer impact on marginal sites, negatively affecting potential wood quality, tree longevity and overall stand health.

In SWWA 2,284 species are considered susceptible and 800 species highly susceptible to the plant pathogen *Phytophthora cinnamomi* (Shearer *et al.* 2004). The extent and impact of disease is greatest in higher rainfall parts of the jarrah forest adjoining and immediately east of the Darling escarpment, reflecting the interaction of site characteristics, soil moisture availability and disturbance history (Shearer and Tippet 1989). Disease impact is generally less in drier eastern parts of the forest, and *P. cinnamomi* has not become widely established in areas of SWWA where historic annual rainfall is below 500 mm, although the pathogen will persist in water gaining sites where annual rainfall is as low as 400mm. How the disease may respond to predicted further declines in annual rainfall will depend on the seasonal distribution of rainfall and in particular the occurrence of extreme rainfall events. Reduced average annual rainfall, resulting in drier soils and declining deep groundwater levels and perched aquifers would tend to result in conditions less favourable for the pathogen. However, episodic heavy summer rainfall events associated with ex-tropical cyclones and other synoptic types moving across the region provide ideal conditions for the spread of *P. cinnamomi* and are linked with the widespread death of susceptible species (MacDougall 1996; Chris Dunne pers. comm.). Such events can lead to intensification of existing infestations through temporary water-logging and downslope movement of inoculum on an extensive scale. Increases in the frequency of these events associated with predicted increase in cyclone and monsoonal activity in north-western Australia may facilitate the spread of the pathogen.

6.3 Altered fire regimes

Fire plays an important role in nutrient cycling, net primary productivity and ecosystem dynamics in SWWA forest ecosystems (Burrows & Wardell-Johnson 2003). The frequency, season, scale and intensity of fires, collectively known as the fire regime will have consequences for a range of forest values. Fire regimes are a function of climate, topography, vegetation and fuels, and sources of ignition. With the exception of topography all of these factors could be modified by global climate change.

High intensity fires that kill a large proportion of mature trees (i.e. stand replacement) may initiate post-fire succession pathways different to those experienced in past decades. Widespread deaths of mature jarrah and marri following the 2003 Mt Cooke fire was unprecedented in recent times, and may represent the most severe event within the past several centuries (Burrows 2009). Frost, drought or heavy grazing impacts following severe fires can adversely affect survival of juvenile plants and potentially result in long term changes to species composition, stand level dominance and productivity, and carbon storage potential of forests.

Some research has investigated the effect of global climate change on fire weather in Australia (Lucas *et al*. 2007, Pitman *et al*. 2007). Most modelled scenarios predict an increase in the severity of burning conditions as quantified by the annual cumulative forest fire danger index (ΣFFDI), and in the risk of extreme fire danger events (Williams *et al*. 2001, Pitman *et al*. 2007, Lucas *et al*. 2007).

No detailed investigations of the potential impacts of climate change on fire weather have been undertaken for SWWA forest ecosystems, although Williams *et al*. (2001) modelled changes in forest fire danger under enhanced CO_2 conditions for Katanning which is at the eastern margin of occurrence of jarrah and marri, and representative of wandoo woodlands in the Great Southern. However some trends may be inferred from work undertaken in Southeast Australia where climate is also projected to become warmer and drier (Lucas *et al.* 2007). They found that by 2020 ΣFFDI increased by between 0-4% for low-severity climate change scenarios and 0-10% for high-severity scenarios. For 2050 the increase was between 0-8% for low-severity scenarios and 10-30% for the high-severity scenarios. The FDI values masked much larger changes in the number of days with significant fire risk. By 2020 the number of 'very high' (FFDI >25) fire danger days increased between 2-13% for low severity scenarios and 10-30% for high-severity scenarios. For 2050, the increase was between 5-23% for the low-severity scenarios and 20-100% for the high-severity scenarios. The number of 'extreme' fire danger days (FFDI >50) increased 5-25% by 2020 for low-severity scenarios and 15-65% for high-severity scenarios. For 2050, the increase was between 10-50% for the low-severity scenarios and 20-100% for the high-severity scenarios (Lucas *et al*. 2007). Applying a similar analytical approach to SWWA could provide valuable insights into the potential impacts of climate change on fire danger.

Other climatically determined components of the fire environment in SWWA include lightning storms which provide a significant source of fire ignition, and the incursion of tropical cyclones down the west coast south of latitude 30°S (McCaw and Hanstrum 2003), The relationship between seasonal climate indicators, synoptic patterns and the incidence of lightning ignition has not been investigated systematically although there is sufficient data to undertake a preliminary analysis. Tropical cyclones are significant because they can generate wind speeds far in excess of those associated with more typical synoptic patterns and have contributed to several extensive bushfire outbreaks in SWWA during the 20th century, notably in 1937 and 1978. An increase in the occurrence of extra-tropical cyclones could have profound effects on the frequency and severity of extreme fire weather events in SWWA (Hanstrum 1990). Recent research has also suggested that atmospheric stability indices generated using mesoscale meteorological models are useful in identifying potential fire behaviour and may provide additional information beyond that provided by conventional fire danger indices calculated from surface level weather observations (Mills and McCaw in press).

7 Response to climate change

Mitigation and adaptation are both essential for coping with anthropogenic climate change. Mitigation is human intervention to reduce the sources of or enhance the sinks of greenhouse gases and thus to reduce the extent of climate change. Adaptation refers to any action that reduces the vulnerability of natural and human systems against actual or expected climate change effects. Mitigation is a global process that can only be achieved through international cooperation, whereas adaptation is essentially a local challenge (Pittock 2009).

Unmitigated climate change would, in the long term, be likely to exceed the capacity of natural, managed and human systems to adapt (IPCC 2007). Current evidence suggests that to avoid the worst effects of climate change, levels of atmospheric CO_2e will need to be stabilized at 445-490 ppm (IPCC 2007), Achieving this stabilization scenario requires global greenhouse gas emissions to peak no later than 2015, and for net global emissions to be reduced by between 50 and 85% by 2050 (relative to 2000). Even then there is more than a 50% likelihood that global temperature increases will exceed 2˚C, and there is a 5% likelihood that temperature increases will exceed 4˚C (Ramanathan & Feng 2008). Achieving this global stabilization target will require strong and urgent international action and cooperation. Nations will have to move quickly to reduce greenhouse gas emissions and remove carbon from the atmosphere and store it in vegetation and soils (Wentworth Group 2009).

Managing natural carbon sinks effectively is an important component of Australia's response to anthropogenic climate change. Australian native forests sequester more greenhouse gases than they emit and therefore help to offset Australia's contribution to global greenhouse gas emissions. Managed native forests offset abut 5.5% of total national greenhouse gas emissions in 2005 (Montreal Process Implementation Group for Australia 2008). The FMP recognizes that forests play a major role in contributing the regulation of global carbon cycles and seeks to sustain the contribution of forests in SWWA to carbon cycling. The Department is planning work to quantify the stocks of carbon in native forest ecosystems with the aim of reducing uncertainties associated with modeling carbon cycles in native forests.

Reducing or stabilizing greenhouse gas emissions may slow global warming, but past emissions will continue to contribute to unavoidable warming and related changes in climate for more than a century at least (IPCC 2007). With further inevitable climate change expected, and obvious signs of difficulties in achieving effective mitigation worldwide in the short term at least, adaptation to inevitable climate change will be necessary.

Predicting future effects of climate change on forest ecosystems is complex (see sections 5 and 6 above) and uncertainty needs to be incorporated into adaptation planning. A basic risk management approach can be used to identify areas where climate variables are predicted to change beyond the current range of conditions. However there is considerable uncertainty about how ecosystems will adapt to changing climate and the extent to which individual species may be vulnerable to change. The current distribution of forest ecosystems is also influenced by soils and competitive interactions between species, neither of which may be responsive to changing climatic variables, at least in the short to medium term.

In the absence of complete knowledge a precautionary approach is required. Management of forests to enhance resilience is advised together with targeted modelling and monitoring programs and adaptive management trials.

8 Preliminary climate change risk assessment for WA forests

This section presents a preliminary risk assessment of vulnerability to climate change for the main forest ecosystems (jarrah, karri, wandoo, tingle) in the area covered by the FMP. This area includes approximately 1.9 million ha of native forest managed by DEC of which slightly more than 1 million ha is multiple-use State forest available for timber production (Table 2). The LCU classification of Mattiske and Havel (2004) provides a basis to further divide each forest ecosystem into areas of similar underlying geology, landforms, soils and climate. Additional data on the occurrence of forest ecosystems by canopy cover class within each LCU is provided in Appendices 2-5.

The risk assessment process recognises the dominant role of moisture availability on the distribution of forest ecosystems based on the work of Gentilli (1989) and identifies areas within each LCU where annual rainfall is predicted to fall below threshold values that correspond with current distribution limits of each forest ecosystem. Historic records for the period 1961–1990 were used to define annual rainfall values that coincide with the current ecosystem distribution. Climate scenarios for the year 2030 were then used to identify areas where rainfall is predicted to decline below these limiting values (Appendix 1). For the jarrah forest ecosystem, a second component of risk is considered by examining changes in summer moisture stress for those LCUs where rainfall becomes limiting.

Table 2 Area statement of forest managed by DEC in the FMP area.

Landscape Conservation Unit	DEC-Managed Land	Multiple Use State Forest	% LCU in Formal Conservation Reserves
Blackwood Plateau	267,630	183,070	32%
Blackwood Scott Plain	8,050	1,760	78%
Central Blackwood	73,790	54,810	26%
Central Jarrah	293,220	243,110	17%
Central Karri	64,980	52,910	19%
Collie Wilga	51,830	32,550	37%
Dandaragan Plateau	180	0	100%
Darkin Towering	2,330	0	100%
Eastern Blackwood	7,870	900	89%
Eastern Dissection	33,750	12,190	64%
Eastern Murray	26,460	16,730	37%
Frankland Unicup Muir	24,510	50	100%
Margaret Plateau	13,770	1,230	91%
Monadnocks Uplands Valleys	89,380	64,680	28%
North Eastern Dissection	13,620	0	100%
Northern Karri	104,280	76,670	26%
Northern Sandy Depression	78,650	38,350	51%
Northern Upper Collie	112,240	59,520	47%
Northern Upper Plateau	26,510	7,060	73%
North Western Dissection	32,960	9,240	72%
North Western Jarrah	91,800	68,910	25%
Redmond Siltstone Plateau	28,220	20	100%
Strachan Cattaminup Jigsaw	64,950	46,720	28%
Southern Dunes	6,850	10	100%
South Eastern Upland	46,780	7,140	85%
Southern Hilly Terrain	81,910	610	99%
Southern Karri	87,650	22,920	74%
Southern Swampy Plains	40,930	1,640	96%
Yornup Wilgarup Perup	111,920	59,100	47%
No LCU-Swan Coastal Plain	28,070	5,990	79%
No LCU-South Coast	660	0	100%
Total	1,915,750	1,067,890*	44%

*Note includes Informal Reserves

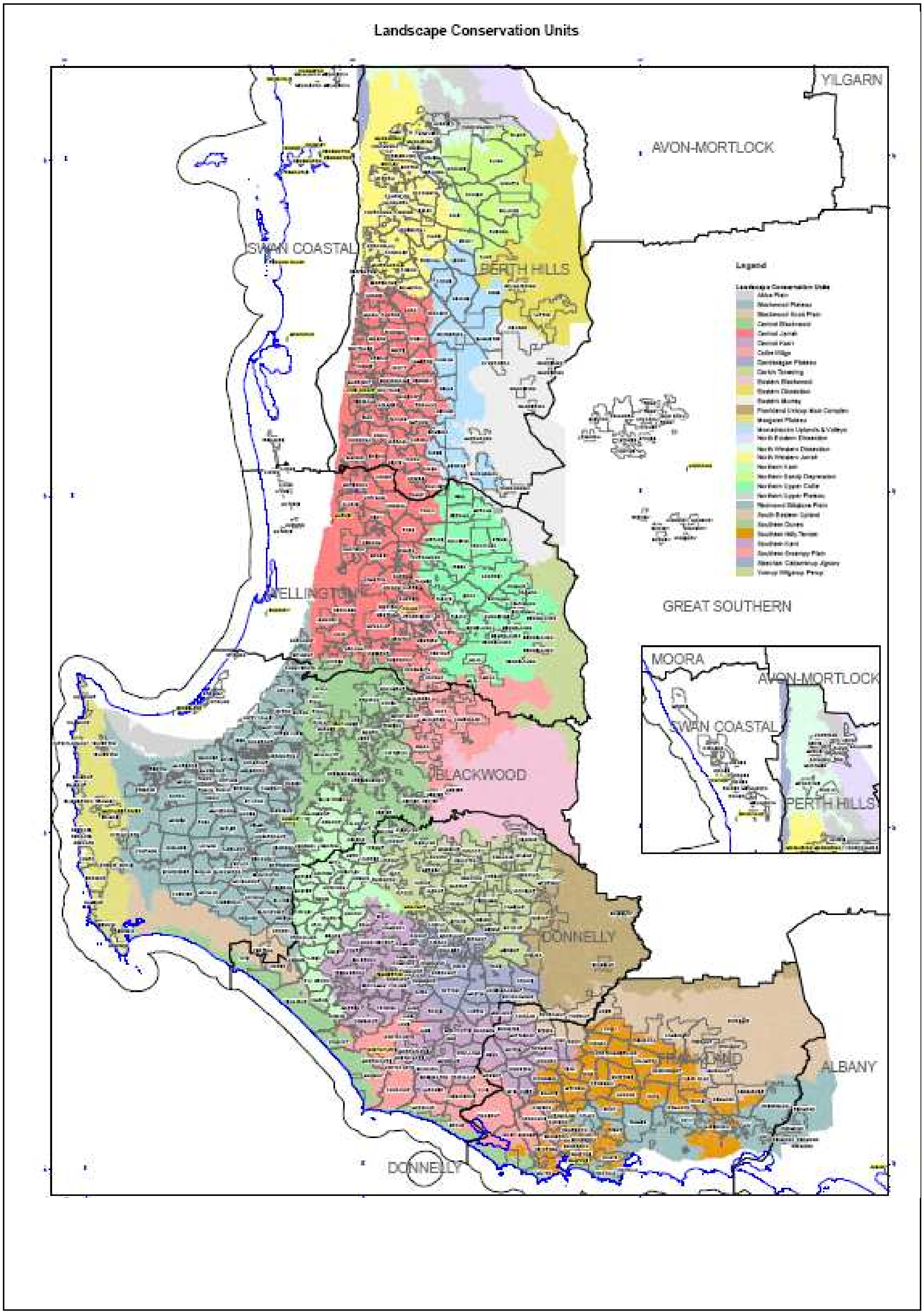

Figure 2. **Forests managed by DEC within the FMP area showing Landscape Conservation Units, forest blocks and DEC administrative boundaries.**

8.1 Climate data

Uncertainties about GCMs and future emissions and climate sensitivity to greenhouse gas forcing contribute to uncertainties in predicting the impacts of climate change. Recent guidelines on forecasting and climate change risk assessment recommend using multiple GCMs and emission scenarios to specify the full range of uncertainties in future climate (CSIRO 2007).

For the purposes of considering the potential impacts of future climate change on the major forest ecosystems of SWWA we consider three climate change severity scenarios that encompass the range of uncertainties in future climate for the region. The three scenarios have been used in recent assessments of the potential impacts of climate change on the distributions of key species in SWWA ecosystems, including *Banksia* (Yates *et al*. 2010) and quokka (*Setonix brachyurus*) (Gibson *et al.* in prep.)

Mean monthly minimum temperature (T_{min}), maximum temperature (T_{max}), precipitation (P_{total}), and areal potential evapotranspiration (*ET*) anomalies for three SRES emission scenarios (B1, A1B and A1FI), three climate sensitivities (low, medium and high) and three time periods (2030, 2050 and 2070) were provided for eight global climate models (GCMs) by CSIRO from their recent regional analysis of climate change in Australia (CSIRO 2007). The three SRES scenarios used represent in relative terms low, moderate and high greenhouse gas emission futures. Descriptions of the SRES economic and social storylines associated with each of the scenarios can be found in IPCC (2007). The actual sensitivity of the climate greenhouse gas forcing is not perfectly known and there are a range of estimates determined from the observed record and proxies. The low climate sensitivity assumes a global warming of 1.7℃ for a doubling of CO_2 from 280 ppm to 560 ppm; the moderate climate sensitivity assumes a global warming of 2.6℃ for a doubling of CO_2 from 280 ppm to 560 ppm; the high climate sensitivity assumes a a global warming of 4.2℃ for a doubling of CO_2 from 280 ppm to 560 ppm. Native GCM resolutions were downscaled by CSIRO using linear interpolation to a standard 0.25° reso lution to produce patterns of change for each month and GCM.

For each GCM the average anomalies for monthly T_{min}, T_{max} and P_{total} for each combination of emission scenario, climate sensitivity and years were calculated for SWWA. Climate anomalies for the models were visually compared and a low-, medium- and high-impact model based on the relative severity of the average predicted anomalies chosen. Based on this three climate change severity scenarios were chosen. These were: (1) Low impact model MIROC-H (Centre for Climate Research, Japan) combined with the B1 emission scenario and low climate sensitivity (hereafter low-severity); (2) moderate impact model MIROC-M (Centre for Climate Research, Japan) combined with the A1B emission scenario and medium climate sensitivity (hereafter medium-severity); (3) high impact model CSIRO Mk 3.5 (CSIRO, Australia) combined with the A1FI emission scenario and high climate sensitivity (hereafter high-severity).

For the three climate change severity scenarios, the annual P_{total} and Summer (December, January, February) *ET* anomalies were converted from 0.25° to 0.025° grid cells using nearest neighbour resampling, which allocates the value of the larger cell to the smaller cells. The resampled anomaly grids were added to the historical 1961-90 average climate grids (0.025°) t o create the P_{total}, and *ET* surfaces for the three scenarios at 2030.

Historical climate (averaging period 1961-1990) was represented using average monthly precipitation (P_{total}) and average monthly areal potential evapotranspiration (*ET*) data layers provided by the Australian Bureau of Meteorology National Climate Centre. These data layers are generated through interpolation of mean monthly climate data from climate stations onto a 0.025° resolution grid for P_{total} and onto a 0.1° grid for *ET*.

8.2 Jarrah forest

8.2.1 Rainfall

Jarrah forest occurs in areas where the mean annual rainfall for 1961-1990 exceeds 600 mm, with occurrence beyond this threshold limited to open woodland formations and scattered outliers. Only

0.5% or 7,870 ha of the 1,579,390 ha of DEC-managed jarrah forest occur in areas where historic mean annual rainfall is less than 600 mm (Fig. 1.)

The area of jarrah forest predicted to fall below the threshold of 600 mm annual rainfall by 2030 under the three climate scenarios increases from 1.3% for the low severity scenario to 5.1% for the high severity scenario (Table 3 and Figure 3). This equates to an additional 11 200 ha of multiple use State forest and 61 870 ha of conservation reserve falling below the threshold for current jarrah forest distribution. Under the low severity scenario, the most extensive areas of multiple use State forest expected to fall below 600 mm rainfall occur in the Eastern Murray, Eastern Blackwood and Yornup Wilgarup Palgarup LCUs (Table 4). Medium and high severity scenarios result in significant expansion in the area below 600 mm rainfall for the Eastern Murray, Eastern Dissection and Northern Upper Collie. The extent of change within individual LCUs reflects both the projected change in rainfall, and the spatial occurrence of forest managed by DEC.

Table 3 Area of Jarrah Forest on DEC-Managed Land with rainfall less than 600 mm.

Climate Scenario	Conservation Estate	Multiple use State forest	Total DEC-Managed Land	Proportion of Total Jarrah Forest
Current (1960-1990)	7,530	340	7,870	0.5 %
Low-severity (2030)	17,680	3,220	20,900	1.3 %
Medium-severity (2030)	52,010	10,480	62,490	4.0 %
High-severity (2030)	69,400	11,540	80,940	5.1 %

Table 4 Area of jarrah multiple use State forest within each Landscape Conservation Unit with historic or projected rainfall less than 600 mm .

LCU Name	Historic (1960-1990)	Low-severity (2030)	Medium-severity (2030)	High-severity (2030)
Eastern Blackwood	90	830	830	830
Eastern Dissection	0	330	1,090	1,490
Eastern Murray	250	1,490	3,140	3,410
Frankland Unicup Muir	0	30	40	40
Monadnocks Upland Valleys	0	0	0	20
Northern Sandy Depression	0	0	20	20
Northern Upper Collie	0	170	4,830	4,970
South Eastern Upland	0	0	160	290
Yornup Wilgarup Perup	0	370	370	470
TOTAL	**340**	**3,220**	**10,480**	**11,540**

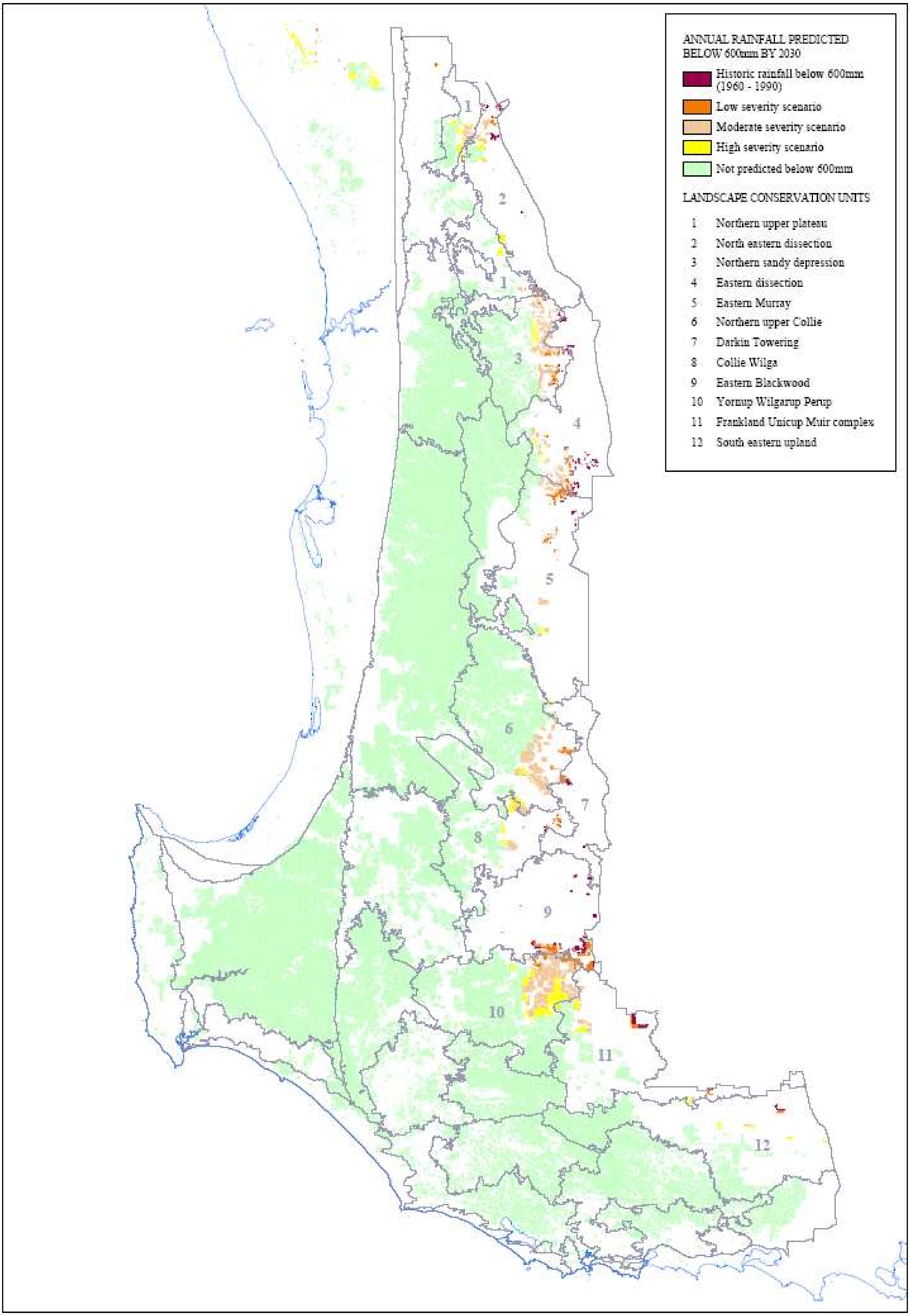

Figure 3 Jarrah forest on DEC-managed land highlighting areas with <600mm rainfall

8.2.2 Summer water stress

Evaporation reduces the total amount of water available for plant use. Gentilli (1989) observed that the distribution of jarrah forest is limited at its northern extent by 765 mm of summer pan evaporation. Where summer (DJF) pan evaporation exceeds 765 mm jarrah occurs as woodland or in outliers of mallee growth habit.

The impact of climate change on summer water stress is an important consideration for of jarrah forest ecosystems. However, there is uncertainty as to how pan evaporation may respond to climate change and recent analysis suggest that much of Australia including SWWA has experienced declining annual pan evaporation (Roderick and Farquar, 2004) possibly due to more cloudy days without rain.

The climate scenarios prepared by CSIRO all forecast increases in areal potential evapotranspiration values by 2030. Areal potential evaporation (ET) is the evapotranspiration that would take place under conditions of unlimited water supply from an area so large that the effects of any upwind boundary transitions are negligible and local variations are integrated to an areal average. This measure is different to pan evaporation but does provide an alternate measure of summer water stress that can be derived from the CSIRO modelled climate data.

Plotting the average values of both rainfall and areal ET in the same manner that Gentilli (1989) did for interpolated pan evaporation data indicates that the jarrah forest is currently limited to areas where the areal ET is below 540 mm (Fig. 4). This analysis does not take into account the influence of soil and other factors on forest distribution.

Higher severity climate change scenarios lead to a greater number of LCUs exceeding the limiting summer areal ET value of 540 mm, including the Eastern Dissection, North Eastern Dissection, Dandaragan Plateau, Northern Upper Plateau, North Western Dissection, Northern Sandy Depression and North Western Jarrah (Fig. 5). Increased summer water stress in these areas could result in a shift from forest to woodland structure. This effect is most pronounced effect for the Eastern Dissection and North Eastern Dissection units which are predicted to fall below current limiting values for both annual rainfall and summer evaporation. Both units are well represented in formal conservation reserves, with reservation levels of 64% and 100% respectively.

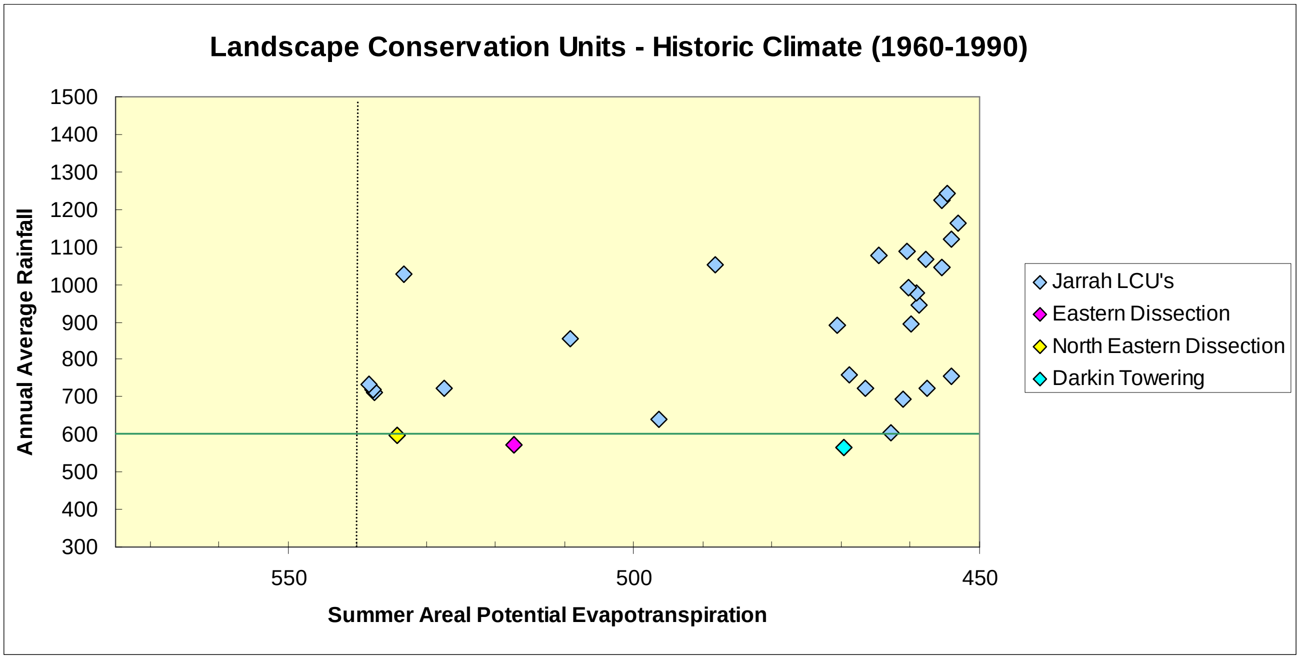

Figure 4. **Climatic definition of jarrah forest Landscape Conservation Units based on average annual rainfall and summer areal potential evaporation for historic climate values (1960-1990), following the approach of Gentilli (1989).**

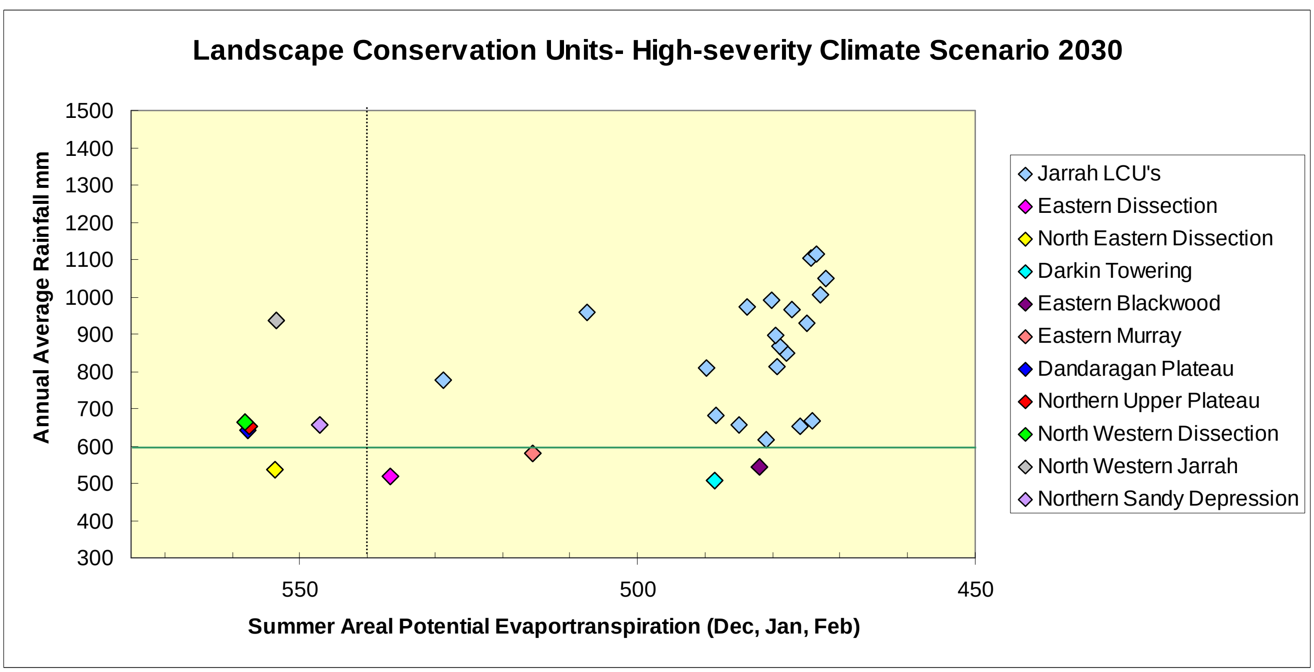

Figure 5. **Climatic definition of jarrah forest Landscape Conservation Units based on average annual rainfall and summer areal potential evaporation for the high severity climate scenario in 2030 following the approach of Gentilli (1989). Landscape Conservation Units that exceed threshold values associated with the current distribution of jarrah forest are identified by name.**

8.3 Karri Forest

All of the 159,320 ha of karri forest on DEC-managed land within the FMP area is confined to areas where mean annual rainfall for 1961-1990 exceeds 900 mm (Figure 6). Karri outliers do occur outside the current 900 mm isohyet on DEC-managed land at Porongurups and Mt Manypeaks and on private land at Rocky Gully and Albany.

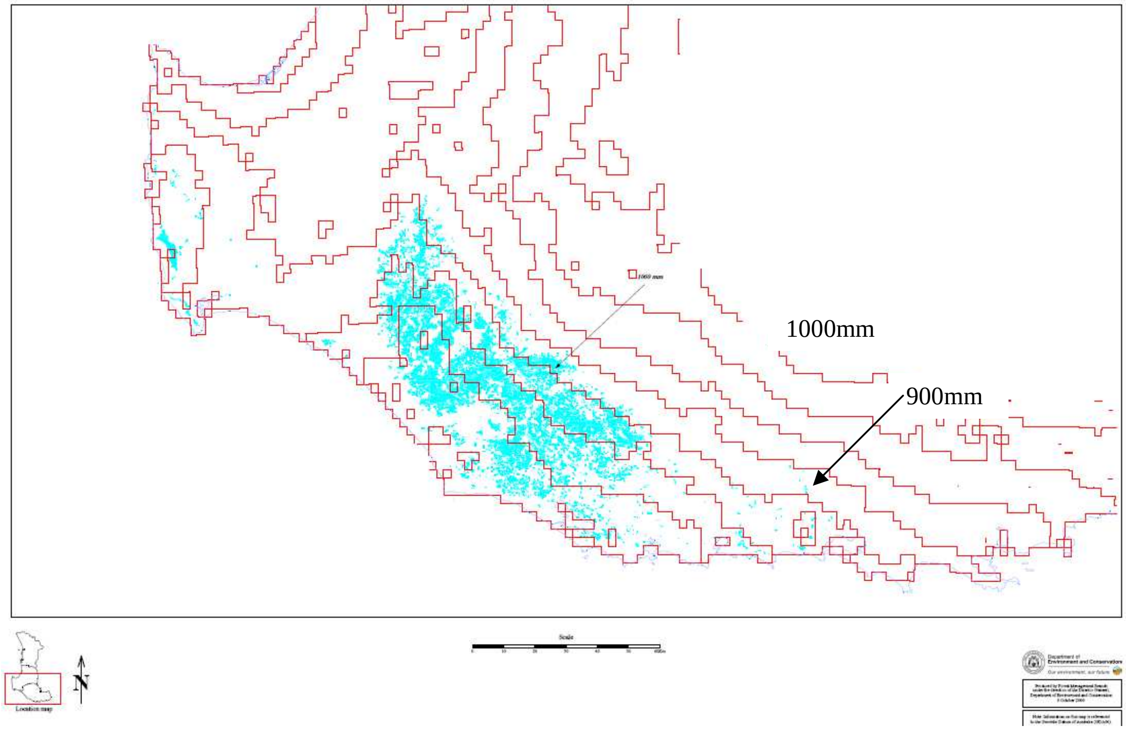

Figure 6 Karri forest distribution on DEC-Managed land within the FMP area showing historical (1961-1990) annual average rainfall

The area of karri forest predicted to fall below the threshold of 900 mm annual rainfall by 2030 under the three climate scenarios increases from 0.1% for the low severity scenario to 6.1% for the high severity scenario (Table 5 and Figure 7). This equates to an additional 7160 ha of multiple use State forest and 2630 ha of conservation reserve below the limit of 900 mm rainfall limit.

Under the low severity scenario, only a small area of karri multiple use State forest forest within the Strachan Cattaminup Jigsaw LCU is predicted to fall below 900 mm annual rainfall (Table 6). Medium and high severity scenarios result in significant expansion in the area below 900 mm rainfall for karri multiple use State forest in the Strachan Cattaminup Jigsaw, Northern Karri, Central Karri, Southern Karri and South Eastern Upland.

Table 5 Area of karri forest on DEC-Managed land with historic or projected rainfall less than 900 mm.

Climate Scenario	Conservation Estate	Multiple use State forest	Total DEC-Managed Land	Proportion of Total Jarrah Forest
Current (1960-1990)	0	0	0	0%
Low-severity (2030)	50	70	120	0.1%
Medium-severity (2030)	1,960	5,000	6,960	4.4%
High-severity (2030)	2,630	7,160	9,790	6.1%

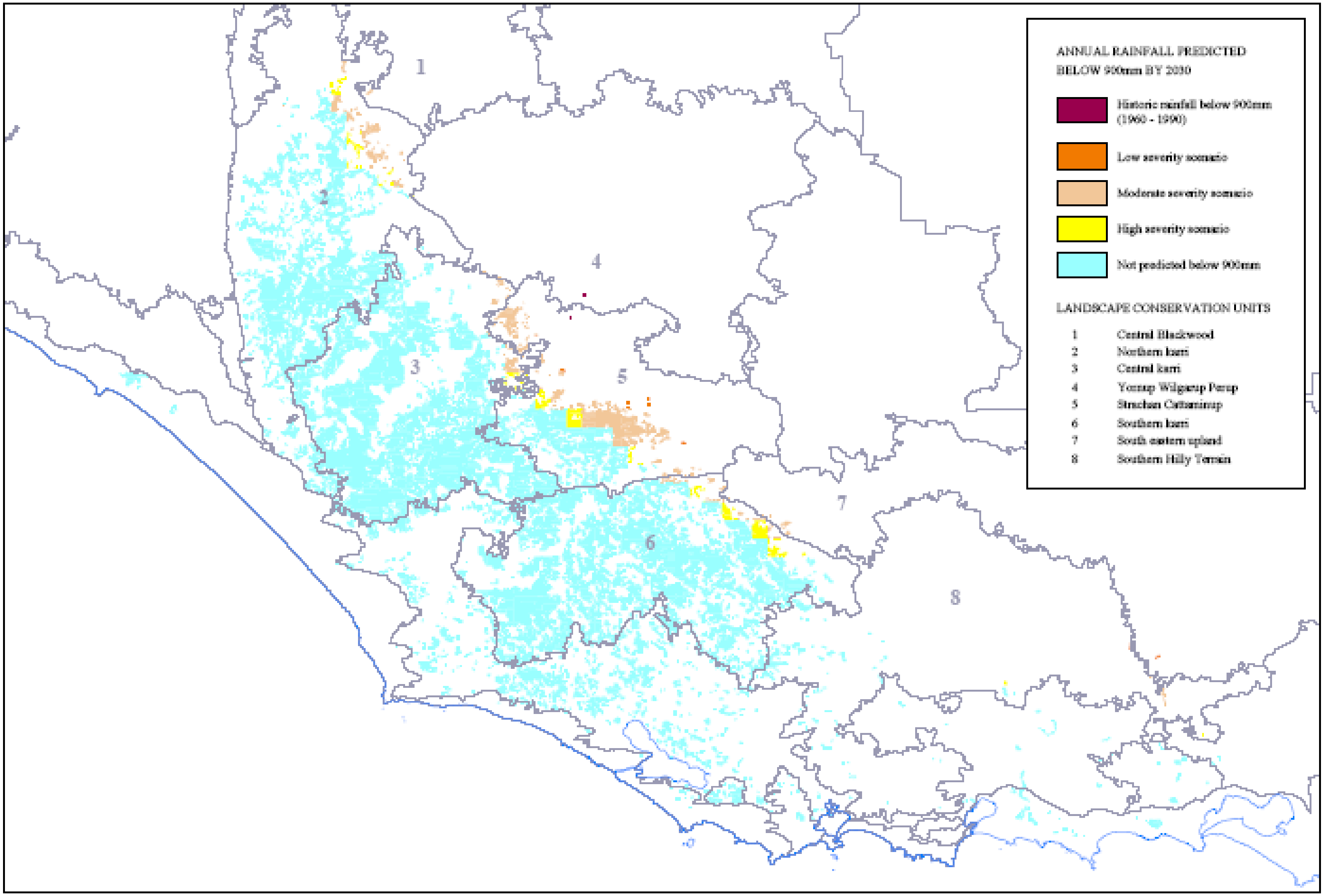

Figure 7 **Karri Forest on DEC-managed land highlighting areas with <900 mm rainfall.**

Table 6 Area of karri multiple use State forest within each Landscape Conservation Unit with historic or projected rainfall less than 900 mm

Landscape Conservation Unit	Current (1960-1990)	Low Severity (2030)	Medium Severity (2030)	High Severity (2030)
Central Karri	0	0	480	670
Northern Karri	0	0	1,050	1,420
South Eastern Upland	0	0	110	110
Southern Hilly Terrain	0	0	40	40
Southern Karri	0	0	280	1,240
Strachan Cattaminup Jigsaw	0	70	3,020	3,640
Yornup Wilgarup Perup	0	0	20	40
TOTAL	0	70	5,000	7,160

8.4 Wandoo Forest

There are 139,331 ha of wandoo forest on DEC-managed land within the FMP area. Wandoo forest and woodland extends well outside lands managed under the FMP which only cover the western, higher rainfall extent of wandoo distribution. No LCU within the current wandoo range is predicted to fall below threshold values for its distribution.

8.5 Tingle Forest

There are 27,480 ha of DEC-managed forest with tingle occurring either as a dominant or minor component of the stand. All of this forest occurs in areas where mean annual rainfall for 1961-1990 exceeds 1000 mm. Two LCU within the current tingle forest ecosystem range are predicted to fall below 1000 mm rainfall by the year 2030, totalling 20,790 ha of tingle forest (Table 7). This represents 76% of the current range of tingle forest ecosystems. There are 70 ha of regrowth yellow tingle forest available for timber production on land held under title by the Executive Director within the area of the Southern Hilly Terrain LCU predicted to fall below 1000 mm annual rainfall.

Table 7 Area of Tingle forest on DEC-Managed land with predicted rainfall less than 1000mm under the high severity climate change scenario.

Landscape Conservation Unit	Total DEC-Managed Land			Multiple use State forest		
	Canopy Cover 10-49%	Canopy cover 50-80%	Canopy cover >80%	Canopy Cover 10-49%	Canopy cover 50-80%	Canopy cover >80%
Redmond Siltstone Plateau	60	560	370	0	0	0
Southern Hilly Terrain	440	14,860	4,500	10	60	0
	20,790			70		

9 Timber harvesting 2010-2012

This section provides an overview of silvicultural objectives for jarrah and karri forests, and identifies areas of forest scheduled for timber harvesting in the three year period from 2010-2012 where annual rainfall is predicted to decline below 600 mm for jarrah dominant or 900 mm for karri dominant forests.

9.1 Silviculture practice – an overview

Timber harvesting occurs in accordance with the FMP 2004-2013 and associated guidelines and is managed according to silviculture objectives based primarily on species composition, forest structure and predicted disease impact.

In jarrah forest there are four silviculture objectives:

- to promote growth on the remaining trees (thinning)
- to reduce competition to allow lignotubers to develop unimpeded into saplings (gaps)
- to reduce competition to allow seedlings to establish and develop into ground coppice (shelterwood)
- to promote resistant species in areas where the impact of *Phytophthora cinnamomi* is expected to be high (dieback selection)

In karri forest there are two silviculture objectives:

- to promote growth on the remaining trees (thinning)
- to reduce competition to allow seedlings to develop unimpeded into saplings (clearfell with or without seed trees)

Figures 8 and 10 illustrate the patch scale harvesting and regeneration cycles for jarrah and karri forest respectively. Patches of regeneration go through a sequence of structural stages until they reach a mature forest stage. In natural situations the mature forest stage leads on to senescence, where health and vigour declines, crowns break down and regeneration establishes in larger openings. Harvesting predominantly mature stands by gap creation in jarrah forest and clearfelling in karri forest creates larger openings in the canopy and patches of regeneration are established. The scale of regeneration establishment varies from two tree heights (approx 0.2 ha) to 10 ha in jarrah forest and 2 tree heights (approximately 1.1 ha) to 40 ha in karri forest.

Juvenile and immature stands of both jarrah and karri may be thinned, however jarrah stands are not usually thinned until late in the immature stage when tree diameters have reached minimum commercial sawlog size. Lack of markets for small diameter jarrah trees usually prevents earlier commercial thinning. First thinning of karri stands usually occurs towards the end of the juvenile stage at an age of approximately 20 years or when stands have reached a top height of 30 metres.

Mature forest characteristics are retained in stands cut to shelterwood and dieback selection. Periodic prescribed burning is undertaken on a rotation of approximately 10 years to encourage the development of lignotubers in shelterwood stands and to prevent accumulation of heavy fuel loads that could contribute to intense bushfires. When sufficient lignotubers have developed, gaps can be cut to release the lignotubers from overstorey competition and allow them to grow unimpeded into saplings.

In areas of forest that are dieback infested or considered unprotectable from the spread of dieback, and where the disease is predicted to have high impact (likely to result in tree deaths), harvesting does not make large openings in the canopy that may lead to intensification of the disease. A uniform selection cut is applied, reducing competition.

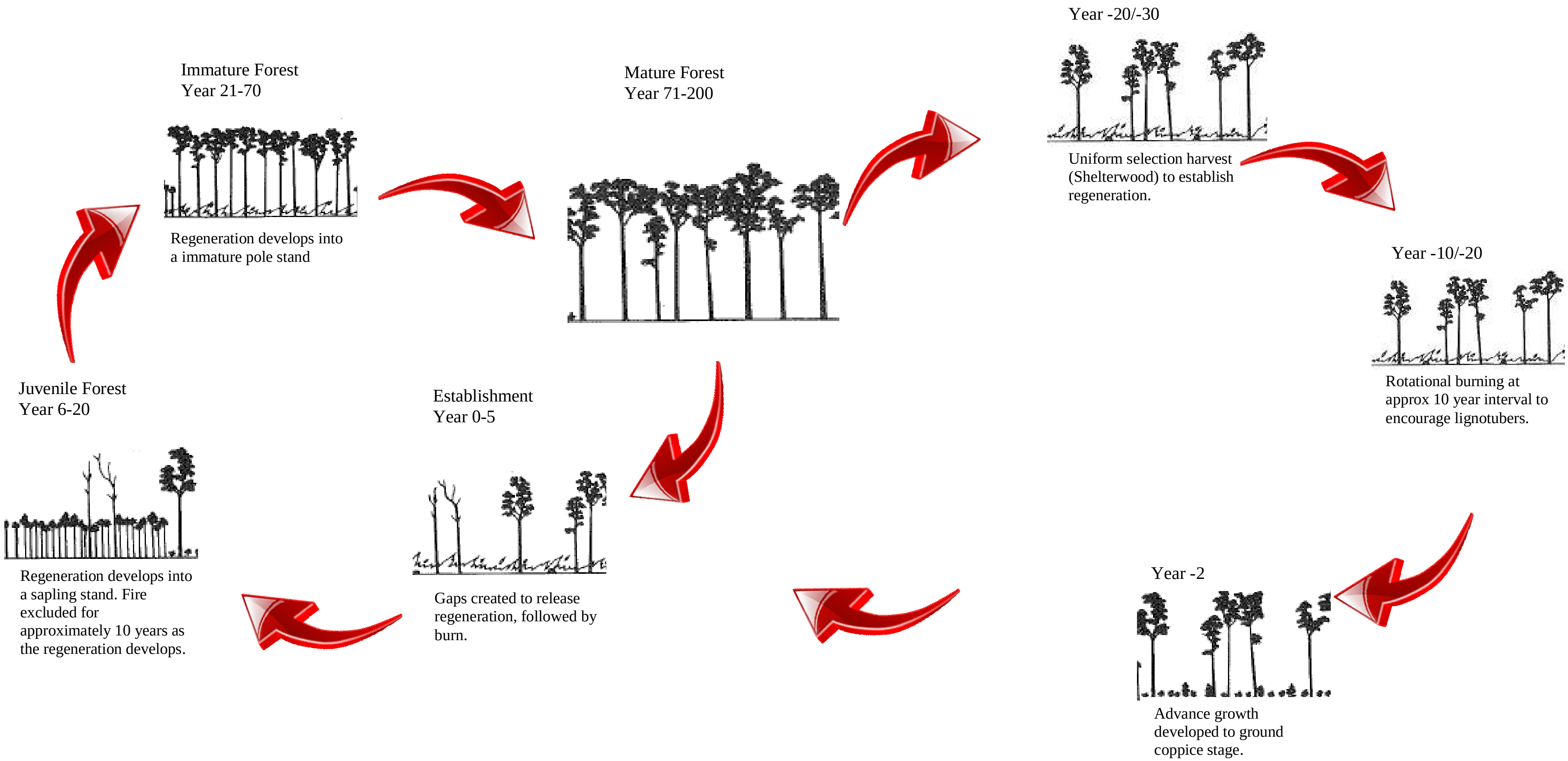

Figure 8 Jarrah Forest – structural stages of regeneration resulting from patch scale harvesting.

Explanation of jarrah structural stages of regeneration depicted in Figure 8.

Establishment (nominally year 0-5)

The establishment structural stage can either begin when gaps are created in the canopy to allow lignotubers to be released and grow into saplings i.e. the shoot exceeds 2 metres in height. In this case it is usually persists for a period of about 3-5 years from the post harvest burn. Fire is excluded from stands during this period as fire may kill the above ground portion of trees resulting in extending this stage until the re-sprouting lignotuber again reaches 2 metres in height.

The establishment stage may be extended by 20 – 30 years and commence when a uniform selection harvest occurs followed by a burn timed to coincide with the presence of a seed crop in the crowns of the retained trees. The overstorey density is substantially reduced during this time to reduce competition and allow regeneration to become established. These areas are burnt on approximately a 10 year rotation to encourage the development of lignotubers.

Juvenile Forest (nominally year 5-20)

Patches of forest are occupied by saplings, they have a crown of small branches, all of which shed as the tree gains height. Crown closure occurs at about 8 years after release and self thinning occurs at a modest rate as trees sort themselves into dominance classes. Fire may be re-introduced when the average diameter of trees is greater than 10cm. This stage ends when the average tree diameter reaches 15cm.

Immature (nominally year 20-70)

The stand has developed into a pole stand and competition between trees for dominance continues and self thinning slows. Lateral spread of the crown commences during this stage. Competition for water is at a maximum and most trees will regularly experience moisture stress during summer months. Understorey density and abundance is likely to be reduced during this period due to competition for water.

Mature (nominally year 71-200)

The mature stage is reached when the average diameter of trees reaches 45cm. Large persistent branches develop. Dead branches are common in the crown towards the end of the mature stage and trees become less able to extend their crowns to occupy spaces created by the removal of individual trees.

In practice, the outcome of timber harvesting is variable. In lower quality sites the outcome in significant areas of jarrah forest is a selective harvest where the retained stand basal area is 18 m^2 ha^{-1} or greater. This occurs as a consequence of lack of markets for low grade sawlogs and residue logs, and a tendency for conservative application of silvicultural guidelines. Results of recent field surveys in eastern jarrah forest by the Forest Products Commission illustrate the difference between the objective and outcome of silvicultural practice (Maher, unpublished data). Field surveys conducted in 1395 ha of eastern jarrah forest revealed that more than half the area of harvested forest was classified as a selective harvest and did not meet retained basal area objectives for either regeneration release or seedling establishment (Table 8). The spatial arrangement of silvicultural outcomes achieved in Leach 4 (1) compartment is illustrated in Fig. 9. Although the silvicultural objective recorded for this compartment was regeneration establishment, this outcome was only achieved on 37.8 ha (25%) of the 150 ha compartment area with patches of regeneration establishment (shelterwood) interspersed with small patches of regeneration establishment (gaps) in a broader matrix of selective harvesting.

Table 8 **Results from a survey of silvicultural outcome following timber harvesting in 1395 ha of eastern jarrah forest.**

Objective	**Proportion of area surveyed**	**Outcome**	**Retained basal area ($m^2\ ha^{-1}$)**	**Outcome Proportion**
Release	14%	gap	0-6	4.0 %
		potential gap	9-17	9.9 %
Establishment	33%	shelterwood	0-10	12.2 %
		potential shelterwood	11-17	20.8 %
Does not meet current silvicultural objective	53%	selective	18+	53.2 %

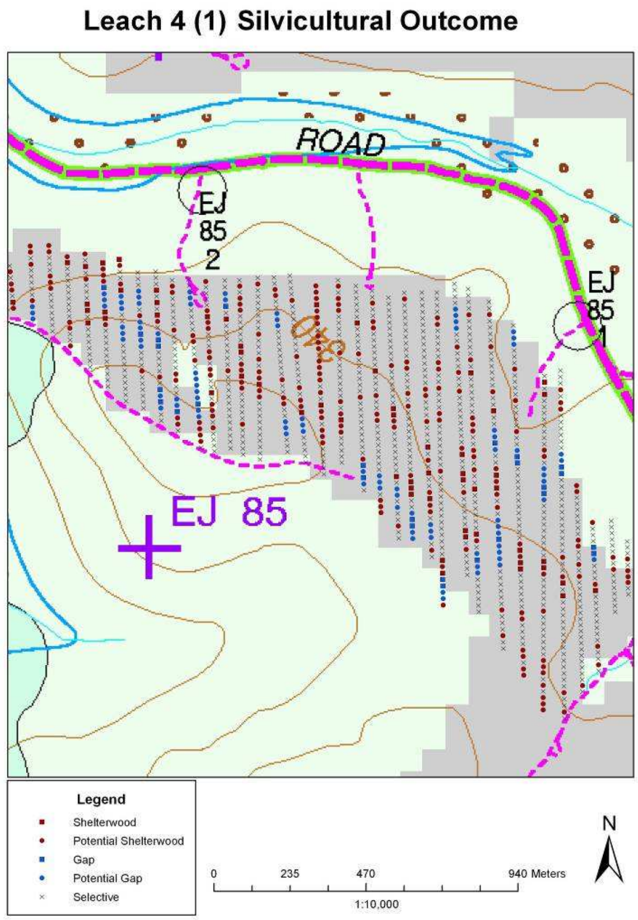

Figure 9. **Variation in silvicultural outcome determined from field survey in Leach 4 compartment 1, Wellington District.**

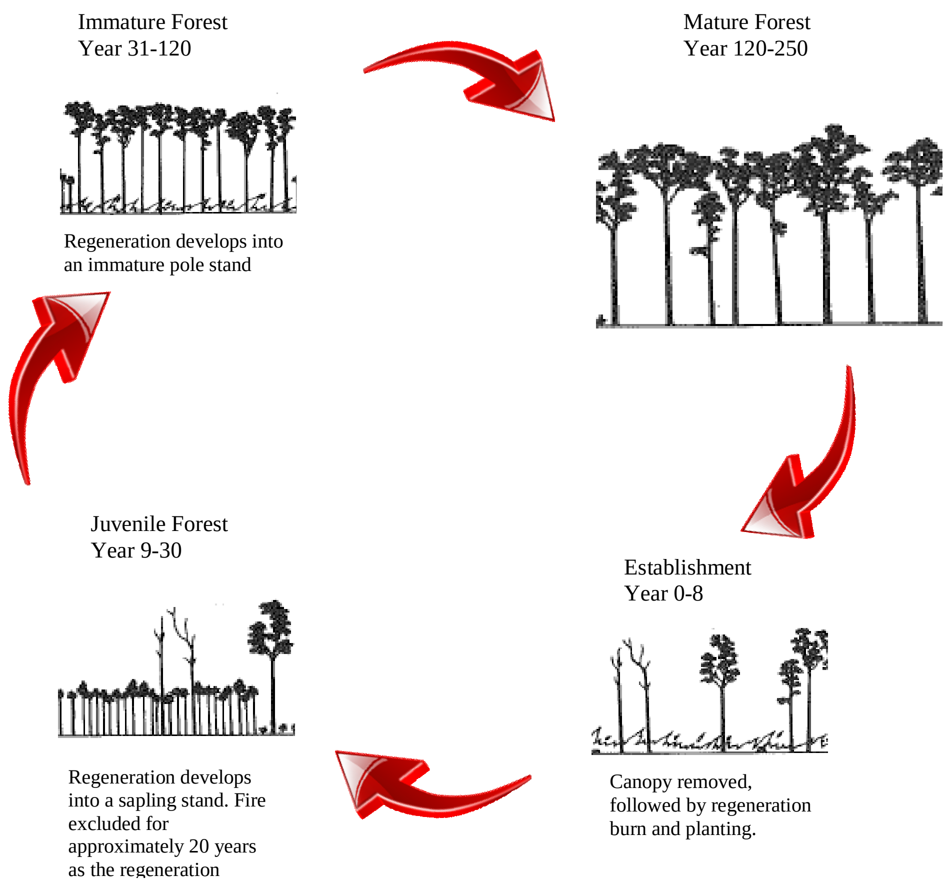

Figure 10 Karri Forest – structural stages of regeneration resulting from patch scale harvesting.

Explanation of karri structural stages of regeneration depicted in Figure 10.

Establishment (nominally year 0-8)
The establishment structural stage begins with removal of sufficient trees in the overstorey to become occupied by seedlings. In stands managed for timber production this is usually achieved by clearfelling and planting.

In natural stands up to 100 000 seedlings will germinate reducing to approximately 5000/ha by about age 8 when crown closure occurs and this stage ends. Saplings are approximately 6-10 metres tall by this stage. Planting density is 2200stems/ha.

Juvenile Forest (nominally year 9-30)
This stage is characterised by intense competition. Numbers will reduce to 400-500 dominant and co-dominant trees. Crown shape will change from conical to more rounded as lower branches shed. Trees are fire sensitive until about age 20.

Immature (nominally year 31-120)
The stand has developed into a pole stand and competition continues, numbers will reduce to about 150 stems/ha. Branches cease to shed cleanly and hollow development processes may begin.

Mature (nominally year 121-250)
Rapid growth ends and trees are unable to increase crown dimensions. Branches periodically break and epicormics form in the crown. Diameter growth steadily increases (Bradshaw and Rayner 1997).

9.2 Timber harvesting scheduled for 2010-2012 in forests potentially vulnerable to climate change

The timber harvesting plan for 2010-2012 identifies a gross area of 68, 560 ha of jarrah and karri forest available for harvest during the three year period. Areas identified as being available under the plan were intersected with areas identified as being potentially vulnerable to climate change for each of the three climate change severity scenarios for the year 2030.

9.2.1 Jarrah forest

The harvest plan includes 23,360 ha of forest in the LCUs identified as potentially vulnerable to climate change, but only 14 ha of forest in compartment Wearne 1 are scheduled for harvesting in areas where rainfall is predicted to decline below 600 mm by 2030. Wearne forest block is classified as eastern jarrah forest according to Appendix 7 of the silvicultural guidelines for jarrah forest (CALM 2004), typified by open jarrah forest with total crown cover predominantly in the 30-49% range, interspersed with wandoo forest (Fig. 10). Harvesting in Wearne 1is scheduled for 2011.

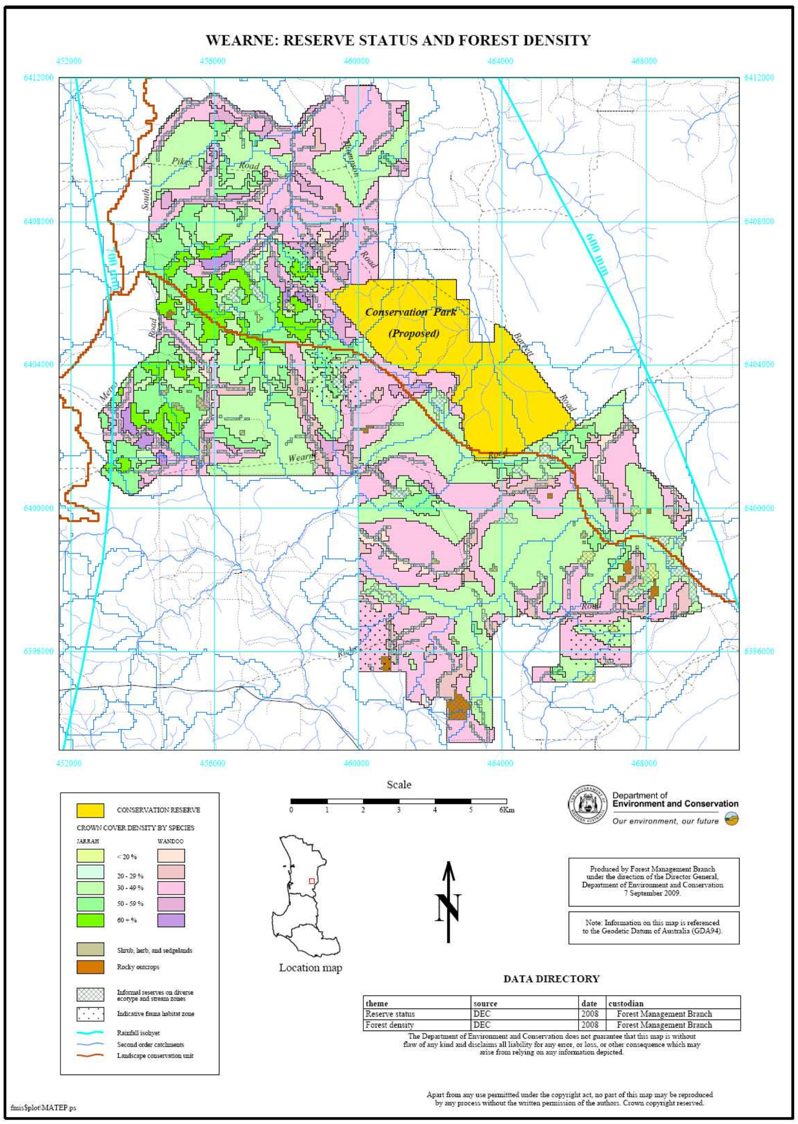

Figure 10 Distribution of vegetation types, informal reserves and formal conservation reserves in Wearne forest block.

9.2.2 Karri forest

The three year plan schedules harvesting in 997 ha of karri forest where rainfall is predicted to fall below 900 mm by 2030 (Table 9). Thinning is scheduled in 747 ha of regrowth forest, and 250 ha of forest are scheduled for clearfell and regeneration, or mixed silvicultural objectives related to forest structure (eg. harvesting in two tiered forest resulting from previous selection harvesting).

Table 9 Timber harvesting scheduled for 2010-2012 in karri forest where annual rainfall is predicted to decline below 900 mm by 2030.

Coupe name	Plan year	Total coupe area	Historic climate	2030 prediction		
				Low-severity scenario	Medium-severity scenario	High-severity scenario
Regrowth thinning areas						
Mattaband 4	2011	31	0	0	11	24
Mattaband 12	2011	146	0	0	1	138
Sutton 5	2012	28	0	0	0	28
Sutton 6	2012	44	0	0	44	44
Sutton 10	2012	268	0	0	0	112
Sutton 11	2012	229	0		217	217
Sutton 12	2012	196	0	0	180	180
Sutton 13	2012	268	0	0	4	4
SUBTOTAL		**1,210**	**0**	**0**	**457**	**747**
Clearfell or mixed objective areas						
Challar 09	2011	109	0	0	5	5
Diamond 2 11	2011	137	0	0	68	134
Dordagup 02	2011	185	0	0	10	46
Dordagup 05	2012	26	0	0	17	17
Nelson 01	2010	530	0	0	5	48
SUBTOTAL		**987**	**0**	**0**	**105**	**250**
GRAND TOTAL		**2,197**	**0**	**0**	**562**	**997**

Scheduled harvesting coupes include a range of forest structures and species composition, as briefly described below:

- Challar 9 is located on the margins of current karri forest distribution and the majority of the coupe is jarrah forest, so a mixed silvicultural prescription for jarrah and karri will be applied;
- Diamond 2 11 is predominantly karri and includes both thinned and un-thinned 1942 regrowth. The coupe adjoins a large river reserve and areas of old growth forest;
- Dordagup 2 is located on the margins of current karri forest distribution and the majority of the coupe is jarrah forest, so a mixed silvicultural prescription for jarrah and karri will be applied;
- Dordagup 5 adjoins the Greater Dordagup National Park and areas of jarrah forest regenerated by gap harvest in 1996.
- Nelson 1 is coupe is predominantly jarrah with most of the karri forest occurring within a creek that will be included in an informal reserve.

10 Adaptation strategies included in the Forest Management Plan

This section outlines risks posed by climate change in SWWA forests including multiple use State forests areas available for timber harvesting. Measures identified in the FMP and associated guidance documents that may either reduce the likelihood or consequence of risk through enhancing the natural resilience of forests are presented. Additional measures that could be applied to further enhance resilience are also identified.

10.1 Overview of the Forest Management Plan

The FMP has adopted the, slightly modified, Montreal Criteria of sustainability as the framework within which to identify management actions in line with the principles of ecologically sustainable forest management. Three scales of management are recognised in the FMP to accommodate better planning for the maintenance of biodiversity, these being:

- *whole of forest*: all land categories that are subject to the FMP;
- *landscape*: defined as 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 or, for convenience, an administrative management unit such as a forest block or aggregation of blocks. Landscape scale is usually tens of thousands to a few thousand ha;
- *operational*: a discrete area of forest to which one or more operations have been or are planned to be applied.

Actions are set for each of the criteria of sustainability, where appropriate at each of the scales of management. A number of these actions, although not primarily formulated to address climate change adaptation, are consistent with the principles formulated in the national assessment of vulnerability of Australia's biodiversity to climate change.

10.2 Adaptation Policy

A national assessment of the vulnerability of Australia's biodiversity to climate change (Steffen *et al.* 2009) commissioned by the Australian Government outlines two key principles for the formulation of climate change policies and management strategies for biodiversity. These are:

- protecting a representative array of ecological systems; and
- maintaining well functioning ecosystems.

Application of these principles aims to minimise loss of biodiversity and manage change rather than preserve all species in their current locations. It is important to note that conservation and management strategies can reduce some of the negative impacts from climate change, but natural adaptation will be increasingly difficult unless action is taken on mitigation with magnitudes of changes to climate variables eventually exceeding the climate tolerances of species and ecosystems.

The key principles can be achieved through the implementation of a number of strategies including:

- reversing or minimize existing stressors;
- enhancing the capability of ecosystems to adapt and self-organize;
- applying a risk management approach to deal with irreducible uncertainties;
- eco-engineering to assist adaptation;
- preserving genetic variation in ex-situ collections if necessary;
- building consensus in the community with regard to views on biodiversity and conservation; and
- applying a risk management approach to deal with irreducible uncertainties.

10.3 FMP measures contributing to the protection of a representative array of ecological systems.

Ensuring that the full diversity of forest ecosystems are represented in areas managed for conservation will not in itself enhance the capability of ecosystems to self-adapt and reorganise in the landscape. However if the reserve system includes many different combinations of underlying environmental gradients then the chance of conserving favourable environments for a wide spectrum of biodiversity is increased (Dunlop & Brown 2008; Steffen *et al* 2009). Maintaining forest ecosystem complexity and heterogeneity through managing patch dynamics, protecting refuges and maintaining ecological connectivity will enhance the capacity of ecosystems to self-adapt and reorganize in the face of climate change. However it must be recognised that inevitably there will be limits beyond which ecosystems may be transformed.

10.3.1 Maintain representative forest types in reserves

A Comprehensive, Adequate Representative (CAR) Reserve System is considered to be a cornerstone of biodiversity conservation. CAR Reserves are protected from major disturbances such as timber harvesting, and ecosystems processes are left to function naturally. This strategy is considered to enhance the capability of the ecosystems to self adapt and reorganise in response to climate change.

Risk	FMP actions to mitigate risk	Additional actions that could be taken in recognition of increased risk from climate change
Unrestricted timber harvesting throughout the public forest estate could result in loss of some structural stages at landscape or whole of forest scale.	The FMP introduced a number of new reserves that ensured that, where possible, at least 15% of pre 1750 extent of forest ecosystems are included in reserves.	No additional measures are proposed.
	Old growth forests are excluded from timber harvesting.	

10.3.2 Provision of climate refuges at multiple scales

Provision of refuges across the landscape offers a place for vulnerable organisms to persist when conditions are hotter and drier. These refuges also provide for a source of migrating flora and fauna to recolonise disturbed areas as they regenerate following disturbances.

Risk	FMP actions to mitigate risk	Additional actions that could be taken in recognition of increased risk from climate change
Species vulnerable to increases in temperature or declines in rainfall cease to exist in areas subject to timber harvesting.	Fauna Habitat Zones (FHZ) have been introduced, whereby patches of forest of approximately 200 ha are systematically located approximately 3 km apart to provide refuges across the forest landscape. The selection criteria for FHZ includes a requirement for topographic diversity and inclusion of southern facing slopes where possible.	Additional significant refugia identified through research and biological survey should be considered for protection in informal or formal reserves.

Species with limited mobility are permanently removed from parts of the landscape.	Informal Reserves - low density woodlands, swamps, large rock outcrops are retained as diverse ecotypes (excluded from harvesting).	Low density wandoo woodlands associated with creeks and wetlands should be excluded from harvesting and treated as diverse ecotype zones.

10.3.3 Connectivity to undisturbed areas.

Connectivity with undisturbed areas enables the migration of fauna populations that require cover. Re-establishment of key functional groups is required for the functioning of the forest ecosystem.

Risk	FMP actions to mitigate risk	Additional actions that could be taken in recognition of increased risk from climate change
Vulnerable species become isolated in undisturbed areas preventing gene flow between populations or disrupting source-sink and meta-population dynamics.	Connectivity of habitat is maintained through network of informal reserves e.g. stream reserves linking formal reserves, old growth patches and fauna habitat zones.	No additional measures are proposed.

10.3.4 Keystone species and legacy elements.

Long-lived tree species have critical roles as keystone ecological structures (Steffen *et al.* 2009).

Risk	FMP actions to mitigate risk	Additional actions that could be taken in recognition of increased risk from climate change
Tree regeneration does not become established.	Jarrah Forest. – Shelterwood. Trees are retained to provide seed to re-colonise the site. Overstorey is retained in stands until sufficient advance growth becomes established. This allows for continued opportunistic recruitment of regeneration into the stand. Jarrah Forest – Gap. Sufficient advance growth must already be present before gaps are created in the canopy. Karri Forest – Local seed is used to grow seedlings for establishment operations.	The specification for jarrah seed trees retained in shelterwood harvest areas should be revised to incorporate the best available knowledge of the relationship between tree attributes and seed crops. Post establishment surveys are required to confirm overstorey composition is reflected in regeneration in mixed karri/jarrah/marri clearfell areas.
	Regeneration surveys are required to be completed for all operations. Karri clearfell and jarrah gap survey information is used to report on KPI 10 on an annual basis.	No additional measures are proposed.

Harvesting removes large trees for timber reducing the number of hollows and potentially affecting the volume coarse woody debris on the forest floor.	Mature forest elements such as habitat trees (jarrah and karri forest) and logs (jarrah forest) are retained	The specification for habitat logs should be reviewed to consider the role of large decayed logs, with or without hollows, as substrates for cryptogams and ferns. Large, well decayed logs should be considered for retention during regeneration operations in karri forest.
Harvesting removes second storey trees affecting the food sources for vertebrates and invertebrates.	Mature examples of second storey species are required to be retained in jarrah forest areas.	No additional measures are proposed.

10.4 FMP measures contributing to the maintenance of well-functioning ecosystems

Well-functioning forest ecosystems are naturally resilient, being able to recover from disturbance and move towards a mature state without external intervention. Forest ecosystems in SWWA are subject to a wide variety of disturbances varying in scale, frequency and intensity; the most widespread being fire and the most intense being bauxite mining. However, some disturbance regimes may exceed the resilience of ecosystems leading to transformation a state controlled by a different set of processes. Climate change may interact with existing stressors and push ecosystems towards topping points much sooner than hitherto realized. Removing or minimising existing stressors from ecosystems that are most at risk from climate change, can help build resilience.

10.4.1 Weeds, pests and diseases

The additional stress placed on an ecosystem by the presence of weeds pests and diseases make it more vulnerable to climate change. New stressors lower ecosystem resilience and can hinder or prevent recovery to the desired pre-disturbance state.

Risk	FMP actions to mitigate risk	Additional actions that could be taken in recognition of increased risk from climate change
Weed infestations lead to lower levels of biodiversity in forest ecosystems.	Control weeds and pests in forest ecosystems.	Locations of weed infestations in harvest coupes should be consolidated in a central database to enable comprehensive monitoring of weeds and their impact on forest ecosystems.
Resilience of forest is lowered by the introduction of *Phytophthora cinnamomi*, directly reducing species richness, understorey density and habitat quality.	Protect from infestation those areas currently free from *P. cinnamomi*	Planning units for harvesting should be modified to include whole landscape units to facilitate low profile roading and the closure of redundant roads.
	All areas of forest subject to harvesting are mapped for the occurrence of *P. cinnamomi*, and hygiene tactics applied to reduce spread of disease	Further training of DEC and Forest Products Commission personnel and contractors to ensure consistent application of hygiene measures during all forest disturbance operations.

Harvesting results in spread and intensification of impact of *P. cinnamomi*.	Areas that have the potential for tree deaths from the infestation with dieback are retained at least 15 m^2/ ha. Gaps are not created to avoid intensification of disease impact.	Areas of forest expressing high impact of dieback infestations should be excluded from harvesting where the live basal area is less than 18 m^2/ha.

10.4.2 Water competition

Competition for water on vulnerable sites can be reduced by thinning the overstorey and managing understorey density. In jarrah forest where trees have reached an average diameter of 45 cm (i.e. the beginning of the mature forest stage) thinning can be achieved by commercial timber harvesting. However where average tree diameter is below minimum sawlog size, timber harvesting may not be commercially feasible.

Thinning can be achieved non-commercially through culling to reduce overstorey density, but the cost of application makes this option prohibitive as a general management option. Where there are other benefits, such as harnessing water for domestic and commercial use, the cost of non-commercial thinning may be worthwhile. The Water Corporation is exploring this option in the Wungong catchment project.

Bio-energy offers an opportunity to implement thinning in a greater proportion of stands. This would be of particular benefit in immature stands where there is a high level of competition for water.

Risk	FMP actions to mitigate risk	Additional actions that could be taken in recognition of increased risk from climate change
Intense competition in densely stocked regrowth stands leads to declining tree health.	The jarrah silviculture guideline permits thinning immature stands i.e. where the average tree stem diameter is less than 20cm 200 stems/ha can be released from competition by non-commercial thinning. The karri silviculture guideline permits thinning even-aged stands when they have achieved a top height of 30 m.	DEC should continue to encourage the Forest Products Commission to seek residue markets for small diameter (15-45 cm) jarrah trees to facilitate thinning of immature stands. Develop thinning schedules that recognize reduced site capacity in areas where annual rainfall is predicted to decline below 900 mm in the karri forest.
Thinning does not lead to decreased water competition.	The jarrah silviculture guidelines requires that thinning stands are culled to the specified density.	The requirement to maintain a basal area of 15 m^2/ha in areas defined as ‘salt sensitive’ should be reviewed.
Overstorey competition results in death of germinants during their first summer.	In the eastern jarrah forest less overstorey is prescribed (6 m^2/ha) for retention than in the higher rainfall western forest (10 m^2/ha), to take into account the greater competition for water. Where the BA of overstorey is greater than 10 m^2/ha in eastern forest and 14 m^2/ha in western forest the guideline prescribes that culling should be undertaken. Monitoring of regeneration establishment occurs at least one summer after germination/planting.	Monitoring the implementation of silvicultural guidelines should continue to be a high priority action for SFM Division, with emphasis on regeneration surveys in areas that are predicted to decline below 600 mm annual rainfall in jarrah forest and 900 mm in karri forest.

Water demand of large scale areas of regeneration reduces abundance of understorey species and runoff into aquatic systems.	Jarrah silviculture requires that gaps are limited to a maximum of 10 ha. Temporary exclusion areas (TEAS) are required to be a minimum of 100 m wide. TEAS may be harvested after 10-20 years. Karri silviculture requires that clearfell patches are limited to a maximum of 40 ha. Adjacent areas may be harvested once the coupe has been regenerated, nominally 3 years.	Reliable long-term regional scale forest health monitoring which combines remote sensing and ground-based measurements of plant water stress is needed to determine the status and trends of plant stress and mortality in SWWA forest ecosystems as the region's climate becomes drier.
	Jarrah Forest. In salt sensitive zones at least 30% of second order catchments are required to be either uncut or retained at a basal area greater than 15 m^2/ha. TEAS may be harvested after 15 years.	No additional measures are proposed.

10.4.3 Fire

Forest ecosystems of south west Western Australia have adapted to disturbance (such as fire, storms and drought), but changes to disturbance regimes can also affect ecosystem condition and health.

Risk	FMP actions to mitigate risk	Additional actions that could be taken in recognition of increased risk from climate change
Altered fire regimes lead to declining forest health because of changes to nutrient cycling and soil microbial activity.	FMP objective is to use fire in a manner that optimises the maintenance of forest ecosystem health and vitality. A precautionary approach to fire management is used whereby prescribed fire to manage fuel accumulation and minimise the potential for severe fire behaviour under dry summer conditions is implemented. FMP introduced a decision matrix for management of karri regrowth stands suffering damage from wildfire, with the aim of sustaining productive capacity of stands. This was implemented as part of SFM Guideline 3 (2004).	No additional measures are proposed.
High intensity fires causes extensive tree mortality, leading to degraded forest condition and reduced growth potential and seed availability in severely crown damaged stands.		
Plants may take longer to mature and accumulate seed stores under drier conditions, leading to decline or loss of populations of obligate seed regenerators.	Understorey regeneration following harvesting is being monitored as part of FORESTCHECK, and at fire effects study sites across a rainfall gradient in the jarrah forest. These address FMP Action 9.2.	No additional measures are proposed.

10.5 Summary of forest vulnerability in areas subject to timber harvesting

Vulnerability to climate change is linked to developmental stage at stand, landscape and whole-of-forest scales and will therefore vary in both space and time.

During the establishment stage, seedlings and young regeneration are vulnerable to climatic events including extremes of heat, cold and water stress. Pests and pathogens that cause seedling mortality in the first few years following regeneration are also likely to be responsive to climate factors, particularly rainfall and temperature. In jarrah forest, risk of establishment failure is mitigated by retaining mature trees in shelterwood stands until regeneration is achieved, and by monitoring to ensure that areas harvested by gap creation to release existing regeneration are adequately stocked. In karri forest, risk is mitigated by comprehensive regeneration survey to identify areas requiring follow-up treatment.

During the latter stages of the establishment stage and throughout the juvenile stage, both jarrah and karri are vulnerable to damage by high intensity fires causing crown defoliation and extensive stem damage. Planned fires of low intensity can be introduced into juvenile jarrah stands at around 10 years after regeneration, and at around 15 years into juvenile karri stands; these thresholds are influenced by site quality, growth rate, and the rate at which fuels accumulate following regeneration. The need to provide strategic protection of young regrowth forest is well recognised in current management planning and is achieved by maintaining buffers of fuel reduced mature forest, and reducing fuels in regenerated forests that have reached a suitable stage of development. These measures will become even more important if predicted trends of continued drying and warming are realised. Fire management will also need to be adaptive to accommodate changes in the duration and seasonality of weather conditions suitable for planned burning.

Stands moving into the immature stage of development approach maximum density and may experience intense intra-specific competition for limited soil moisture and nutrients. Active silvicultural management by thinning can reduce severe water stress and arrest the decline of groundwater tables (Kinal 2009), thereby reducing the risk of declining tree health or tree mortality and ameliorating impacts on important aquatic ecosystems. Monitoring of forest health at whole of forest and landscape scales would provide additional information to guide decisions related to the timing and intensity of thinning operations.

The impacts of timber harvesting on forest ecosystem biodiversity and resilience are addressed by the FORESTCHECK integrated monitoring system. However the existing network of 48 FORESTCHECK sites was not designed specifically to consider risks posed to forest ecosystems by climate change or the interaction between climate change and other disturbances. Additional FORESTCHECK monitoring sites could be established in areas identified as vulnerable to climate change and scheduled for timber harvesting in the period 2010-2013.

11 Recommendations

The following recommendations are provided to the Director of Sustainable Forest Management in relation to management of timber harvesting under the influence of climate change:

1. Timber harvesting should proceed as scheduled in the three year harvesting plan 2010-2012 subject to implementation of the strategies to further enhance resilience identified in Section 10 of this report.
2. An integrated forest health monitoring program should be developed and implemented to provide a systematic framework for understanding the effects of climate change on forests. Monitoring should be undertaken at the three scales of management recognised in the FMP:
   - whole of forest – utilising remote sensing;
   - landscape – utilising and enhancing the FORESTCHECK protocol to ensure representative monitoring of a range of elements of biodiversity across major climate gradients;
   - operational (stand) scale monitoring of the outcomes of silvicultural practice including adequacy of silvicultural treatment, protection of retained habitat elements, and regeneration effectiveness.
3. The findings of this vulnerability assessment should be considered in the context of Action 9.1 of the FMP which requires the Department to undertake biological surveys of priority areas determined in consultation with the Conservation Commission and used, where appropriate, to assist in evaluating the extent to which biodiversity is being conserved and the need for any review of the reserve system. This could include establishing additional FORESTCHECK monitoring sites in areas of jarrah and karri forest identified as potentially vulnerable to climate change by 2030 and where timber harvesting is scheduled during the period 2010-2013.
4. Investigate regeneration practices for mixed karri jarrah marri stands to determine whether current practices are effective in maintaining representative species composition, and whether alternative practices need to be developed.
5. Develop a guidance document for salvage harvesting and post-fire rehabilitation in the event of an extensive high intensity bushfire so that response actions are well considered and based on contemporary ecological and silvicultural understanding (see Lindenmayer, Burton and Franklin 2008. Salvage logging and its ecological consequences).
6. Undertake further research into the eco-hydrology for major forest tree species to allow improved modelling of landscape level impacts of changes in moisture availability from declining rainfall and groundwater levels.

12 References

Abbott I (1984) Ecological features of an outlying stand of jarrah (*Eucalyptus marginata*) at Jilakin Rock, Western Australia. *Journal of the Royal Society of Western Australia* **66**, 107-110.

Abbot I, Smith R, Williams M, Voutier R (1991) Infestation of regenerated stands of karri (*Eucalyptus diversicolor*), by bullseye borer (*Tryphocaria acanthocera, Cerambycidae*) in Western Australia. *Australian Forestry* **54**, 66-74.

Abbott, I. and Burrows, N. (2004) Monitoring biodiversity in jarrah forest in south-west Western Australia: the FORESTCHECK initiative. In *Conservation of Australia's Forest Fauna* (second edition). (ed. D. Lunney), pp. 947-958, Royal Zoological Society of New South Wales, Mosman, New South Wales.

Ainsworth E, Long S (2005) What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2. *New Phytologist* **165**, 351-372.

Allen C (2009) Climate-induced forest dieback: an escalating global phenomenon? *Unasylva* **60**, 43-49

Atahan P, Dodson J, Itzstein-Davey F (2004) A fine resolution Pliocene pollen and charcoal record from Yallalie, south-western Australia. *Journal of Biogeography* **31**, 199-205.

Aukema B, Carroll A, Zheng Y, Zhu J, Raffa K, Moore R, Stahl K, Taylor S (2008) Movement of outbreak populations of mountain pine beetle: Influence of spatiotemporal patterns and climate. *Ecography* **31**, 348-358.

Barber P, Hardy G (2006) *Research into the Causes and Management of Tuart Decline*. Tuart Health Research Group, Murdoch University, Perth.

Bates B, Hope P, Ryan B, Smith I, Charles S (2008) Key findings from the Indian Ocean Climate Initiative and their impact on policy development in Australia. *Climatic Change* **89**, 339-354.

Batini F (2009) *Responses to a Drying Climate in the Northern Jarrah Forest*. Proceedings of the Biennial Conference of the Institute of Foresters of Australia, Caloundra, September 2009.

Beard J (1990) *Plant Life of Western Australia*. Kangaroo Press, Australia.

Bell D, Heddle E (1989) Floristic, morphological and vegetational diversity. In *The Jarrah Forest: A Complex Mediterranean Ecosystem*. (eds Dell B, Havel J, Malajczuk N), pp. 13-22, Kluwer Academic Publishers, Dordrecht.

Bradley K, Pregitzer K (2007) Ecosystem assembly and terrestrial carbon balance under elevated CO2. *TREE* **22**, 538-547.

Bradshaw F, Collins P, McNamara P (1997) *Forest Mapping in the South West of Western Australia.* Department of Conservation and Land Management, Perth.
Christenson P, Liddelow G, Hearn R (2005) *Assessment of Vertebrate Fauna Prior to Disturbance: Timber Harvesting and Prescribed Burning in the Forests of Western Australia*. The Forest Fauna Distribution Information System. Department of Conservation and Land Management, Perth.

Bradshaw F, Rayner M (1997) Age structure of the karri forest: 1. Defining and mapping structural development stages. *Australian Forestry* **60** (3), 188-195.

Breshears D, Cobb N, Rich P, Price K, Allen C, Balice R, Romme W, Kastens J, Floyd M, Belnap J, Anderson J, Myers O, Meyer C (2005) Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Sciences of the United States of America* **102**(42), 15144-15148.

Burrows N (2009) *Wildfires Can Be Bad for Biodiversity*. Science Division Information Sheet, 17/2009.

Burrows N, Wardell-Johnson G (2003) Interactions of fire and plants in south-western Australia's forested ecosystems: a review. In *Fire in Ecosystems of South-West Western Australia: Impacts and Management* (eds Abbott I, Burrows, N), pp. 225-268. Backhuys Publishers, Leiden.

Byrne M (2008) Evidence for multiple refugia at different time scales during Pleistocene climatic oscillations in southern Australia inferred from phylogeography. *Quaternary Science Reviews* **27**, 2576-2585.

Byrne M, Yeates D, Joseph L, Kearney M, Bowler J, William M, Cooper S, Donnellan S, Keogh J, Leys R, Melville J, Murphy D, Porch N, Wyrwoll K (2008) Birth of a biome: insights into the assembly of and maintenance of the Australian arid zone biota. *Molecular Ecology* **17**(20), 4398-4417.

Cai W, Shi G, Li Y (2005) Multidecadal fluctuations of winter rainfall over south west Western Australia simulated in the CSIRO Mark 3 coupled model. *Geophysical Research Letters* **32**, 1270.

CALM (2004) *Silvicultural practice in the jarrah forest. Silvicultural guideline for the jarrah forest.* CALM, Perth.

Chambers L (2008) Trends in timing and migration of south-western Australian birds and their relationship to climate. *Emu* **108**, 1-14.

Charles S, Bates B, Hughes J (1999a) A spatio-temporal model for downscaling precipitation occurrence and amounts. *Journal of Geophysical Research* **104**, 31657-31669.

Charles S, Bates B, Whetton P, Hughes J (1999b) Validation of a downscaling model for changed climate conditions in southwestern Australia. *Climate Research* **12**,1-14.

Churchward M, Dimmock G (1989) The soils and landforms of the northern Jarrah forest. In *The Jarrah Forest: A Complex Mediterranean Ecosystem*. (eds Dell B, Havel J, Malajczuk N), pp. 13-22, Kluwer Academic Publishers, Dordrecht.

Churchill D (1968) The distribution and prehistory of *Eucalyptus diversicolor* F. MUELL., *E. marginata* DONN EX SM., and *E. calophylla* R. BR in relation to rainfall. *Australian Journal of Botany* **16**, 125-151.

Coates D, Sokolowski R (1989) Geographic patterns of genetic diversity in karri (*Eucalyptus diversicolor* F. Muell.). *Australian Journal of Botany* **37**, 145-156.

Conservation Commission (2004) *Forest Management Plan 2004-2013.* Conservation Commission of Western Australia, Perth, Western Australia.

Cowan I (1981) Regulation of water use in relation to carbon gain in higher plants. In *Physiological Plant Ecology II: Water Relations and Carbon Assimilation. Encyclopaedia of Plant Physiology Vol. 12B.* (eds Lange O, Nobel P, Osmond C, Ziegler H), pp. 589-614, Springer, Berlin.

Crucifix M, Betts R, Hewitt C (2005) Pre-industrial potential and Last Glacial Maximum global vegetation simulated with a coupled climate-biosphere model: diagnosis of bioclimatic relationships. *Global and Planetary Change* **45**, 295-312.

CSIRO (2007) *Climate Change in Australia-Technical Report 2007*. CSIRO Bureau of Meteorology, Melbourne, Victoria.

Cullen L, Grierson P (2008) Multi-decadal scale variability in autumn-winter rainfall in south-western Australia since 1655 AD as reconstructed from tree rings of *Callitris columellaris*. *Climate Dynamics* **33**, 433-444.

Dodson J, Lu J (2000) A late Holocene vegetation and environment record from Byenup Lagoon, south-western Australia. *Australian Geographer* **31**, 41-54.

Dortch J (2004) Late Quaternary vegetation change and the extinction of the Black-flanked Rock Wallaby (*Petrogale lateralis*) at Tunnel cave, southwestern Australia. *Paleogeography, Paleoclimatology, Paleoecology* **211**, 185-204.

Dunlop N (2001) Sea-change and fisheries: a bird's eye view. *Western Fisheries Magazine*, Spring, 11-14.

Dunlop M, Brown P (2008) *Implications of climate change for Australia's National Reserve System: a preliminary assessment*. Prepared for the Federal Government by CSIRO scientists.

English V, Jasinska E and Blyth J (2003) *Aquatic Root Mat Community of Caves of the Swan Coastal Plain, and the Crystal Cave Crangonyctoid Interim Recovery Plan 2003-2008*. Department of Conservation and Land Management, Perth, Australia.

Farr J (2002) Biology of the gumleaf skeletoniser, *Uraba lugens* Walker (Lepidoptera: Noctuidae), in the southern jarrah forest of Western Australia. *Australian Journal of Entomology* **41**, 60-69.

Farr J, Dick S, Williams M, Wheeler I (2000) Incidence of bullseye borer (*Phoracantha acanthocera*, (Macleay) *Cerambycidae*) in 20-35 year old regrowth karri in the south west of Western Australia. *Australian Forestry* **63**, 107-123.

Fischlin A, Midgeley G, Price J, Leemans R, Gopal B, Turley C, Rounsevell M, Dube O, Tarazona J, Velichko A (2007) Ecosystems, their properties, goods and services. *Climate Change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Parry M, Canziani O, Palutikof J, van der Linden P, Hanson C), pp 211-272. Cambridge University Press, Cambridge.

Fitzpatrick M, Gove A, Sanders N, and Dunn R (2008) Climate change, plant migration, and range collapse in a global biodiversity hotspot: the Banksia (Proteaceae) of Western Australia. *Global Change Biology* **14**, 1-16.

Florence R (1981) The biology of the Eucalypt forest. In *The Biology of Australian Plants* (eds Pate J, McComb A), pp147-180. University of Western Australia Press, Western Australia.

Frederiksen J, Frederiksen C (2007) Interdecadal changes in southern hemisphere winter storm track modes. *Tellus* **59**, 599-617.

Froend R, Drake P (2006) Defining phreatophyte response to reduced water availability: preliminary investigations on the use of xylem cavitation vulnerability in *Banksia* woodland species. *Australian Journal of Botany* **54**, 173-179.

Gaff D (1981) The biology of resurrection plants. In *The Biology of Australian Plants* (eds Pate J, McComb A), pp115-146. University of Western Australia Press, Western Australia.

Gentilli J (1989) Climate of the Jarrah forest. In *The Jarrah Forest: A Complex Mediterranean Ecosystem*. (eds Dell B, Havel J, Malajczuk N), pp. 23-40, Kluwer Academic Publishers, Dordrecht.

Gibson L, McNeill A, de Tores P, Wayne A, Yates C (in prep) Are future climate predictions likely to threaten the persistence of a range restricted endemic species, the quokka (*Setonix brachyurus*), in south west Australia?

Groom P (2004) Rooting depth and plant water relations explain species distribution patterns within a sandplain landscape. *Functional Plant Ecology* **31**, 423-428.

Groom P, Froend R, Mattiske E (2004) Impact of groundwater abstraction on a Banksia woodland, Swan Coastal Plain, Western Australia. *Ecological Management and Restoration* **1**, 117-124.

Hanstrum B (1990) Fire weather in relation to tropical cyclones over south-west Western Australia. In *Proceedings of the Thrid Australian Fire Weather Conference.* Pp. 79-84, 18-20 May 1989, Hobart. Bureau of Meteorology, Melbourne.

Havel J (1975a) *Site-Vegetation Mapping in the Northern Jarrah Forest (Darling Range) 1. Definition of Site Vegetation Types.* Forests Department, Bulletin **86**. Perth, Western Australia.

Havel J (1975b) *Site-Vegetation Mapping in the Northern Jarrah Forest (Darling Range) 2. Location and Mapping of Site Vegetation Types.* Forests Department, **87**. Perth, Western Australia.

Havel J, Mattiske E (2000) *Vegetational Mapping of South-West Forest Regions of Western Australia*. Department of Conservation and Land Management, Perth.

Heddle (1980) *Effects of Changes in Soil Moisture on the Native Vegetation of the Northern Swan Coastal Plain, Western Australia*. Forests Department, Bulletin 92, Perth, Western Australia.

Hopper S, Gioia P (2004) The Southwest Australian Floristic Region: evolution and conservation of a global hotspot of biodiversity. *Annual Review of Ecology and Systematics* **35**, 623-650.

Hopper S, Harvey M, Chappill J, Main A, Main B (1996) The Western Australian biota Gondwanan heritage – a review. In *Gondwanan Heritage* (eds S Hopper, J Chappill, M Harvey, A George), pp. 1-46. Surrey Beatty and Sons, Chipping Norton, NSW.

Hope P, Drosdowsky W, Nicholls N (2006) Shifts in synoptic systems influencing south west Western Australia. *Climate Dynamics* **26**,751-764.

Indian Ocean Climate Initiative (2005a) *How our river flows have changed*. Climate Note 7/05. www.ioci.org.au

Indian Ocean Climate Initiative (2005b) *How our groundwater has changed*. Climate Note 8/05. www.ioci.org.au

IPCC (2000) Emmissions scenarios. In *Special Report of the Intergovernmental Panel on Climate Change* (eds N Nakichenovic, R Swart), pp 570. Cambridge University Press, Cambridge.

IPCC (2007) Summary for policy makers. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds S Soloman, D Quin, M Manning, M Marquis, M Averyt, M Tignor, H Miller), pp 1-18. Cambridge University Press, Cambridge.

Kinal J (2009) *Hydrological impacts of timber harvesting*, Department of Environment and Conservation Science Division Information Sheet 22.

Konkin D, Hopkins A (2009) Learning to deal with climate change and catastrophic forest disturbances. *Unasylva* **60**, 17-23.

Körner C (2003) Ecological impacts of atmospheric CO2 enrichment on terrestrial ecosystems. *Philosophical Transactions of the Royal Society of London A* **361**, 2023-2041.

Klausmeyer K, Shaw M (2009) Climate change, habitat loss, protected areas and the climate adaptation potential of species in Mediterranean ecosystems worldwide. *Public Library of Science* ONE 4, e6392.

Lange R (1960) Rainfall and soil control of tree species distribution around Narrogin, Western Australia. *Journal of the Royal Society of Western Australia* **43**, 104-110.
Mattiske E, Havel J (2004) *Delineation of Landscape Conservation Units in the Southwest Region of Western Australia*. Report Prepared for Department of Environment and Conservation, Perth.

Montreal Process Implementation Group for Australia (2009) *Australia's State of the Forests Report 2008*. Bureau of Rural Sciences, Canberra.

Lindenmayer D, Burton P, Franklin J (2008) *Salvage Logging and it's Ecological Consequences*. Island Press.

Lucas C, Hennessy K, Mills G, Bathols J (2007) *Bushfire Weather in Southeast Australia: Recent Trends and Projected Climate Change Impacts*. Consultancy Report prepared for The Climate Institute of Australia. Bushfore Cooperative Research Centre, Australia.

MacKellar N, Hewitson B, Tadross M (2007) Namaqualand's climate: Recent historical changes and future scenarios. *Journal of Arid Environments* **70**, 604-614.

Main A (1996) Ghosts of the past: where does environmental history begin? *Environment and History* **2**, 97-114.

Mattiske E, Havel J (2004) *Delineation of Landscape Conservation Units in the Southwest Region of Western Australia*. Report prepared for Department of Conservation and Land Management.

McCaw L, Hanstrum B (2003) Fire environment of Mediterranean south-west Western Australia. In *Fire in Ecosystems of south-west Western Australia: impacts and management*. (eds Abbott I, Burrows, N), pp. 87-106, Backhuys Publishers, Leiden.

McDougall K (1996) *Vegetation Patterns in the Northern Jarrah Forest of Western Australia in Relation to Dieback History and the Current Distribution of Phytophthora cinnamomi*. PhD Thesis, Murdoch University, Western Australia.

McDowell N, Pockman W, Allen C, Breshears D, Cobb N, Kolb T, Sperry J, West A, Williams D, Yepez, E (2008) Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? Tansley Review. *New Phytologist* **178**, 719-739.

Mills G, McCaw L (in press) *Atmospheric Stability Environments and Fire Weather in Australia-Extending the Haines Index*. Bureau of Meteorology Research Centre Technical Report.

Morgan L, Anne Molin J, George R, McKellar R, Conte J (2008) *Climate Change, Vulnerability and Adaptation for south west Western Australia 1970 to 2006*. Western Australian Agriculture Authority, Perth.

Myers N, Mittermeier R, Mittermeier C, da Fonseca G, Kent J (2000) Biodiversity hotspots for conservation priorities. *Nature* **403**, 803-808.

Newsome J, Pickett C (1993) Palynology and paleoclimatic implications of two Holocene sequences from southwestern Australia. *Paleogeography, Paleoclimatology, Paleoecology* **101**, 245-261.

Niklaus P, Spinnler D, Körner C (1998) Soil moisture dynamics of calcareous grassland under elevated CO2. *Oecologia* **117**, 201-208.

Parmesan C (2006) Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution and Systematics* **37**, 637-659.

Pate J, Dixon K (1981) Plants with fleshy underground storage organs-a Western Australian survey. In *The Biology of Australian Plants* (eds Pate J, McComb A), pp181-215. University of Western Australia Press, Western Australia.

Pickett C, Newsome J (1997) Eucalyptus (Myrtaceae) pollen and its potential role in investigations of Holocene environments in southwestern Australia. *Review of Paleobotany and Palynology* **98**, 187-205.

Pitman A, Narisma G, Pielke R Sr, Holbrook N (2004) Impact of land cover change on the climate of southwest Western Australia. *Journal of Geophysical Research* **109,** D18109.

Pitman A, Narisma G, McAneney J (2007) The impact of climate change on the risk of forest and grassland fires in Australia. *Climatic Change* **84**, 383-401.

Pittock A (2009) *Climate Change: The Science, Impacts and Solutions.* CSIRO Publishing, Collingwood, Victoria.

Raffa K, Aukema B, Bentz B, Carroll A, Hicke J, Turner M, Romme W (2008) Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. *Bioscience* **58** (6), 501-517.

Rahmstorf S, Cazenave A, Church J, Hansen J, Keeling R, Parker D, Somerville R (2007) Recent climate change observations compared to projections. *Science* **316**, 709.

Ramanathan V, Feng Y (2008) On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead. *PNAS* **105**, 14245-14250.

Randall D, Wood R, Bony S, Colman R, Fichefet T, Fyfe J, Kattsov V, Pitman A, Shukla J, Srinivasan J, Stouffer R, Sumi A, Taylor K (2007) Climate models and their evaluation. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds S Solomon, D Qin, M Manning, Z Chen, M Marquis, K Averyt, M Tignor, H Miller), pp. 589-662. Cambridge University Press, Cambridge.

Raupach M, Marland G, Ciais P, Le Quére C, Canadell J, Klepper G, Field C (2007) Global and regional drivers of accelerating CO2 emissions. *Proceedings of the Natural Academy of Sciences* **104**, 10288-10293.

Roderick M, Farquar G (2004) Canges in Australian pan evaporation from 1970 to 2002. *International Journal of Climatology* **24**, 1077-1090.

Rosenzweig C, Karoly D, Vicarelli M, Neofotis P, Wu Q, Casassa G, Menzel A, Root T, Estrella N, Seguin B, Tryjanowski P, Liu C, Rawlins S, Imeson A (2008) Attributing physical and biological impacts to anthropogenic climate change. *Nature* **453**, 353-357.

Shearer B, Crane C, Cochrane A (2004) Quantification of the susceptibility of the native flora of the South-West Province, Western Australia to *Phytophthora cinnamomi*. *Australian Journal of Botany* **52**, 435-443.

Shearer B, Tippet J (1989) *Jarrah Dieback: the Dynamics and Management of Phytophthora cinnamomi in the jarrah (Eucalyptus marginata) Forest of South-Western Australia*. Department of Conservation and Land Management, Research Bulletin No. 3.

Spinnler D, Egli P, Körner C (2002) Four-year growth dynamics of beech-spruce model ecosystems under CO2 enrichment on two different forest soils. *Trees: Structure and Function* **16**, 423-436.

Steffen J, Burbidge A, Hughes L, Kitching R, Lindenmayer D, Musgrave W, Stafford Smith M, Werner P (2009) *Australia's Biodiversity and Climate Change: A Strategic Assessment of the Vulnerability of Australia's Biodiversity to Climate Change*. Technical synthesis of a report to the Natural Resource Management Ministerial Council commissioned by the Australian Government. Department of Climate Change, Canberra.

Strelein G (1988) Gum leaf skeletoniser moth, *Uraba lugens*, in the forests of Western Australia. *Australian Forestry* **51**, 197-204.

Thackway R, Cresswell I (1995) *An Interim Biogeographical Regionalisation for Australia: A Framework for Establishing the National System of Reserves*. Version 4.0. Australian Nature Conservation Agency, Canberra.

Treble P (2004) *A 200 year paleo-rainfall record constructed for southwest Western Australia from speleotherm trace elements*. Department of Earth and Space Sciences, University of California, Los Angeles.

Wand S, Midgley G, Jones M, Curtis P (1999) Responses of wild C4 and C3 grass (Poaceae) species to elevated atmospheric CO2 concentration: a meta-analytic test of current theories and perceptions. *Global change Biology* **5**, 723-741.

Wandoo Recovery Group (2006) *Wandoo Crown Decline – Summary of Research*. University of Western Australia and Wandoo Recovery Group.

Wardell-Johnson G, Williams J, Hill K, Cumming R (1997) Evolutionary biogeography and contemporary distribution of eucalypts. In *Eucalypt Ecology: Individuals to Ecosystems* (eds Williams J, Woinarski, J), pp. 92-128. Cambridge University Press, Cambridge.

Wentworth Group of Concerned Scientists (2009) *Optimising Carbon in the Australian Landscape: How to Guide the Terrestrial Carbon Market to Deliver Multiple Economic and Environmental Benefits*.

Wheeler M, Byrne M (2006) Congruence between phylogeographic patterns in cpDNA variation in *Eucalyptus marginata* (Myrtaceae) and geomorphology of the Darling Plateau, south-west of Western Australia. *Australian Journal of Botany* **54**, 17-26.

Williams A, Karoly D, Tapper N (2001) The sensitivity of Australian fire danger to climate change. *Climatic Change* **49**, 171-191.

Yates C, Abbott I, Hopper S, Coates D (2003) Fire as a determinant of rarity in the south-west Australian global biodiversity hotspot. In *Fire in Ecosystems of South-West Western Australia: Impacts and Management*. (eds Abbott I, Burrows N), pp. 395-420. Backhuys Publishers, Leiden.

Yates C, Ladd P, Coates D, McArthur S (2007) Hierarchies of cause: understanding rarity in an endemic shrub *Verticordia staminosa* (Myrtaceae) with a highly restricted distribution. *Australian Journal of Botany* **55**, 194-205.

Yates C, Elith J, Latimer A, Le Maitre D, Midgley G, Schurr F, West A (2009) Projecting climate change impacts on species distributions in megadiverse South African Cape and Southwest Australian Floristic Regions: Opportunities and challenges. *Austral Ecology*

Yates C, McNeill A, Elith J, Midgley G (2009) Assessing the impacts of climate change and land transformation on Banksia in the South West Australian Floristic Region, *Diversity & Distribution*s, 1-15.

Zenkich S, Froend R, Turner J, Gailitis V (2002) Influence of groundwater depth on the seasonal sources of water accessed by *Banksia* tree species on a shallow, sandy coastal aquifer. *Oecologia* **131**, 8-19.

Appendix 1 Historic and predicted climate for forested Landscape Conservation Units.

LCU NAME	Historic Climate (1960-1990)		Low Climate Change Impact Scenario_2030		Moderate Climate Change Impact Scenario_2030		High Climate Change Impact Scenario_2030	
	Summer Areal Potential Evapotranspiration (mm)	Average Annual Rainfall (mm)	Summer Areal Potential Evapotranspiration (mm)	Average Annual Rainfall (mm)	Summer Areal Potential Evapotranspiration (mm)	Average Annual Rainfall (mm)	Summer Areal Potential Evapotranspiration (mm)	Average Annual Rainfall (mm)
Abba Plain	460	894	467	868	476	817	479	813
Blackwood Plateau	460	991	467	962	476	904	480	898
Blackwood Scott Plain	458	1068	465	1037	474	974	477	966
Central Blackwood	471	893	476	866	486	815	490	809
Central Jarrah	488	1054	493	1022	504	965	508	960
Central Karri	453	1162	460	1128	469	1059	472	1048
Collie Wilga	458	721	462	700	472	659	476	653
Dandaragan Plateau	538	711	541	690	554	659	558	643
Darkin Towering	470	565	473	549	484	517	489	509
Eastern Blackwood	463	605	467	588	478	552	482	545
Eastern Dissection	517	572	521	557	531	527	537	518
Eastern Murray	496	641	500	623	511	588	516	582
Frankland Unicup Muir	461	692	466	673	476	631	481	617
Margaret Plateau	461	1090	468	1059	477	995	480	989
Monadnocks Uplands Valleys	509	855	513	830	524	784	529	777
North Eastern Dissection	534	597	538	581	549	553	554	538
North Western Dissection	538	735	542	714	554	680	558	665
North Western Jarrah	533	1029	537	998	549	946	553	935
Northern Karri	465	1076	471	1044	480	981	484	971
Northern Sandy Depression	527	723	531	703	542	666	547	655
Northern Upper Collie	467	723	470	702	481	662	485	655
Northern Upper Plateau	538	721	542	701	553	667	557	652
Redmond Siltstone Plateau	459	979	465	952	475	891	479	866
South Eastern Upland	454	756	459	736	469	688	474	668
Southern Dunes	455	1223	462	1187	471	1114	474	1103
Southern Hilly Terrain	455	1045	461	1016	471	951	475	930
Southern Karri	454	1121	460	1089	470	1021	473	1006
Southern Swampy Plains	455	1242	461	1207	470	1131	473	1116
Strachan Cattaminup	459	943	465	916	474	859	478	848
Yornup Wilgarup Perup	469	758	474	736	484	692	488	681

Appendix 2 Distribution of jarrah forest by Landscape Conservation Units

Landscape Conservation Unit	DEC Estate			TOTAL	Multiple use State forest			TOTAL	%
	Canopy Cover 10-49%	Canopy cover 50-80%	Canopy cover >80%		Canopy Cover 10-49%	Canopy cover 50-80%	Canopy cover >80%		
Blackwood Plateau	64,250	201,550	1,770	267,570	46,130	136,020	910	183,060	32%
Blackwood Scott Plain	3,010	4,880	100	7,990	560	1,200	-	1,760	78%
Central Blackwood	6,700	65,900	1,080	73,680	5,000	48,910	850	54,760	26%
Central Jarrah	76,160	214,620	1,870	292,650	64,530	177,220	900	242,650	17%
Central Karri	1,070	14,840	110	16,020	690	11,480	90	12,260	23%
Collie Wilga	10,870	38,210	50	49,130	6,340	25,570	10	31,920	35%
Dandaragan Plateau	120	-	-	120	-	-	-	-	100 %
Darkin Towering	1,090	500	-	1,590	-	-	-	-	100 %
Eastern Blackwood	3,300	4,140	-	7,440	130	720	-	850	89%
Eastern Dissection	9,630	4,150	-	13,780	4,220	2,980	-	7,200	48%
Eastern Murray	9,500	6,140	-	15,640	7,110	4,530	-	11,640	26%
Frankland Unicup Muir	11,000	11,240	-	22,240	40	10	-	50	100 %
Margaret Plateau	1,400	8,240	40	9,680	580	600	-	1,180	88%
Monadnocks Uplands Valleys	32,100	47,710	50	79,860	22,170	36,060	50	58,280	27%
Northern Upper Plateau	14,400	2,920	-	17,320	2,230	2,810	-	5,040	71%
North Eastern Dissection	6,150	20	-	6,170	-	-	-	-	100 %
North Western Dissection	10,540	5,420	190	16,150	1,590	3,270	170	5,030	69%
North Western Jarrah	22,300	66,490	530	89,320	16,490	51,130	520	68,140	24%
Northern Karri	8,840	66,160	1,630	76,630	6,930	51,580	780	59,290	23%
Northern Sandy Depression	29,320	14,200	-	43,520	14,530	10,740	-	25,270	42%
Northern Upper Collie	31,870	67,700	80	99,650	14,590	38,340	80	53,010	47%
Redmond Siltstone Plateau	3,690	22,720	470	26,880	10	10	-	20	100 %
South Coast	40	160	-	200	-	-	-	-	100 %
South Eastern Upland	9,280	36,990	380	46,650	530	6,500	-	7,030	85%
Southern Dunes	3,380	2,860	-	6,240	-	-	-	-	100 %
Southern Hilly Terrain	9,800	48,380	1,340	59,520	40	350	-	390	99%
Southern Karri	4,000	36,180	220	40,400	730	7,330	10	8,070	80%
Southern Swampy Plains	8,650	11,730	10	20,390	140	350	-	490	98%
Strachan Cattaminup Jigsaw	5,020	46,710	10	51,740	3,190	35,030	10	38,230	26%
Swan Coastal Plain	15,310	1,680	-	16,990	3,650	730	-	4,380	74%
Yornup Wilgarup Perup	15,040	89,030	150	104,220	5,910	52,550	30	58,490	44%
Total	427,830	1,141,470	10,080		228,060	706,020	4,410		
	1,579,380				938,490				41%

Appendix 3 Distribution of karri forest by Landscape Conservation Units

Landscape Conservation Unit	DEC Estate				Multiple use State forest				
	Canopy Cover <50%	Canopy cover 50-80%	Canopy cover >80%	TOTAL	Canopy Cover <50%	Canopy cover 50-80%	Canopy cover >80%	TOTAL	%
Blackwood Plateau	10	50	-	60	-	10	-	10	83%
Blackwood Scott Plain	40	20	-	60	-	-	-	-	100%
Central Blackwood	-	70	-	70	-	10	-	10	86%
Central Karri	2,890	44,050	2,020	48,960	2,680	36,010	1,960	40,650	17%
Margaret Plateau	600	3,480	10	4,090	20	30	-	50	99%
Northern Karri	3,680	23,790	180	27,650	3,100	14,220	60	17,380	37%
Redmond Siltstone Plateau	80	260	10	350	-	-	-	-	100%
South Coast	160	300	-	460	-	-	-	-	100%
South Eastern Upland	-	130	-	130	-	110	-	110	15%
Southern Dunes	50	560	-	610	-	10	-	10	98%
Southern Hilly Terrain	80	2,490	20	2,590	10	130	10	150	94%
Southern Karri	4,400	42,540	280	47,220	2,230	12,520	100	14,850	69%
Southern Swampy Plains	1,390	12,480	10	13,880	150	1,000	-	1,150	92%
Strachan Cattaminup Jigsaw	190	12,960	10	13,160	150	8,300	10	8,460	36%
Yornup Wilgarup Perup	-	40	-	40	-	40	-	40	0%
Total	13,570	143,220	2,540		8,340	72,390	2,140		
	159,330				82,870				48%

Appendix 4 Distribution of wandoo forest by Landscape Conservation Units

Landscape Conservation Unit	DEC Estate				Multiple use State forest				
	Canopy Cover 10-49%	Canopy cover 50-80%	Canopy cover >80%	TOTAL	Canopy Cover 10-49%	Canopy cover 50-80%	Canopy cover >80%	TOTAL	%
Central Blackwood	10	30	0	40	10	30	0	40	0%
Central Jarrah	380	190	0	570	310	150	0	460	19%
Collie Wilga	1,330	1,370	0	2,700	220	410	0	630	77%
Dandaragan Plateau	60	0	0	60	0	0	0	-	100%
Darkin Towering	600	140	0	740	0	0	0	-	100%
Eastern Blackwood	200	230	0	430	10	40	0	50	88%
Eastern Dissection	16,400	3,570	0	19,970	3,750	1,240	0	4,990	75%
Eastern Murray	9,090	1,730	0	10,820	4,340	750	0	5,090	53%
Franklin Unicup Muir	810	1,460	0	2,270	0	0	0	-	100%
Monadnocks Uplands Valleys	7,250	2,260	10	9,520	4,760	1,630	10	6,400	33%
Northern Upper Plateau	8,570	620	0	9,190	1,600	420	0	2,020	78%
North Eastern Dissection	7,200	250	0	7,450	0	0	0	-	100%
North Western Dissection	13,920	2,870	20	16,810	2,740	1,470	0	4,210	75%
North Western Jarrah	1,570	910	0	2,480	290	480	0	770	69%
Northern Sandy Depression	29,450	5,680	0	35,130	9,690	3,390	0	13,080	63%
Northern Upper Collie	7,170	5,420	0	12,590	3,320	3,190	0	6,510	48%
Strachan Cattaminup Jigsaw	0	50	0	50	0	30	0	30	40%
Swan Coastal Plain	850	0	0	850	30	0	0	30	96%
Yornup Wilgarup Perup	2,320	5,330	10	7,660	130	440	0	570	93%
Total	107,180	32,110	40		31,200	13,670	10		
	139,330				44,880				68%

Appendix 5 Distribution of tingle forest by Landscape Conservation Units

Landscape Conservation Unit	DEC Estate				Multiple use State forest				
	Canopy Cover 10-49%	Canopy cover 50-80%	Canopy cover >80%	TOTAL	Canopy Cover 10-49%	Canopy cover 50-80%	Canopy cover >80%	TOTAL	%
Redmond Siltstone Plateau	60	560	370	990	0	0	0	-	100%
Southern Hilly Terrain	440	14,860	4,500	19,800	10	60	0	70	100%
Southern Karri	0	30	0	30	0	0	0	-	100%
Southern Swampy Plains	340	6,160	160	6,660	0	0	0	-	100%
Total	840	21,610	5,030		10	60	0		
	27,480				70				100%