DEPARTMENT OF PLANNING, INDUSTRY & ENVIRONMENT

Climate change impacts in the NSW and ACT Alpine region

Impacts on biodiversity

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ACT	Australian Capital Territory
BCC	Bioclimatic Class
BIAP	Biodiversity Impacts and Adaptation Project
CSIRO	Commonwealth Scientific and Industrial Research Organisation
EHA	effective habitat area
FPC	foliage projective cover
DPIE	Department of Planning, Industry and Environment
GCM	Global Climate Model
GDM	Generalised Dissimilarity Model
GIS	geographic information system
KNP	Kosciuszko National Park
KTPs	Key Threatening Processes
MCAS-S	Multi-Criteria Analysis Shell for Spatial Decision Support
NARCliM	NSW/ACT Regional Climate Modelling project
NPWS	NSW National Parks and Wildlife Service
NSW	New South Wales
NVM	Native Vegetation Management
OEH	Office of Environment and Heritage
REMP	Rapid Evaluation of Metapopulation Persistence
RCM	Regional Climate Model
RGB	red green blue
SoS	*Saving our Species*
UNE	University of New England
3CMP	climate ready metapopulation analysis

Summary of findings

Impacts on biodiversity in the NSW and ACT Alpine region

1. Vegetation communities are projected to experience 21–70% change in species composition in the far future (2060 to 2079). Alpine Herbfields, Montane Bogs and Fens, Grassy Woodlands and Wet Sclerophyll Forest are projected to decrease in area and compositional suitability as climatic conditions transition to those better suiting species of Subalpine Woodland and Dry Sclerophyll Forest, which are predicted to expand accordingly.
2. Key flora species are predicted to be impacted by future changes in climate, including plants listed as critically endangered: the black-hooded sun orchid (*Thelymitra atronitida*), Kelton's leek orchid (*Prasophyllum keltonii*) and *Prasophyllum bagoense*. These species will be under increasing pressure as climate change proceeds.
3. Other threatened flora species predicted to be impacted are pale pomaderris, suggan buggan mallee, feldmark grass, anemone buttercup, austral pillwort, mauve burr-daisy, slender greenhood, Max Mueller's burr-daisy, shining cudweed, leafy anchor plant, Monaro golden daisy, slender greenhood, Kiandra leek orchid.
4. Mammals from habitats predicted to be most impacted by future climate change include southern myotis (*Myotis macropus*), eastern pygmy possum (*Cercartetus nanus*), mountain pygmy possum (*Burramys parvus*), broad-toothed rat (*Mastacomys fuscus*), smoky mouse (*Pseudomys fumeus*), spotted-tailed quoll (*Dasyurus maculatus*) and brush-tailed rock-wallaby (*Petrogale penicillate*).
5. The Australian painted snipe (*Rostratula australis*) is an endangered bird species that occupies montane lakes, and bogs and fens. These areas are likely to contract under the projected future climate, potentially placing the snipe at greater risk from habitat loss. Other bird species listed as vulnerable are projected to be impacted by climate change. Most utilise a variety of habitats and the advantage of high mobility may provide some flexibility as they are confronted with changing climatic conditions.
6. Subalpine Woodlands, Alpine Heaths and Herbfields, and Alpine Bogs and Fens are habitat for several species of frogs listed as critically endangered. These vegetation classes also provide habitat for the endangered alpine she-oak skink (*Cyclodomorphus praealtus*) and the Guthega skink (*Liopholis guthega*). These habitats are predicted to experience large change by 2060 to 2079. It is predicted that the southern corroboree frog (*Pseudophryne corroboree*) and alpine tree frog (*Litoria verreauxii alpina*) will also be severely impacted.
7. Where habitat condition and connectivity permit, some of the region's biodiversity will have the opportunity to migrate to emerging suitable habitats at higher altitudes. This may lead to conflicting management priorities, as native species compete for resources. Although the velocity of change is expected to be less than in other parts of the state, consequences may be greater as the Alpine region sits at the edge of a major environmental gradient. There is nowhere for species to migrate beyond mountain tops as temperatures increase and colder high elevation climate envelopes contract. This presents unique challenges to the conservation of alpine biodiversity.
8. Species already listed as threatened may need novel management interventions to persist through near and far future climate. It is likely more species and their ecosystems will need special management in the future even though they may appear to have sufficient habitat and stable populations at present. Where species are isolated or without the ability to propagate and colonise emerging areas of suitable habitat, assisted relocation may be necessary.

1. Introduction

1.1 Background

Alpine regions throughout the world are important biodiversity hotspots with high levels of endemism. During the last five decades, unprecedented changes to ecosystems have occurred globally due to changing climate and human activities (Millennium Ecosystem Assessment 2005; Chapin et al. 2009). Accelerating climate change combined with other anthropogenic disturbances leads to habitat loss and alteration, as well as shifts in species compositions and assemblages. This process threatens biodiversity and ultimately the resilience of ecosystems and entire regions (Chapin et al. 2009). Alpine biodiversity is highly vulnerable to the impacts of climate change (IPCC 2007; Buytaert et al. 2011).

Predicting the response of alpine biodiversity to climate change has become a research priority (Hennessy et al. 2007; Worboys et al. 2010; Morrison & Pickering 2013). Conserving the Alpine region's biodiversity requires understanding potential future risks and anticipating biodiversity's response to climatic and ecological changes (Pereira at al. 2010).

Climate projections are predicting increased variability in climate, above average temperature and longer dry seasons (IPCC 2007; Buytaert et al. 2011). High variability will disrupt ecosystem functions, resulting in higher rates of species loss and turnover (Boulanger et al. 2007; Buytaert et al. 2009). Australian native vegetation is naturally dynamic, transitioning along the different phases of an adaptive cycle after a disturbance (Thapa et al. 2016). Severe or ongoing disturbance and climate change cause ecosystem processes to cross thresholds, leading to state change; for example, from grassland to woodland (Wolf et al. 2007). Changes such as temperature increases, sea level rise and changing patterns of precipitation may also result in 'multi-directional' species movement (VanDerWal et al. 2013). Species are generally expected to follow climatic niches, the area in which climatic conditions are suitable, by shifting to higher altitudes or latitudes. Successful response of individual species to these changes depends on their adaptive capacity and that of the ecosystems they inhabit.

When landscape effects (distances and habitat fragmentation) are considered, it becomes apparent that biodiversity cannot always keep pace with the rate of environmental change, or find migratory pathways to more suitable habitat. Without management intervention, this will lead to local or global extinctions. Some areas that have lost their historic biota and where neighbouring communities are unable to colonise will become home to novel communities that have not previously existed. Pioneer species may appear from elsewhere or from a previously suppressed seed bank, and new or invasive species may colonise the system. This could be in the form of unprecedented weed invasions (Whalley et al. 2011).

Despite representing only 0.16% of Australia's land surface, the NSW and ACT Alpine region is disproportionately important nationally and internationally due to its conservation significance, economic values, provision of ecosystems goods and services (Worboys et al. 2010; Morrison & Pickering 2013), and its social and cultural heritage (Morrison & Pickering 2013). The region is trending towards higher temperatures and decreasing precipitation, resulting in dramatic changes to existing ecosystems, and to the ski/tourism and hydropower generation industries (Hennessy et al. 2007; Worboys et al. 2010). These changes will adversely impact on economies downstream as agriculture, tourism and hydropower all rely on a secure supply of water from upstream.

Endemic alpine species are often dependent on adequate snow cover for their habitats (Pickering et al. 2004; Hughes L 2011). The endangered mountain pygmy possum is expected to suffer substantial habitat loss due to changes in snow cover (Hughes 2011). Species interactions may be affected and there may be increased predation by foxes and cats associated with decreased snow cover (Hughes 2011). This may also threaten vulnerable broad-toothed rat populations, as this species has a narrow environmental tolerance and would be at increased risk of predation.

With increasing summer temperatures and decreasing precipitation, the intensity of bushfires in the NSW and ACT Alpine region is expected to rise. It is predicted that by 2020 the intensity of fires may increase by 65% under the worst-case scenario, and by 300% by 2050 (Lucas et al. 2007). The NSW and ACT Regional Climate Modelling (NARCliM) projections have predicted that the Alpine region is likely to experience higher temperatures, fewer cold nights, lower precipitation and lower snowfall in the near and far futures. The frequency and intensity of extreme events, such as floods, erosion and fire, are also expected to increase, irreversibly influencing the composition, structure and function of the alpine ecosystems.

Ecosystem processes change at multiple scales (Forman & Godron 1986; Turner 2005) as different controls and processes are characteristic of each scale in time and space (Wu 1999) and are differentiated by biotic and abiotic structure (Pickett & Cadenasso 1995). Understanding how and why ecosystems change requires an understanding of the key drivers that operate at different scales and is central to ecosystem science (Sutherland et al. 2013). Spatial scale is a window through which ecosystems can be viewed (Wiens 1989; Parsons & Thoms 2007). What is seen at any scale is related to the size of the window through which the system is viewed (Wiens 1989) and to the way the scales of observation used relate to the hierarchical organisation of processes operating within the system (Dollar et al. 2007). Thus, this analysis is discussed in the context of three regions of varying scale (Figure 1), allowing important ecological processes to be adequately framed, and providing a broader context to our interpretations of ecosystem behaviour.

This report is part of a larger project delivered by the NSW Department of Planning, Industry and Environment (DPIE) on the various impacts from climate change on the NSW and ACT Alpine region, hereafter referred to as the Alpine region.

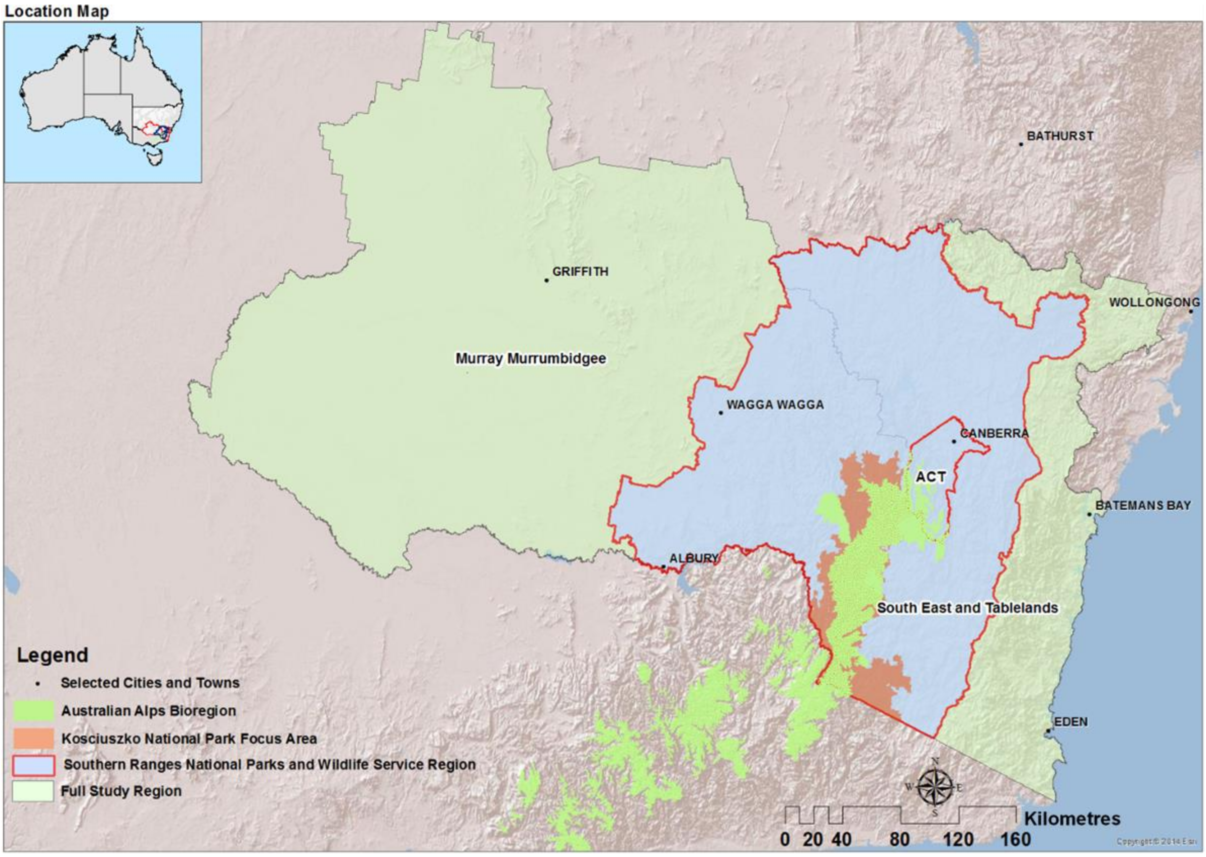


Figure 1 **Study areas used to assess the biodiversity impacts of climate change in the Alpine region at three spatial scales**

The three spatial scales are: full study region (light green), Southern Ranges National Parks and Wildlife Service region (light blue) and Kosciuszko National Park focus area (orange). The Australian Alps bioregion is also shown (green).

1.2 Objectives

This study used recent biodiversity impacts and adaptation modelling of the direct influence of climate change on species composition and the resulting impacts on biodiversity persistence to report on the impacts for biodiversity in the Alpine region and surrounding areas. This assessment reports on how the recent historic (baseline period 1990 to 2009) biodiversity of the Alpine region is likely be impacted under NARCliM modelled near future (2020 to 2039) and far future (2060 to 2079) climate projections. The adaptive capacity of alpine vegetation classes and the habitats of threatened flora and fauna are assessed by considering their current condition, and levels of habitat fragmentation and connectivity. The benefits that result from potential biodiversity conservation or restoration actions are also reported to support biodiversity management in the alpine and surrounding region aimed at delivering better long-term biodiversity outcomes.

1.3 Outputs

Output	Details	Key user
Report	Five sections detailing climate change impacts on the region's biodiversity including vegetation communities and fauna	Biodiversity conservation policy and management sectors; private sector that contributes to biodiversity conservation; those interested in understanding more about climate change impacts on biodiversity
Maps and tables	Twenty-six figures and 14 tables representing analysis findings	Biodiversity conservation policy and management sectors; private sector contributing to biodiversity conservation; researchers in the fields of ecology, resilience, climate change
Spatial and tabular data	The spatial and tabular data underpinning the findings of this analysis (see Appendix A for a complete list of source data)	Researchers who work in the fields of ecology, resilience, climate change; those wishing to conduct further analysis or reporting on the available data

1.4 Focus region

The Alpine region is located in the south-eastern corner of mainland Australia, forms the southern end of the Great Dividing Range and covers a total area of 1.64 million hectares that extend over 500 kilometres (Morrison & Pickering 2013). The highest peak, Mount Kosciuszko, rises to an altitude of 2228 metres. There are 11 national parks and reserves within the region and it extends across most of the Alpine bioregion (Crabb 2003). Kosciuszko National Park (KNP) and its plant communities are recognised by UNESCO as a World Biosphere Reserve and the park is listed in the National Heritage List (ISC 2004).

The climate within the Alpine region is highly variable. The annual average temperature in the areas surrounding KNP is 4°C. The summer average temperature ranges from 10–12°C with an average maximum range of 14–16°C. In comparison, the average minimum winter temperature ranges from –6 to –4°C. Average minimum and maximum annual rainfall varies considerably, both spatially and temporally.

The long-term temperature has been increasing since the 1990s (Hennessy et al. 2007). The mean temperature has risen by 0.5°C per decade since 1990 and is projected to increase by 2.6–3°C by 2070 (AdaptNSW website). Long-term rainfall is also highly variable and is projected to decrease in winter and spring and increase in autumn (AdaptNSW website; Hennessy et al 2007). The predicted increase in temperature and decrease in precipitation will likely result in dramatic changes in existing ecosystem functions and cause the loss of ecosystem services (Hennessy et al. 2007; Worboys et al. 2010). Further, these changes in climate may result in loss of endemic alpine herbfields, bogs and fens and change in species richness.

The focus of this study is KNP, which is also viewed in the context of the Southern Ranges National Parks and Wildlife Service (NPWS) region and the full study region, which takes in the coast to the east and the NSW Murray River catchment area to the west. Considering cross-scale effects is considered essential to successful natural resource management (Walker & Salt 2012) and the use of three different regions is intended to provide a more complete picture of biodiversity in the Alpine region and how it responds to the impacts of climate change.

Changes in ecosystems are rarely simple, as responses to drivers of change are mediated through a range of interactions and feedbacks between biotic and abiotic components and processes. Understanding the patterns of response at different scales is critical to our ability to manage the complex ecosystems of the Alpine region, and to be able to make predictions about their future conditions.

2. Method

To report climate change impacts on alpine biodiversity, this study primarily draws on information from the Biodiversity Impacts and Adaptation Project (BIAP) (OEH 2016; Drielsma et al. 2017), which extended ‘3C’ modelling for biodiversity under future climate (Drielsma et al. 2015) by including 12 additional NARCliM simulations. The BIAP forecasted broad impacts of climate change on biodiversity across eastern Australia and identified adaptation opportunities to minimise biodiversity loss. This analysis also draws on regional-scale connectivity modelling performed by DPIE for the south-east (Love et al. 2015) and Riverina (Love et al. 2017) Local Land Services and presents draft species occupancy modelling currently being prepared for the NSW *Saving our Species* (SoS) program.

The 3C modelling for biodiversity under future climate project extended under BIAP was part of the Australian Government’s Regional Natural Resource Management Planning for Climate Change, stream 2. More information about 3C and its products are available online on the TerraNova Climate Change Adaptation Information Hub.

2.1 Source of data

NARCliM simulations from four Coupled Model Intercomparison Project phase 3 (CMIP3) Global Climate Models (GCMs) were used to drive three Regional Climate Models (RCMs) to form a 12-member GCM/RCM ensemble (Evans et al. 2014). The four selected GCMs cover a broad range of possible climate outcomes. This includes MIROC3.2, which is a warm/wet scenario, ECHAM5, a hot/similar precipitation scenario, CCCMA3.1, a hot/wet scenario, and CSIRO-Mk3.0, a warm/dry scenario. For future projections, the Special Report on Emissions Scenarios (SRES) business-as-usual A2 scenario was used (IPCC 2000). The three selected RCMs are three physics scheme combinations of the Weather Research and Forecasting (WRF) model. Each simulation consists of three 20-year runs (1990 to 2009, 2020 to 2039, and 2060 to 2079). The four GCMs were chosen based on a number of criteria: i) adequate performance when simulating historic climate; ii) most independent; iii) cover the largest range of plausible future precipitation and temperature changes for Australia. The three RCMs correspond to three different physics scheme combinations of the WRF V3.3 model (Skamarock et al. 2008), which were also chosen for adequate skill and error independence, following a comprehensive analysis of 36 different combinations of physics parameterisations over eight significant East Coast Lows (ECLs) (Evans et al. 2012; Ji et al. 2014). For the selected three RCMs, the WRF Double Moment 5-class (WDM5) microphysics scheme and NOAH land surface scheme are used in all cases. Refer to Evans et al. (2014) for more details on each physics scheme.

We acknowledge that the results are model dependent (as all model studies are) but through the use of this carefully selected ensemble we have attempted to minimise this dependence. By using this model selection process, we have shown that it is possible to create relatively small ensembles that are able to reproduce the ensemble mean and variance from the large parent ensemble (i.e. the many GCMs) as well as minimise the overall error (Evans et al. 2013a).

Some initial evaluation of NARCliM simulations shows that they have strong skill in simulating the precipitation and temperature of Australia, with a small cold bias and overestimation of precipitation on the Great Dividing Range (Evans et al. 2013b; Ji et al. 2016). The differing responses of the different RCMs confirm the utility of considering model independence when choosing the RCMs. The RCM response to large-scale modes of variability also agrees well with observations (Fita et al. 2016). Through these evaluations we found that while there is a spread in model predictions, all models perform adequately with no single model performing the best for all variables and metrics. The use of the full ensemble provides a measure of robustness such that any result that is common through all models in the ensemble is considered to have higher confidence.

Data for this analysis (listed in Appendix A) were sourced from BIAP and 3C derived products and DPIE corporate datasets such as the BioNet Atlas and the NSW vegetation map version 3. The findings from BIAP will be available alongside snapshots for other impact and adaptation themes on the AdaptNSW website. More detailed findings, products and data arising from BIAP will be downloadable via the AdaptNSW data portal.

The statewide native vegetation condition layer (Appendix B, *B1. Current vegetation condition*) was originally developed for the NSW Native Vegetation Management (NVM) benefits analyses (Drielsma et al. 2010; Drielsma et al. 2012) and extended under BIAP. Effective habitat area (EHA) mapping uses the cost–benefit approach (Drielsma et al. 2007a; Drielsma et al. 2014). Habitat connectivity (Appendix B, *B3. Habitat connectivity*) and metapopulation analysis (Appendix B, *B4. Climate ready metapopulation analysis*) were sourced from the 3C project and additional fine-scale analysis undertaken for Local Land Services (Love et al. 2015; Love et al. 2017) using the spatial links tool (Drielsma et al. 2007b). The biodiversity benefits mapping, including conservation and revegetation benefits (Appendix B, *B6. Conservation manage benefits* and *B7. Revegetation benefits*) are sourced from BIAP and the projected changes in benefits over time (Appendix B, *B8. Relative change in benefits*) are sourced from 3C. The 3C products were modelled between 2000 and 2050.

Keith (2002) has derived a NSW wide composite spatial data layer differentiating vegetation types from a classification of 106 native vegetation classes and shows vegetation types for extant native vegetation across NSW and the ACT (Keith 2002, data.environment.nsw.gov.au). Each class is composed of related plant communities with structural and compositional similarities and common habitat characteristics. At the time of our analysis this layer provided the most consistent and complete mapping of vegetation types across the entire analysis region.

Draft species occupancy models (Section 3.7) were supplied from 'Spatial prioritisation for species resilience' (OEH & UNE unpub.), a research project currently being undertaken for SoS. *Saving our Species* is an ongoing statewide program addressing the growing number of plants and animals in New South Wales facing extinction.

Species occupancy models are currently draft products and are provided as examples of additional information relevant to managing the region's biodiversity (OEH & UNE unpub.).

2.2 Analysis

This analysis used existing spatial products relating to biodiversity resilience and adaptive capacity, climate change impacts, and management to aid adaptation, to report on measures for vegetation classes and threatened flora and fauna considered to be important indicators of the impacts of climate change on biodiversity in the Alpine region.

This analysis reported on climate change impacts for:

- the mapped extents of 13 vegetation classes most relevant to the Alpine region, out of the 68 vegetation classes mapped as occurring in the full study region
- site occurrence records for 11 threatened flora and 23 threatened fauna species from within the full study area that are under the greatest pressure from future climate change, with a focus on those that occur in the KNP
- estimated dissimilarity in species composition between current and future climate projections, reported at each location (grid cell). This analysis estimated and mapped how unsuitable each location will become in the near (2020 to 2039) and far future (2060 to 2079) NARCliM projection periods for the species it currently supports, and how compositionally dissimilar the vegetation that is best suited to future conditions is, to that which currently occurs
- changes to the expected biodiversity benefits across the region. Expected biodiversity benefits measure the expected gains in regional biodiversity persistence that result from retaining intact habitats or restoring lost habitats. Using 3C modelling (Drielsma et al. 2015), we report on how climate change is expected to change these benefits between the recent past (2000 baseline) and 2050.

In addition, three spatial products relating to the resilience of biodiversity and its current capacity to respond to climate change were reported:

- current vegetation condition (as of 2012) – estimating how intact or degraded native vegetation at each location (grid cell) or region is, relative to a maximum potential ‘pristine’ state
- effective habitat area – measuring the habitat’s spatial context, which integrates the condition of vegetation at each location (grid cell) with measures of its connectivity to, and the condition of, surrounding habitat
- habitat connectivity – measuring how the placement and structure of habitat is most likely to facilitate the movement of biodiversity through the landscape.

Initially, datasets from past DPIE (previously Office of Environment and Heritage) projects (including 3C Modelling, BIAP and regional-scale products) were assessed in terms of their relevance to measuring climate change impacts on alpine biodiversity and their suitability for reporting within the applied framework. The selected products, while predominantly developed to provide statewide coverage, were considered suitable for regional-scale analysis and most suitable for reporting the biodiversity impacts of climate change in the Alpine region.

All raster data were converted to Lamberts conformal coordinate systems in ArcMap 10.1, with a spatial resolution of 250 metres used for consistency. The method of extracting values from existing products involved intersecting raster layers using GIS analysis tools in ArcGIS 10.1. The analysis primarily consisted of developing statistics using the spatial analysis zonal statistics toolset. This toolset was used to summarise raster layers within the mapped extents of vegetation classes. Threatened species records were extracted from the BioNet Atlas and similarly used for reporting impact related spatial information.

Maps and graphs in this report, and associated data, were all prepared using ArcMap 10.1, R Studio and Microsoft Excel.

2.3 Bioclimatic Class envelopes

The modelling of biodiversity impacts under climate change relies on a representation of biodiversity provided here by spatially interpolated Bioclimatic Class (BCC) envelopes. BCCs are a data driven classification of biodiversity based on a Generalised Dissimilarity Model (GDM) produced for the NARCliM region (OEH 2016) and based on vascular plant records and environmental predictor surfaces. BCCs were developed specifically as a surrogate for biodiversity as they allow unconstrained modelling of biodiversity shifts in response to dynamic climate variables, without needing to relate back to existing vegetation communities that may be displaced or not exist at all under future climates. The probabilistic rendering of BCC envelopes (henceforth referred to as BCC envelopes or 'envelopes') across space (Figure 2) allows for the expected disaggregation of existing relationships as overlaps between classes and the species they represent change and new compositional overlaps emerge (Drielsma et al. 2015; Drielsma et al. 2017).

The compositional similarity between individual BCC envelopes is displayed graphically by employing relative RGB colouring, whereby classes with similar species composition are portrayed with similar colour (e.g. Figure 2). Species composition is the result of a history of relationships, events and variables, some relatively static such as geology and terrain, others dynamic such as patterns of weather and fire regime. The BCC envelopes spatially define biophysical capability to support each BCC. Each location has been allocated probabilistically to each envelope at the 1990 to 2009 baseline, and projected at 2020 to 2039 and 2060 to 2079 for each of the NARCliM climate futures. As the climatic conditions at a location change, envelopes shift, favouring shifts in BCC distribution, subject to the possibility of migration. This is displayed as a change in colour over time at any location (shown in Figure 3 for the three RCMs under the CSIRO-Mk3.0 GCM for 2020 to 2039 and 2060 to 2079).

At the 1990 to 2009 baseline period, we expect that the distribution of each BCC aligns closely to its corresponding envelope. Subsequent predicted shifts do not signify a complete or sudden turnover of all species. At least in the short term, transitions are generally between BCC envelopes with similar species composition, indicated graphically by a subtle change in colour. Actualised transitions will occur over time whereby a proportion of species leave or enter each location, while others may be able to adapt and remain. However, species and ultimately whole communities will diminish if: envelopes disappear completely; the velocity of change is too high for successful migrations to occur; or environmental gradients are naturally or anthropogenically truncated or fragmented.

BCC envelopes are used to represent the potential composition and distribution of biodiversity across the full study region. To accommodate reporting, BCC envelopes were overlaid with vegetation classes (Section 2.4). This allowed reporting of what changes in biodiversity the Alpine region can expect with future changing climate in the context of known and identifiable vegetation types. Figure 3 shows BCC envelope distributions under the baseline period and the CSIRO-Mk3.0 GCM for the three RCMs for the near and far future separately.

Overall, the distribution of BCC envelopes is predicted to change dramatically across the full study region in the far future relative to the baseline period; however, changes in BCC envelopes differ greatly under the 12 NARCliM scenarios. Across both climate futures, the most dramatic changes are consistently observed between Wagga Wagga and Griffith. In the higher altitude alpine areas, the velocity of change is slower, shown by smaller geographic shifts in BCC envelopes with transitions to relatively similar BCCs over near and far future periods; however, biodiversity represented by classes contracting at higher altitudes lacks emerging suitable habitats in the future; therefore, species in these areas may be more at risk from change. Along the Alpine regions of New South Wales and the ACT, the greatest compositional changes in BCCs are predicted along the south-eastern, south-western and the northern edges of KNP.

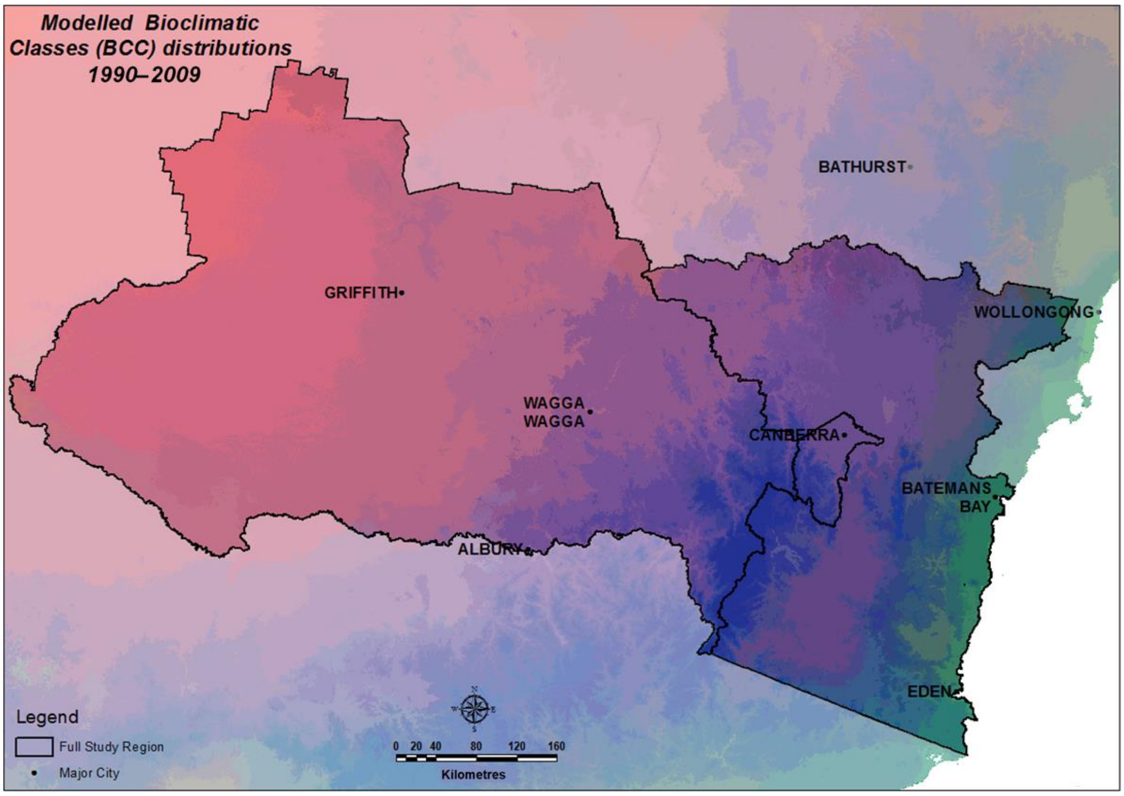


Figure 2 **Modelled Bioclimatic Class (BCC) envelope distributions for the full study region for the 1990 to 2009 baseline period**

Colours of similar hue represent BCCs with similar species compositions.

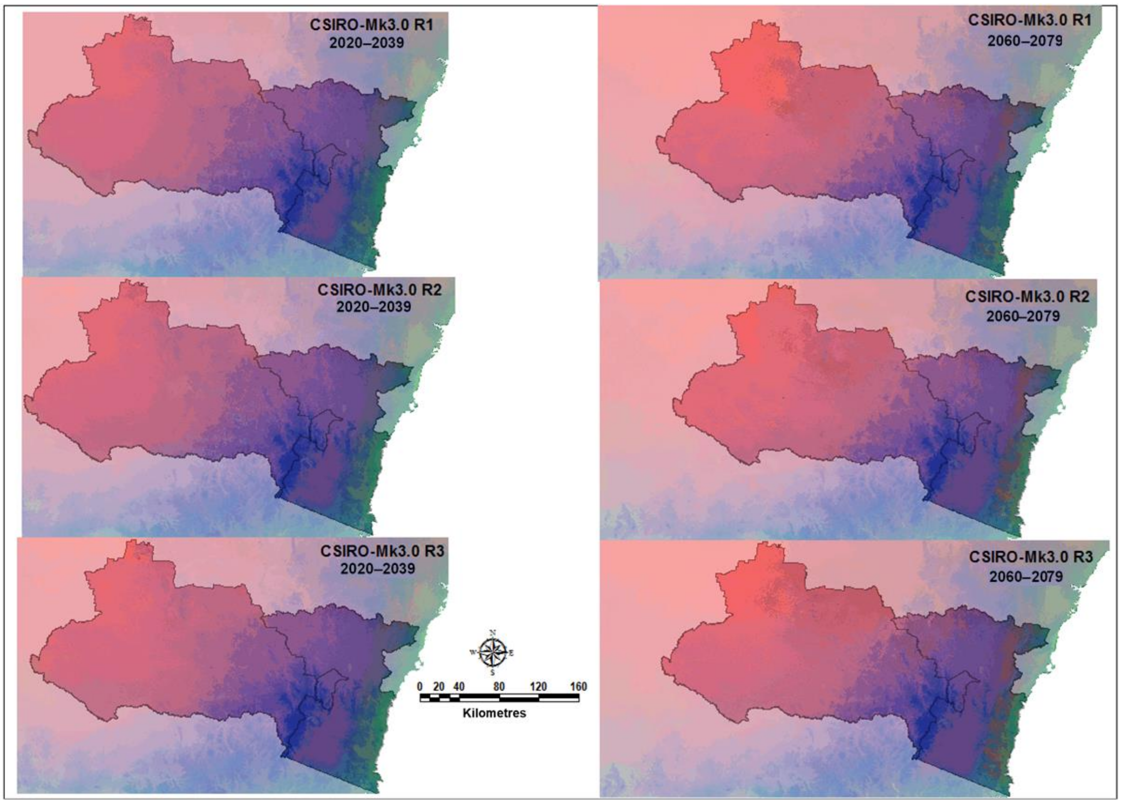


Figure 3 **Modelled Bioclimatic Class envelope distributions for the full study region under the CSIRO-Mk3.0 GCM showing differences under the three RCMs for the near future (2020 to 2039) and far future (2060 to 2079)**

Colours of similar hue represent BCCs with similar species compositions.

2.4 NSW vegetation classes

BCC envelopes are useful for climate impact and adaptation modelling as their distributions can routinely be recalculated for any time-step of any climate scenario where projected climate variables are available; however, BCCs are not a familiar or relatable classification scheme so we have intersected their distribution with the current distributions of vegetation classes (Figure 4) (Keith 2002; Keith & Simpson 2017) for reporting. This aids in assessing and communicating impacts and possible adaptation strategies by relating analysis results to well-known surrogates.

There are 68 vegetation classes within the full study region. Thirty-one are within the NPWS estate and 18 of these are found in KNP. The Alpine region is dominated by Subalpine Woodlands with a total area of approximately 3.5 million hectares. Montane Wet Sclerophyll Forest occupies over 78,000 hectares, followed by Alpine Heaths with approximately 72,000 hectares. Alpine Fjaeldmarks has the smallest extent of all alpine vegetation classes.

Out of the 68 vegetation classes in the full study region, the 13 most related to alpine biodiversity (Table 1 and Figure 4) were selected for impact analysis and reporting. The mapped extents of these 13 classes were intersected with the current distribution of 79 BCC envelopes (Table 2) to observe how changes in BCC envelopes modelled under climate change may relate to impacts on different vegetation types (Figure 5). They are also intersected with the full suite of spatial products used to report on the impacts of climate change and biodiversity's ability to successfully respond.

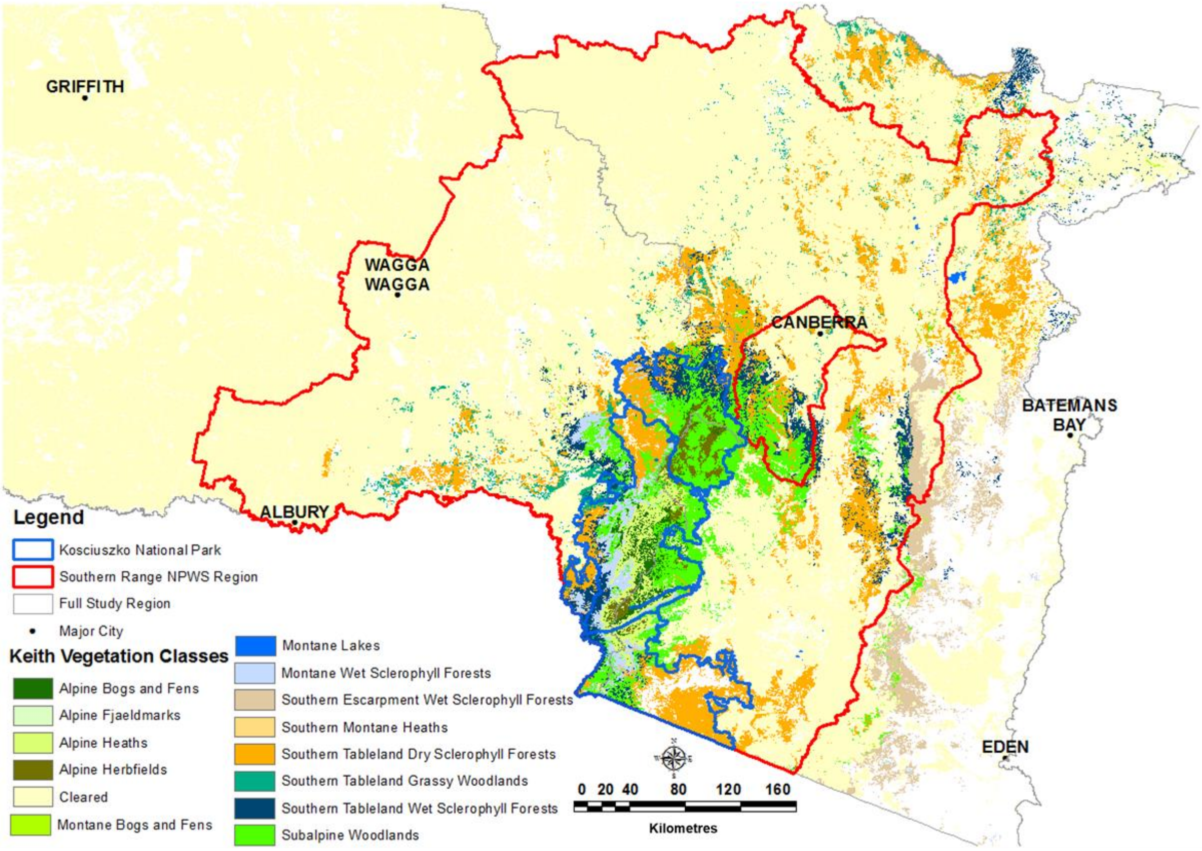


Figure 4 **The mapped extent of the 13 alpine related vegetation classes selected for reporting, extracted from the NSW vegetation map version 3.0 (Keith 2002; Keith & Simpson 2017)**

Table 1 **The 13 vegetation classes in the Alpine region selected for reporting, and their mapped extent**

Vegetation class	Area (ha)
Alpine Bogs and Fens	40,431
Alpine Fjaeldmarks	175
Alpine Heaths	71,781
Alpine Herbfields	39,113
Montane Bogs and Fens	12,625
Montane Lakes	2,906
Montane Wet Sclerophyll Forests	78,119
Southern Escarpment Wet Sclerophyll Forests	195,275
Southern Montane Heaths	8,281
Southern Tableland Dry Sclerophyll Forests	692,644
Southern Tableland Grassy Woodlands	105,231
Southern Tableland Wet Sclerophyll Forests	197,288
Subalpine Woodlands	366,619

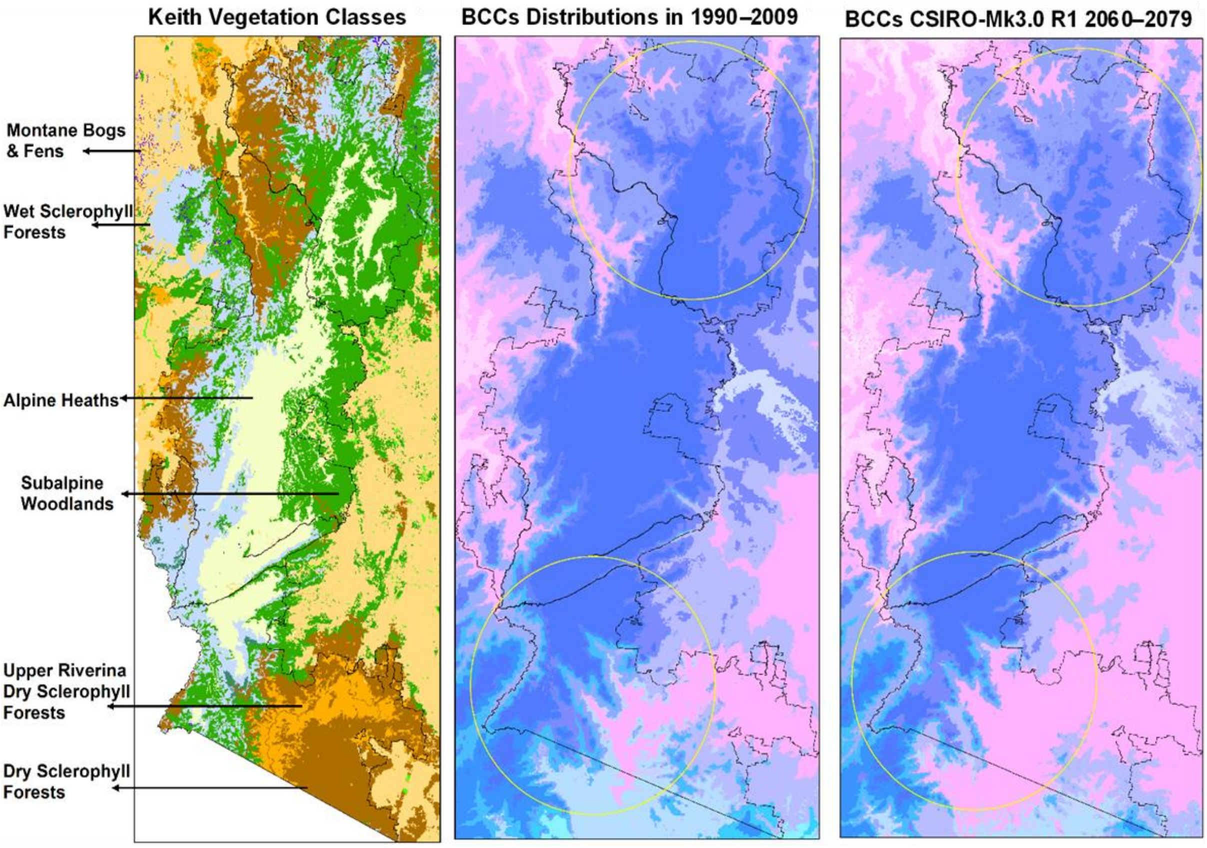


Figure 5 **Keith vegetation classes in the Alpine region (left), with comparisons of modelled Bioclimatic Class envelope distributions at the baseline period (1990 to 2009) (centre) and CSIRO-Mk3.0 R1 GCM for 2060 to 2079 (right)**

Colours of similar hue represent BCCs with similar species composition.

Table 2 **The 79 Bioclimatic Classes present in the full study region and their respective areas in the 1990 to 2009 baseline period**

Colours of similar hue represent BCCs with similar species composition.

BCC Class	No of pixels	Area (hectares)	Colour	BCC Class	No of pixels	Area (hectares)	Colour	BCC Class	No of pixels	Area (hectares)	Colour
1	2072	12950.00	■ 1	73	209909	1311931.25	■ 73	157	150	937.5	■ 157
10	421	2631.25	■ 10	74	2	12.5	■ 74	158	5986	37412.5	■ 158
11	699	4368.75	■ 11	80	67174	419837.5	■ 80	161	43166	269787.5	■ 161
14	50	312.50	■ 14	90	27267	170418.75	■ 90	164	14090	88062.5	■ 164
16	476	2975.00	■ 16	91	16791	104943.75	■ 91	165	150095	938093.75	■ 165
17	356	2225.00	■ 17	94	30239	188993.75	■ 94	170	562	3512.5	■ 170
19	2727	17043.75	■ 19	95	56259	351618.75	■ 95	177	2223	13893.75	■ 177
21	7922	49512.50	■ 21	96	23	143.75	■ 96	190	10707	66918.75	■ 190
23	128285	801781.25	■ 23	100	48462	302887.5	■ 100	191	62971	393568.75	■ 191
24	12076	75475.00	■ 24	104	87	543.75	■ 104	192	18188	113675	■ 192
27	3	18.75	■ 27	105	2	12.5	■ 105	202	52	325.00	■ 202
31	26797	167481.25	■ 31	106	36125	225781.25	■ 106	207	1266	7912.50	■ 207
35	5586	34912.50	■ 35	109	15428	96425	■ 109	208	64	400.00	■ 208
40	13128	82050.00	■ 40	110	11	68.75	■ 110	217	2025	12656.25	■ 217
42	471342	2945887.50	■ 42	114	14534	90837.5	■ 114	221	11446	71537.50	■ 221
43	81137	507106.25	■ 43	116	270899	1693118.75	■ 116	223	9046	56537.50	■ 223
46	16413	102581.25	■ 46	120	1267	7918.75	■ 120	228	62	387.50	■ 228
47	32134	200837.50	■ 47	122	47066	294162.5	■ 122	233	1098	6862.50	■ 233
52	93539	584618.75	■ 52	125	6	37.5	■ 125	234	1787	11168.75	■ 234
53	2521	15756.25	■ 53	131	36595	228718.75	■ 131	244	928	5800.00	■ 244
55	3138	19612.50	■ 55	135	934	5837.5	■ 135	247	1417	8856.25	■ 247
58	3104	19400.00	■ 58	137	13149	82181.25	■ 137	248	1843	11518.75	■ 248
64	15388	96175.00	■ 64	143	12078	75487.5	■ 143	250	6	37.50	■ 250
65	18	112.50	■ 65	146	937	5856.25	■ 146				
68	23945	149656.25	■ 68	149	3774	23587.5	■ 149				
70	16006	100037.50	■ 70	150	508979	3181118.75	■ 150				
71	20	125.00	■ 71	154	3191	19943.75	■ 154				
72	3524	22025.00	■ 72	156	23707	148168.75	■ 156				

Within our study area there are 79 BCCs altogether with a total area of 17,168,125 hectares.

2.5 BioNet Atlas records

Occurrence records for 11 threatened flora species (Table 3) and 23 threatened fauna species (Table 4) were extracted for reporting from the NSW DPIE BioNet Atlas records. These species were selected due to their high level of future climate impact when assessed, compared with other threatened species in the region.

Table 3 Threatened flora from the Alpine region selected for reporting

Common name	Scientific name
Anemone buttercup	*Ranunculus anemoneus*
Austral pillwort	*Pilularia novae-hollandiae*
Cotoneaster pomaderris	*Pomaderris cotoneaster*
Feldmark grass	*Rytidosperma pumilum*
Leafy anchor plant	*Discaria nitida*
Mauve burr-daisy	*Calotis glandulosa*
Monaro golden daisy	*Rutidosis leiolepis*
Pale pomaderris	*Pomaderris pallida*
Shining cudweed	*Argyrotegium nitidulum*
Slender greenhood	*Pterostylis foliata*
Suggan buggan mallee	*Eucalyptus saxatilis*

Table 4 Threatened fauna from the Alpine region selected for reporting

Common name	Scientific name
Alpine she-oak skink	*Cyclodomorphus praealtus*
Alpine tree frog	*Litoria verreauxii alpina*
Australian painted snipe	*Rostratula australis*
Booroolong frog	*Litoria booroolongensis*
Broad-toothed rat	*Mastacomys fuscus*
Brown treecreeper (eastern subspecies)	*Climacteris picumnus victoriae*
Brush-tailed rock-wallaby	*Petrogale penicillata*
Dusky woodswallow	*Artamus cyanopterus cyanopterus*
Eastern pygmy possum	*Cercartetus nanus*
Eastern quoll	*Dasyurus viverrinus*
Glossy black-cockatoo	*Calyptorhynchus lathami*
Hooded robin (south-eastern form)	*Melanodryas cucullata cucullata*
Mountain pygmy possum	*Burramys parvus*
Northern corroboree frog	*Pseudophryne pengilleyi*
Smoky mouse	*Pseudomys fumeus*
Sooty owl	*Tyto tenebricosa*
Southern bell frog	*Litoria raniformis*
Southern corroboree frog	*Pseudophryne corroboree*
Southern myotis	*Myotis macropus*
Spotted-tailed quoll	*Dasyurus maculatus*
Turquoise parrot	*Neophema pulchella*
White-bellied sea-eagle	*Haliaeetus leucogaster*
White-fronted chat	*Epthianura albifrons*

2.6 *Saving our Species* dynamic occupancy modelling

Examples of relevant species occupancy modelling currently being developed for the SoS program are also provided. Projected species occupancy modelling based on NARCliM climate models is being used to identify priority areas for conservation action that will benefit multiple threatened fauna species. This work extended habitat suitability modelling developed by Macquarie University by using the Rapid Evaluation of Metapopulation Persistence (REMP, Drielsma & Ferrier 2009), a raster-based metapopulation process model that accounts for local extinctions and colonisations from adjoining areas, subject to the arrangement of habitat in the region. This prioritisation work provides guidance on where and what types of conservation actions will most benefit biodiversity. It also provides information on population viability and how this is likely to change under different climate scenarios.

2.7 Quality control

Inputs for this study were sourced from either the BIAP project or DPIE corporate systems. The BIAP and 3C data have been through control processes that ensure they are suitable for public release. Descriptions of inputs are provided in Appendix B. Source data from DPIE corporate systems are also specified and the source origin should be referred to for data quality statements. There is no way of assessing the accuracy of NARCliM climate projections adopted for BIAP, or products that are based on these. Instead, modelling a range of projected climate futures and where possible reporting on multi-model mean or other aggregation statistics to identify areas of agreement between models was considered a suitable approach to address future climate uncertainty.

Software used for BIAP, including the biodiversity forecasting tool (Drielsma et al. 2014), REMP (Drielsma & Ferrier 2009) and spatial links software (Drielsma et al. 2007b) are considered mature and well-tested, and the methodologies they employ are all peer reviewed and published. Additional spatial analysis was performed in ArcMap 10.1 software using the standard suite of data management and spatial analysis tools. Where inputs are based on in-house or 3rd party processes that are not part of the standard ArcMap 10.1 suite of tools, either complete descriptions are provided, or documented methodology cited. Where task automation such as batch processing has been employed, the methods used, inputs and outputs at each stage have been thoroughly assessed to ensure correct software behaviour.

All derived products have been reviewed internally by multiple team members prior to delivery. Outputs and other intermediate or derived data have been manually assessed to ensure they accurately represent the information they intend to provide. During analysis, internal file naming, folder structure and versioning conventions were adopted that reflect those developed and used during the NARCliM region wide BIAP analysis.

A complete draft version of this report was externally peer reviewed by Professor Nick Reid from the University of New England (UNE) prior to finalising. Comments and recommendations were addressed (available on request).

2.8 Data storage and access

All output data were converted to raster format (ArcGIS ESRI grid) and supplied to the MCAS-S (Multi-Criteria Analysis Shell for Spatial Decision Support) datapacks for distribution and storage. All input data to the model and by-products are stored on hard disk drives. All data are in the NARCliM coordinate system. The extent of the datasets includes the Murray-Murrumbidgee state planning region, ACT and South East and Tablelands with the boundary at top: –32.671254, left: 143.317445, right: 150.745676, and bottom: –37.505077.

Where suitable, derived products (including spatial and tabular data) have been named using the NARCliM Impact Science – Directory and File Naming Convention. Where this is not applicable, descriptive product names have been applied to derived data. Refer to Appendix A for product details.

3. Results

3.1 Predicted impacts on biodiversity

The BIAP analysis (Drielsma et al. 2015; Drielsma et al. 2017) of NARCliM and 3C climate futures reports that by 2070 CE, habitats in New South Wales will be 30–60% less suitable for the composition of species they currently support. Similar impacts are reflected in the alpine and surrounding areas of the full study region. It was found that near and far future climate change will most greatly impact biodiversity through the central part of the full study region, between Wagga Wagga and Griffith (Sections 3.3 and Appendix B, *B4. Climate ready metapopulation analysis*). Habitats in these areas have already been severely impacted by past land clearing (Sections 3.2 and Appendix B, *B1. Current vegetation condition*), limiting the capacity of species and ecosystems to respond successfully to climate change.

In the higher altitude areas of the Southern Ranges NPWS region, the greatest climate induced impacts are expected along the south-eastern extent and areas surrounding the ACT. Impacts on biodiversity in the KNP are expected to be relatively gradual when compared with other areas in the full study region; however, consequences for biodiversity are likely to be greater as suitable habitats for species and ecosystems are contracting with nowhere for new suitable habitats to emerge.

Table 5 summarises the results of this analysis for the 13 selected vegetation classes occurring in the Alpine region. Additionally, these results are presented as a series of charts and maps (Figure 6 to Figure 11). Table 6 and Table 7 provide summaries for the 11 threatened flora and 23 threatened fauna species selected for reporting (Section 2.5). These measure the current status of each vegetation class or habitat for each species, providing an indication of their adaptive capacity by assessing their current condition, level of fragmentation (EHA) and its contribution to habitat connectivity; how different future species composition within each class or habitat is likely to be under future climatic conditions; and the relative benefit of restoring or revegetating degraded habitat or maintaining the condition of relatively intact remnants.

3.2 Adaptive capacity of current vegetation classes

Current vegetation condition modelling (Appendix B, *B1. Current vegetation condition*) suggests that biodiversity in the central part of the full study region, while experiencing the greatest impacts from climate change, will also be less resilient to change due to the habitat loss and degradation that has already occurred. This was especially evident between Wagga Wagga and Griffith, where large areas of habitat have been removed or heavily modified (Figure 16), primarily to support agricultural production.

Overall, the lowest vegetation condition values were observed in agricultural land in the central and western parts of the full study region, and higher condition values were observed within the Southern Ranges NPWS region and the KNP (Figure 16). The more intact and connected habitats in the east of the full study region are expected to better support species and ecosystems responding to climate change.

The mean vegetation condition values for each of the 68 vegetation classes occurring in the full study region ranged from 33–86, from a possible range of 0–100. The condition of vegetation classes within KNP was generally the highest out of those in the full study region; however, this varies considerably. The mean condition values of the 13 vegetation classes selected for reporting (Table 5) ranged from 50–86 indicating they are currently in moderate (~50) to very good (>75) condition, suggesting a general capacity to remain resilient in the face of climate change.

Montane Lakes, Grassy Woodland, Montane Bogs and Fens had the lowest mean condition values (Table 5) suggesting their capacity to adapt to change in the near to far future is lower than the other selected vegetation classes. These classes will need considered management to protect them from future impacts of changing climate and to ensure the persistence of the species they support. Dry and Wet Sclerophyll Forests and Subalpine Woodlands have mean condition values of 71, 77 and 75 respectively, indicating that although they are not in a pristine state, being relatively intact they're likely to have more resilience to climate change with a greater likelihood of species persisting.

As with condition, EHA values vary greatly across the full study region, ranging from low (0) to high (98) (Figure 17), covering almost the full range of possible values (0–100). The 13 selected vegetation classes have mean EHA values ranging from 63–91 (Table 5), which are higher than their mean condition values, suggesting that while some degradation has occurred, they occur in areas with relatively well-connected and functionally-intact habitats.

The lowest EHA (Appendix B, *B2. Effective habitat area*) observed amongst the 13 selected classes was for Montane Lakes (mean EHA of 63). Grassy Woodlands, Montane Bogs and Fens and Dry Sclerophyll Forests had mean EHA values of 72, 77 and 78 respectively (Table 5). The remaining selected vegetation classes all have relatively good spatial context with mean EHA values above 80.

Out of the 13 selected vegetation classes, Montane Lakes, Grassy Woodlands, Dry and Wet Sclerophyll Forests and Montane Bogs and Fens have the lowest mean connectivity (Appendix B, *B3. Habitat connectivity*) values of 95, 111, 128 and 139 (out of a possible 255) respectively (Table 5). As a result, species (both flora and fauna) in these classes have limited ability to disperse through the landscape, reducing their capacity to reach emerging areas of suitable habitat and undertake successful migratory responses to climate change.

Out of the 13 selected vegetation classes, the resilience of Montane Lakes to future climate change is expected to be the most negatively impacted by surrounding habitat fragmentation and loss of connectivity. Their widespread but locally restricted nature is likely to compound climate change impacts by limiting access to emerging suitable habitats. The unique environmental characteristics associated with such habitats also limit the likelihood of similar environments capable of supporting propagules emerging under future climate.

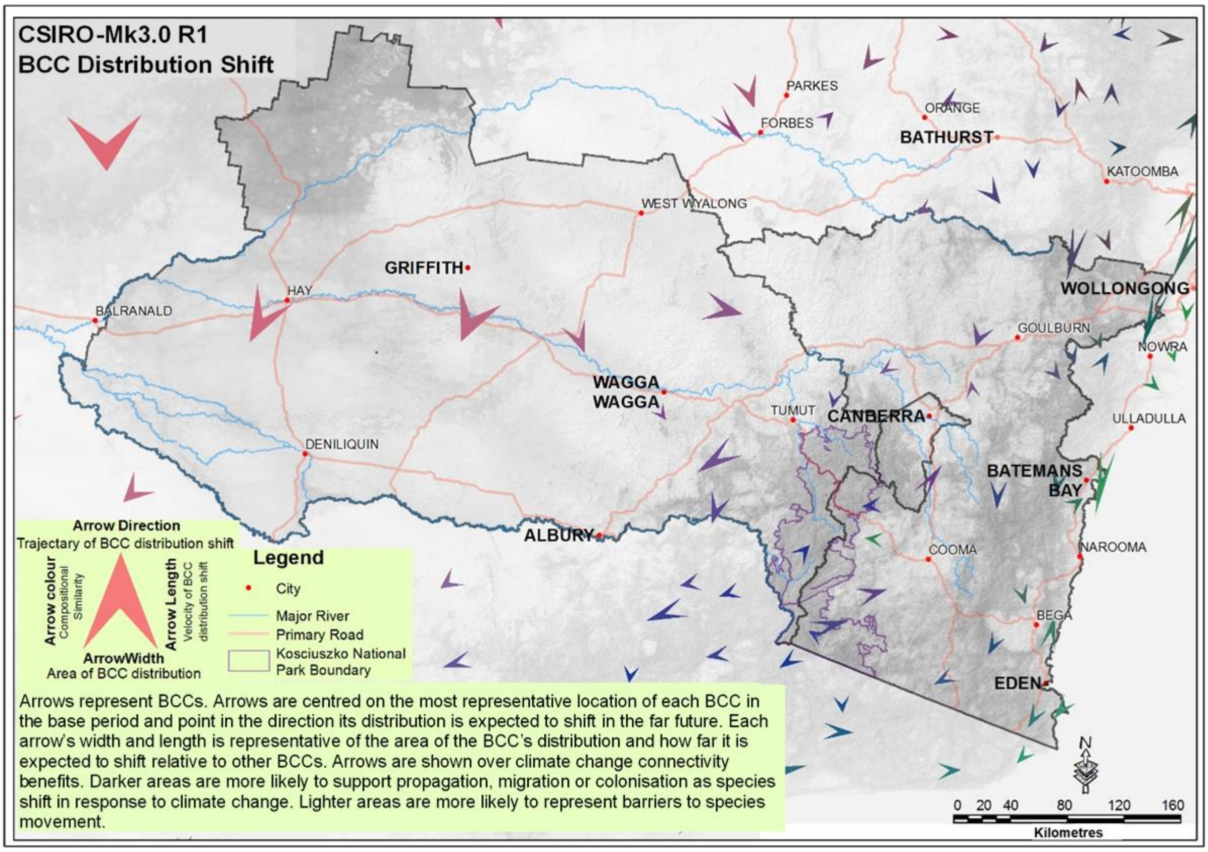
Climate ready metapopulation analysis (Appendix B, *B4. Climate ready metapopulation analysis*) undertaken for the 3C project identifies areas in the study region that are relatively stable under climate change and support depleted (highly cleared or degraded) ecosystems into the future, or have the capacity to passively transition between depleted ecosystems by allowing colonisation and unhindered movement of biodiversity as BCC envelopes shift. Figure 19 shows a band of high value (green) that includes Griffith and Wagga Wagga indicating a functional 'climate corridor' with potential to facilitate the movement of species (and thus communities) from west to east. However, north–south movements are impeded by unsuitable environmental conditions and land uses in the western part of the study region.

3.3 Impacts of climate change on vegetation classes

The significance of the Alpine region to the overall biodiversity of New South Wales is highlighted by the fact that more than one third of the state's BCCs are found in the full study region. Of the 250 BCCs covering the entire NARCliM extent, 79 were recorded between the far south coast and the western plains for the baseline period of 1990 to 2009 (Table 2).

The distribution of BCC envelopes is projected to change dramatically across the full study region in 2060 to 2079 relative to 1990 to 2009 (e.g. Figure 3); however, changes in BCC envelopes differ greatly under the 12 NARCliM scenarios. Across both climate futures, the most dramatic changes are consistently observed between Wagga Wagga and Griffith. In the higher altitude alpine areas, the velocity of change is slower, with smaller geographic shifts in BCC envelopes and transitions to relatively similar BCCs for both future periods; however, biodiversity represented by classes contracting at higher altitudes lacks emerging suitable habitats in the future. Along the alpine regions of New South Wales and the ACT, the greatest changes in BCC envelopes are predicted along the south-eastern, south-western and the northern edges of KNP.

In and around the alpine regions, BCC envelopes are mostly small in extent, and are predicted to move slowly and in multiple directions – influenced by terrain, with most shifts towards higher altitudes (see Figure 6). In comparison, on the mostly flat terrain further west, between Wagga Wagga and Griffith, BCC envelopes are larger in extent and they shift mostly southwards at a relatively rapid velocity, with some easterly movement on the south-west slopes between Wagga Wagga and the Alpine region.



Arrows represent BCCs. Arrows are centred on the most representative location of each BCC in the base period and point in the direction its distribution is expected to shift in the far future. Each arrow's width and length is representative of the area of the BCC's distribution and how far it is expected to shift relative to other BCCs. Arrows are shown over climate change connectivity benefits. Darker areas are more likely to support propagation, migration or colonisation as species shift in response to climate change. Lighter areas are more likely to represent barriers to species movement.

Figure 6 **Bioclimatic Class envelopes shifting under the CSIRO-Mk3.0 GCM R1, shown as arrows representing their current extent (arrow width), trajectory (arrow directions) and relative velocity at which they're expected to shift (arrow length) under this scenario**

Figure 6 illustrates the dynamic process of BCC envelope distribution shifts based on the CSIRO-Mk3.0 GCM R1 model. Each arrow is located at the spatial centroid of the BCC envelope it represents for 1990 to 2009. The arrows point in the direction of the centroid's projected shift for 2060 to 2079, the arrow's length indicates the velocity of the shift (longer arrows indicating higher velocity) and its width represents the envelope's spatial extent for 1990 to 2009. The arrows pointing towards the KNP boundary show the shift of BCCs to higher altitudes (Figure 6). Arrows are shown over a base-map of 3C climate change connectivity (Appendix B, *B3. Habitat connectivity*). Darker areas have higher connectivity and are more likely to support actual propagation, migration or colonisation as BCC envelopes shift in response to climate change.

When existing vegetation class mapping is overlaid with BCCs, Montane Lakes, Alpine Herb fields, Southern Escarpment Wet Sclerophyll Forests, Southern Tablelands Grassy Woodlands, Montane Bogs and Fens and Southern Tableland Wet Sclerophyll Forests are most aligned with BCCs that are largely projected to decrease in area in the far future (Figure 5). This is because environmental conditions transition to those more suited to supporting Subalpine Woodland and Southern Tableland Dry Sclerophyll Forest. The BCC envelopes that are currently most aligned with Subalpine Woodland and Southern Tableland Dry Sclerophyll Forest are predicted to expand in the region accordingly.

In the KNP and surrounding high altitude areas of the Southern Ranges NPWS region habitats are expected to experience a slower decline in suitability for existing species and ecosystems than lower altitude western and coastal areas of the full study region (Figure 8 and Figure 9). This relative stability over time highlights the importance of the Alpine region for biodiversity conservation.

The compositional dissimilarity (Appendix B, *B5. Climate impacts – dissimilarity with baseline biodiversity*) of a location (grid cell) measures its expected change in species composition over time. Compositional dissimilarity values range from 0–1 and have been scaled here by multiplying by 1000. A location with a value of 0 indicates that no change in species composition is expected over the specified period, while a value of 1000 indicates that no species currently occurring at the location are expected to occur there in the future. The compositional dissimilarity (x1000) for the 13 selected vegetation classes averaged across the NARCliM models shows that in the near future (2020 to 2039) the greatest compositional changes are projected in the Montane Lakes, Grassy Woodlands, Montane Bogs and Fens (Table 5).

For the far future (2060 to 2079), the species composition of Montane Lakes, Montane Heaths, Wet and Dry Sclerophyll Forest, Grassy Woodland and Montane Bogs and Fens are projected to undergo greater change than other vegetation classes within the Alpine region (Table 5). The compositional dissimilarity for the extents of these classes for 2060 to 2079 relative to 1990 to 2009 ranges between of 300 and 600, with mean values between 400 and 500.

Grassy Woodland's projected compositional dissimilarity for 2020 to 2039 relative to 1990 to 2009 is 330, increasing to 420 for 2060 to 2079. Likewise, Escarpment Wet Sclerophyll Forest projected compositional dissimilarity for 2020 to 2039 relative to 1990 to 2009 is 330, increasing to 440 for 2060 to 2079. The compositional dissimilarity of Montane Lakes is also projected to change from 370 in 2020 to 2039 to 480 in the 2060 to 2079 projection period. The NARCliM models project that areas currently supporting Grassy Woodlands, Alpine Herbfields, Escarpment Wet Sclerophyll Forest and Montane Lakes will experience the greatest changes in species composition for 2060 to 2079.

The vegetation of the Alpine region is projected to remain relatively stable in composition for 2060 to 2079 when compared with vegetation across the full study region and further to the west, as well as other parts of New South Wales; however, future compositional dissimilarity is likely to result in greater species loss rather than distribution shifts as contractions of suitable habitat occur, and no new areas of suitable habitat emerge.

3.4 Vegetation management for climate change adaptation

Biodiversity benefits measure the benefit to regional biodiversity persistence that occurs if certain management is undertaken at each location (grid cell). Conservation benefits measure the outcome of retaining existing intact habitat, proportional to the avoided loss that would result from its removal. Revegetation benefits measure the gain that would result from revegetating or actively restoring the species that would have occurred or are likely to occur in areas of degraded habitat. These benefits consider the representativeness and condition of habitat at each location (grid cell), and how well connected it is to other surrounding habitat (up to a 5 km radius). They also consider changes in species composition under the future climate projections and the resulting change in benefits up to 2050 (Drielsma et al. 2015).

Within the selected vegetation classes, mean conservation benefit values (Appendix B, *B6. Conservation manage benefits*) were lowest for Montane Lakes, Alpine Herbfields, Alpine Heaths, Montane Bogs and Fens (Table 5). This suggests that despite the long-term threat to these ecosystems, there is relatively less urgency to undertake conservation action in these areas due to a slower rate of change relative to that impacting other vegetation classes. However, this does not imply that species and ecosystems represented in these vegetation types are not under threat. Conservation benefits increase in higher altitude areas from the 2000 baseline to 2050. This trend is likely to continue beyond 2050 and these vegetation types will face ongoing pressure.

Under current management and future climate, Montane Lakes and Grassy Woodlands will benefit the most from revegetation (Table 5) relative to the other selected vegetation classes, due to their current level of condition and fragmentation. The highest revegetation benefits (Appendix B, *B7. Revegetation benefits*) in the full study region occur further west where a greater proportion of the original habitat has been lost or degraded. Between now and 2050, the expected benefits from conservation actions only increase, not decrease, across the full study region (Appendix B, *B8. Relative change in benefits*), indicating increasing pressure on biodiversity from climate change, and therefore an increasing need to undertake actions intended to benefit regional biodiversity persistence.

Important alpine habitats with benefits already in the upper range are increasing disproportionally in relation to habitats in lower slopes and the plains to the west. This highlights the increasing role for alpine areas in biodiversity conservation. As BCCs shift altitudinally in response to increasing temperatures, these areas will need to accommodate retreating climate refugees from other areas, while also remaining the last refuge of species that already depend on alpine environments. As these areas act as climate refugia, they are likely to become increasingly important for regional biodiversity conservation.

The least change in benefits occurs in the central part of the full study region where high levels of habitat loss and degradation have already occurred. These are areas where the benefits to be gained from retaining remaining intact habitat and restoring heavily cleared and degraded habitat types are already relatively high but increase less over the period to 2050, relative to other areas (including higher altitude areas such as KNP). Biodiversity investment in these areas would provide the greatest benefit now and in the future; however, there is less change in the relative benefit of conserving or revegetating habitats in these areas, much of which are likely to remain under agricultural land uses.

Table 5 Measures used to assess the biodiversity impacts of climate change showing mean values for the 13 selected vegetation classes

Vegetation class	Area (ha)	Vegetation condition (0–100)	Effective habitat area (0–100)	Habitat connectivity (0–255)	Meta-population links (0–1000)	Composition dissimilarity 2020–2039 change (0–1000)	Composition dissimilarity 2060–2079 change (0–1000)	Conservation benefits 2060–2079 change (0–255)	Revegetation benefits 2060–2079 change (0–255)	Benefits change 2050 change (0–1000)
Alpine Bogs and Fens	40,431	79	85	153	826	245	231	81	43	409
Alpine Fjaeldmarks	175	86	90	150	467	224	287	87	25	405
Alpine Heaths	71,781	77	84	147	742	244	320	77	46	407
Alpine Herbfields	39,113	74	83	145	833	260	344	77	56	384
Montane Bogs and Fens	12,625	68	77	128	693	325	414	79	76	281
Montane Lakes	2,906	50	63	95	516	365	476	73	124	249
Montane Wet Sclerophyll Forests	78,119	80	86	140	640	253	366	80	46	348
Southern Escarpment Wet Sclerophyll Forests	195,275	81	86	150	834	332	438	82	47	297
Southern Montane Heaths	8,281	77	84	144	795	353	448	87	58	279
Southern Tableland Dry Sclerophyll Forests	692,644	96	78	128	693	330	429	93	78	248
Southern Tableland Grassy Woodlands	105,231	63	72	101	545	330	424	85	92	226
Southern Tableland Wet Sclerophyll Forests	197,288	77	83	139	721	318	415	87	57	280
Subalpine Woodlands	366,619	75	82	141	798	274	379	83	59	333

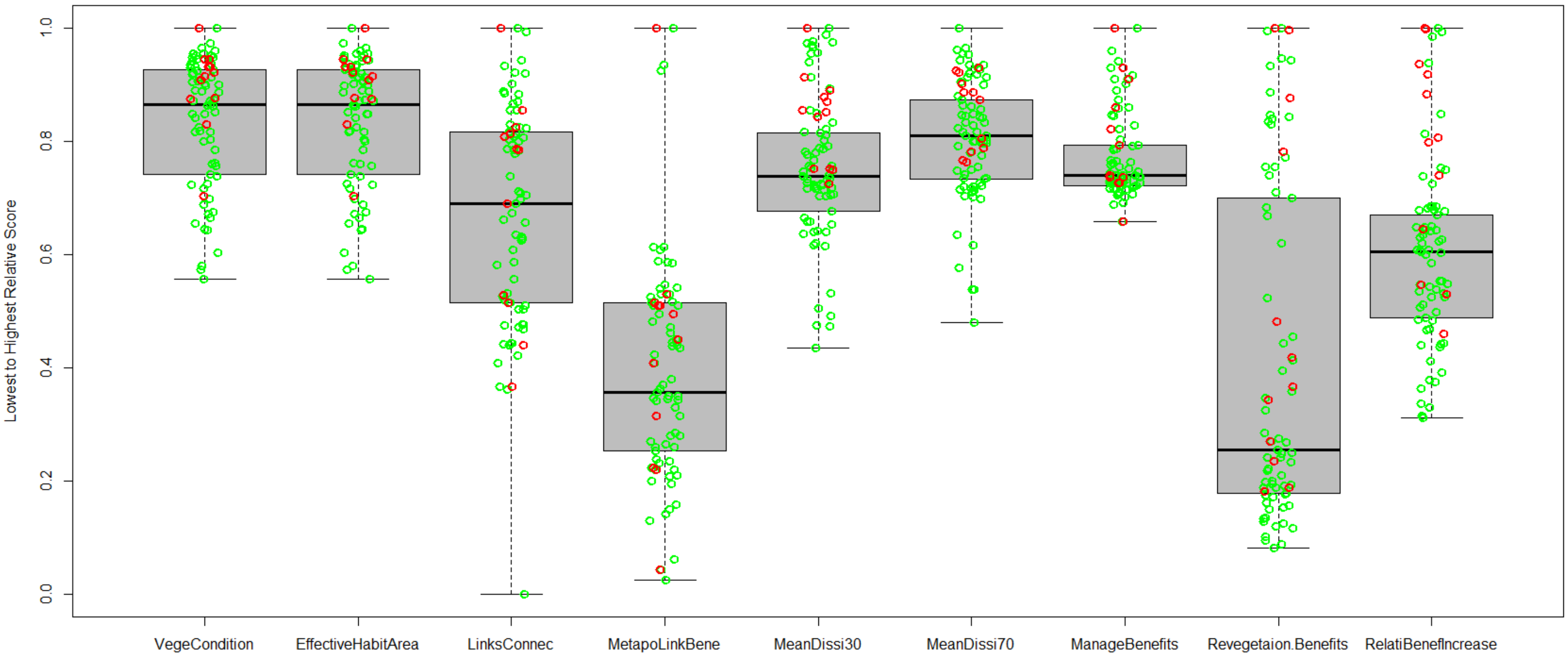


Figure 7 **Box plot showing the 1st and 3rd quartiles and the mean values of vegetation classes within the nine different biodiversity variables assessed**

All variables have been standardised to between 0 and 1. The open green circles show all 68 vegetation classes within the full study region, and the red open circles show the 13 selected vegetation classes.

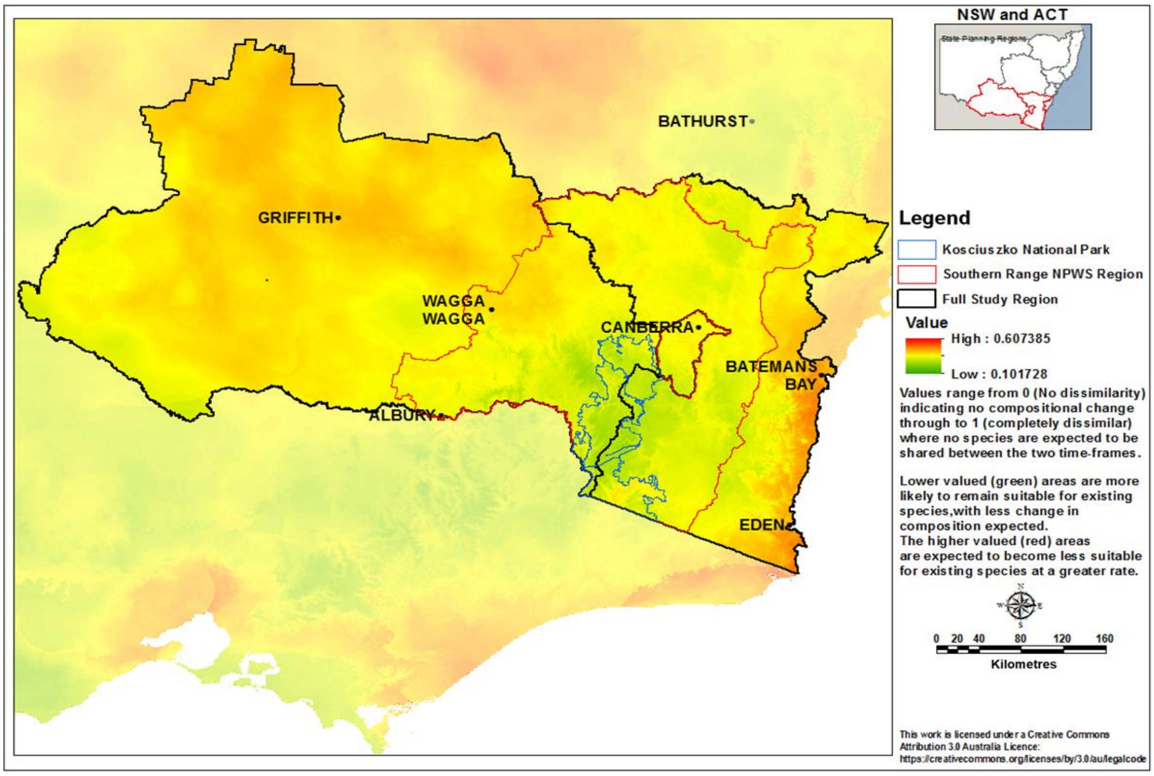


Figure 8 Compositional dissimilarity for 2020 to 2039 relative to 1990 to 2009 averaged across NARCliM models (CSIRO-Mk3.0 R1, CCCMA3.1 R1 R2 R3, ECHAM5 R1 R2 R3 and MIROC3.2 R1 R2 R3). Compositional dissimilarity values range from 0 to 1 and they represent the proportion change.

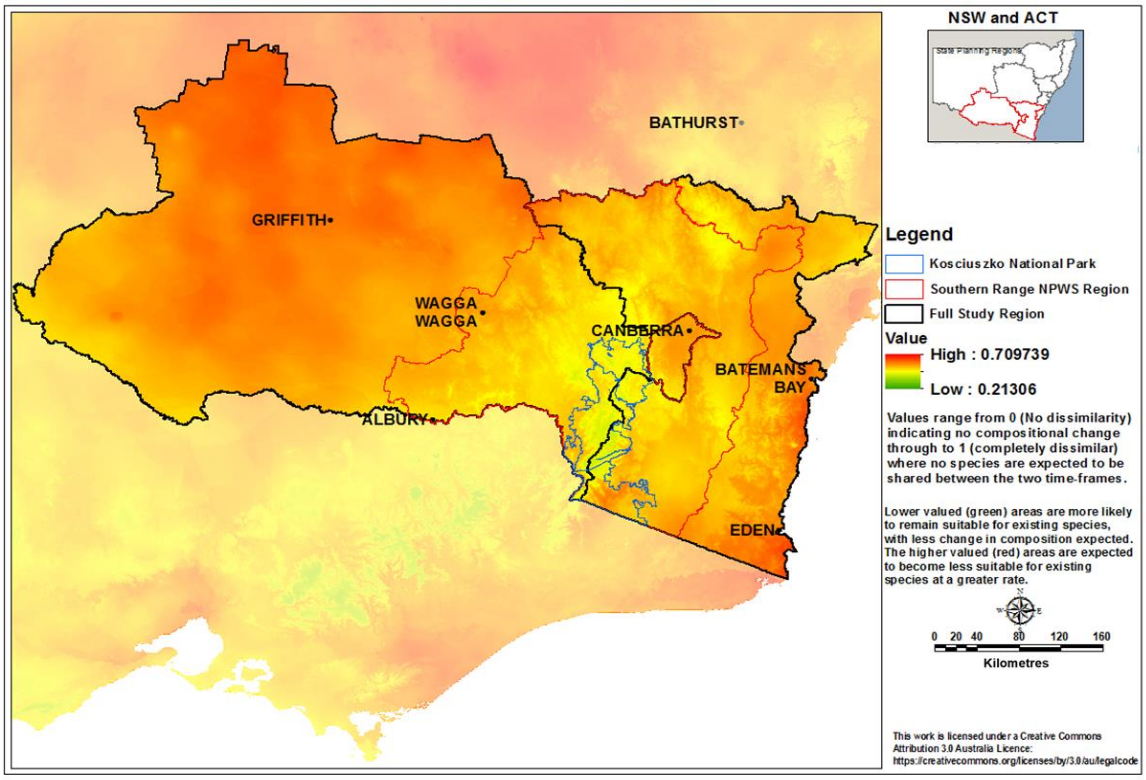
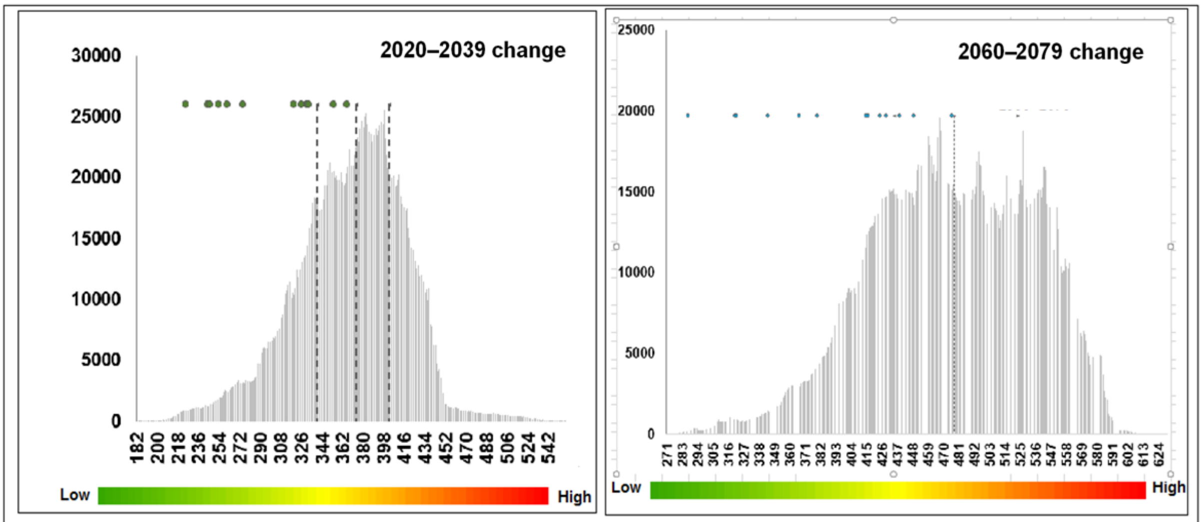


Figure 9 Compositional dissimilarity for 2060 to 2079 relative to 1990 to 2009 averaged across NARCliM models (CSIRO-Mk3.0 R1, CCCMA3.1 R1 R2 R3, ECHAM5 R1

R2 R3 and MIROC3.2 R1 R2 R3). Compositional dissimilarity values range from 0 to 1 and they represent the proportion change.

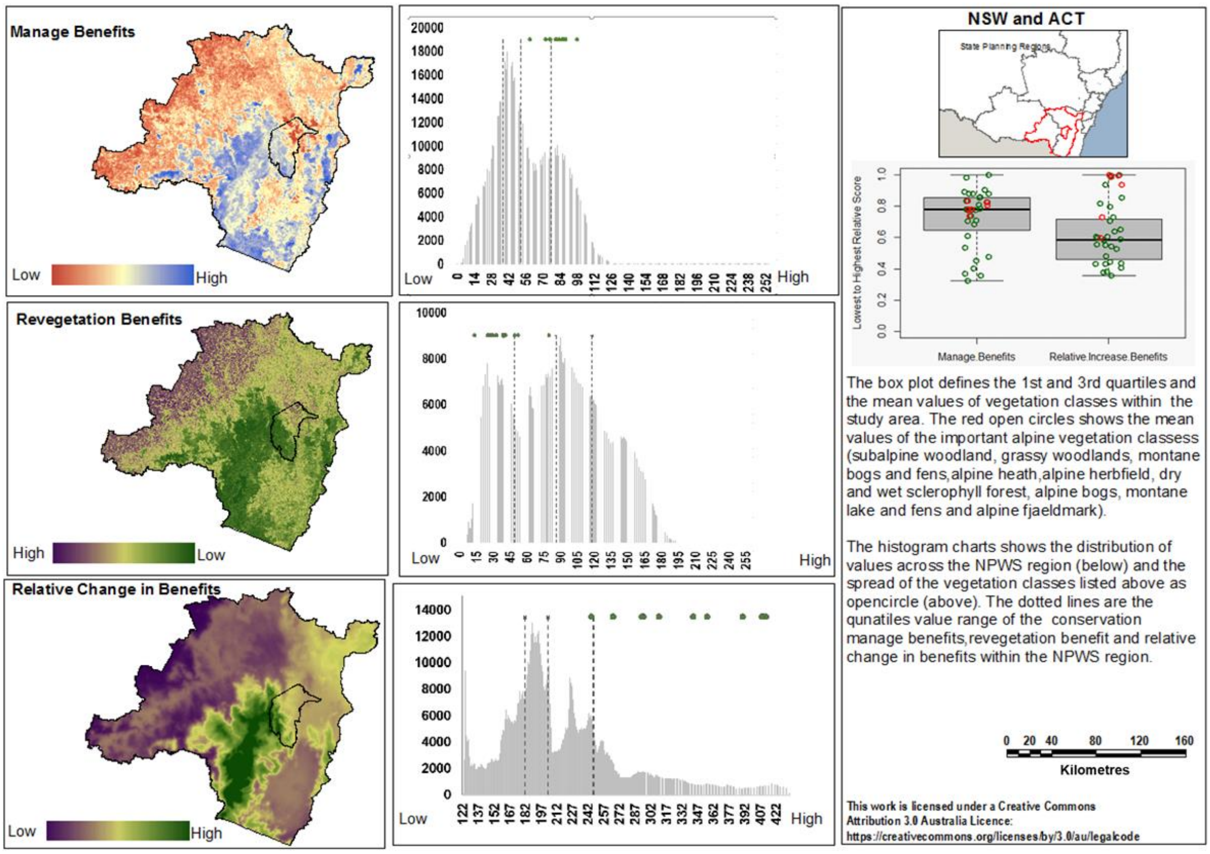


Keith vegetation classes	AreaHect.	Min	Max	Mean	St Deviation
Southern Tableland Grassy Woodlands	105231.25	225	435	329.80	32.20
Southern Tableland Dry Sclerophyll Forests	692643.75	211	450	330.12	40.51
Southern Tableland Wet Sclerophyll Forests	197287.50	198	450	318.37	41.58
Montane Bogs and Fens	12625.00	200	450	325.06	57.33
Subalpine Woodlands	366618.75	188	407	274.30	32.41
Southern Escarpment Wet Sclerophyll Forests	195275.00	227	491	331.52	36.44
Montane Lakes	2906.25	226	388	364.54	21.55
Southern Montane Heaths	8281.25	277	450	353.46	49.23
Alpine Heaths	71781.25	182	379	243.78	19.66
Montane Wet Sclerophyll Forests	78118.75	187	463	252.92	35.45
Alpine Bogs and Fens	40431.25	182	303	245.43	18.09
Alpine Herbfields	39112.50	199	308	260.27	19.76
Alpine Fjaeldmarks	175.00	217	229	224.46	2.86

Keith vegetation classes	AreaHect.	Min	Max	Mean	St Deviation
Southern Tableland Grassy Woodlands	105231.25	313	534	424.03	38.61
Southern Tableland Dry Sclerophyll Forests	692643.75	304	544	428.51	45.54
Southern Tableland Wet Sclerophyll Forests	197287.5	305	532	415.26	43.28
Montane Bogs and Fens	12625	295	522	413.77	53.81
Subalpine Woodlands	366618.75	271	525	378.92	43.96
Southern Escarpment Wet Sclerophyll Forests	195275	352	570	437.99	31.22
Montane Lakes	2906.25	288	499	475.65	27.15
Southern Montane Heaths	8281.25	375	532	447.99	37.36
Alpine Heaths	71781.25	275	468	320.34	20.39
Montane Wet Sclerophyll Forests	78118.75	284	541	365.81	41.55
Alpine Bogs and Fens	40431.25	276	470	320.99	27.73
Alpine Herbfields	39112.5	272	484	343.65	34.07
Alpine Fjaeldmarks	175	279	295	286.75	4.41

Figure 10 **Charts showing the distribution of mean compositional dissimilarity values (x1000) for 2020 to 2039 relative to 1990 to 2009 (left) and 2060 to 2079 relative to 1990 to 2009 (right)**

The open circles above the charts show the spread of selected vegetation class mean values as shown in the table below the charts, and the dotted lines within the histograms show the mean, 1st and 3rd quantiles of the two mean dissimilarity raster layers.



The box plot defines the 1st and 3rd quartiles and the mean values of vegetation classes within the study area. The red open circles shows the mean values of the important alpine vegetation classess (subalpine woodland, grassy woodlands, montane bogs and fens,alpine heath,alpine herbfield, dry and wet sclerophyll forest, alpine bogs, montane lake and fens and alpine fjaeldmark).

The histogram charts shows the distribution of values across the NPWS region (below) and the spread of the vegetation classes listed above as opencircle (above). The dotted lines are the qunatiles value range of the conservation manage benefits,revegetation benefit and relative change in benefits within the NPWS region.

Figure 11 **Maps and charts showing the distribution of values within conservation benefits, relative change in benefits and CSIRO-Mk3.0 layers for 2060 to 2079 relative to 1990 to 2009**

The open circles in the box plot are the spread of the selected vegetation classes mean values and the dotted lines within the histograms are the quantiles of the three raster layers (left-hand corner).

3.5 Predicted impacts on threatened flora

Threatened floral species that are in further danger from future climate change within the Alpine region and selected for reporting in this study are listed in Table 3. Of these species, austral pillwort occurs in areas with the lowest mean vegetation condition (31) and lowest mean EHA (48), and also the lowest mean habitat connectivity (71). Austral pillwort also has the second highest dissimilarity (361) for 2020 to 2039, and highest dissimilarity (473) for 2060 to 2079 of these species (Table 6), indicating it has less intact suitable habitat remaining in its current environment and that its habitat is likely to become less suitable under climate change when compared with other threatened flora species. Likewise, cotoneaster pomaderris has a mean dissimilarity value of 363 projected for 2020 to 2039 (the highest of the selected species) and 462 for 2060 to 2079, suggesting its current habitat is also likely to become much less suitable in the far future projection period (Table 6).

All threatened flora in the Alpine region will need considered management plans that address the impacts of climate change. Where conditions supporting these species cease to exist, new conservation techniques that may challenge convention will be required. This may involve relocating to areas where future environmental conditions can support these species, though they may never have naturally occurred, selectively breading to produce individuals better able to adapt to future conditions, or in extreme cases, the preservation of specimens in artificial environments. As many endemic alpine species depend on a shrinking niche of environmental conditions, there will be increasing cases where conservation is not practical, and the acceptance of extinction becomes a more common reality.

3.6 Predicted Impacts on threatened fauna

A total of 164 threatened faunal species have been identified as occurring within the full study region (based on BioNet Atlas records). This comprises 93 bird species, 45 species of mammals, 14 species of amphibian, 10 reptiles, and two species of insects. The 23 threatened species under the greatest pressure from future climate change within the Alpine region, with a focus on KNP, are listed in Table 4. Some are endemic alpine species that are dependent on cold temperatures and adequate snow cover for their habitats. In terms of conservation, these species require concentrated attention. Currently, they occur in low numbers and this analysis suggests they are predicted to be impacted heavily by future climate change.

Species found in lower mean vegetation condition or effective habitat area are more likely to already be under pressure from habitat degradation or fragmentation. For species that occur in higher revegetation benefit areas, investment in increasing or improving habitat is likely to also benefit the representation or configuration of important native vegetation and improve regional biodiversity outcomes. Managing remaining good quality habitat for species in areas of high biodiversity benefits (see Appendix B, *B6. Conservation manage benefits* and *B7. Revegetation benefits*) is also expected to contribute to better regional biodiversity outcomes.

For those species located in areas of higher mean dissimilarity in both projection periods (Table 7), greater compositional change in their existing habitat is expected and the species or ecosystems they depend on may cease to exist in situ. These species will be under greater pressure to move to emerging suitable habitat or adapt to a changing environment. Where species occur in higher connectivity areas (Table 7), the landscape in which their habitat occurs may facilitate suitable dispersal and migration, allowing species to range-shift in response to changing environmental conditions.

For those species occurring in lower connectivity landscapes, bolstering or restoring lost connectivity will be more necessary to allow species to shift in response to climate change. Where this occurs in areas with high mean revegetation benefit values (Table 7), additional regional-scale biodiversity benefits are also likely to result. Where habitat fragmentation impedes the ability of species to respond to changing environmental conditions, other interventions such as translocation to emerging areas of suitable habitat may become necessary to avoid extinction.

Table 6 Measures used to assess the biodiversity impacts of climate change showing mean values for selected threatened flora

Threatened flora species	Vegetation condition (0–100)	Effective habitat area (0–100)	Habitat connectivity (0–255)	Composition dissimilarity 2020–2039 change (0–1000)	Composition dissimilarity 2060–2079 change (0–1000)	Conservation benefits 2060–2079 change (0–255)	Revegetation benefits 2060–2079 change (0–255)	Relative change in benefits 2050 change
Anemone buttercup	84	89	149	229	292	85	28	408
Austral pillwort	31	48	71	361	473	57	154	155
Cotoneaster pomaderris	76	82	139	363	462	94	66	243
Feldmark grass	95	93	155	223	289	95	13	404
Leafy anchor plant	69	78	134	274	391	75	69	347
Mauve burr-daisy	53	67	115	288	407	62	106	269
Monaro golden daisy	62	73	124	287	382	67	88	319
Pale pomaderris	61	71	107	355	471	90	100	233
Shining cudweed	85	90	160	233	296	87	28	412
Slender greenhood	83	87	142	293	385	95	50	292
Suggan buggan mallee	77	83	154	332	462	91	65	251

Table 7 Measures used to assess the biodiversity impacts of climate change showing mean values for selected threatened fauna species

Threatened fauna species	Vegetation condition (0–100)	Effective habitat area (0–100)	Habitat connectivity (0–255)	Composition dissimilarity 2020–2039 change (0–1000)	Composition dissimilarity 2060–2079 change (0–1000)	Conservation benefits 2060–2079 change (0–255)	Revegetation benefits 2060–2079 change (0–255)	Relative change in benefits 2050 change
Southern bell frog	33	51	66	369	490	67	157	158
Australian painted snipe	36	53	83	374	487	72	154	196
White-fronted chat	45	60	82	387	503	84	142	218

Threatened fauna species	Vegetation condition (0–100)	Effective habitat area (0–100)	Habitat connectivity (0–255)	Composition dissimilarity 2020–2039 change (0–1000)	Composition dissimilarity 2060–2079 change (0–1000)	Conservation benefits 2060–2079 change (0–255)	Revegetation benefits 2060–2079 change (0–255)	Relative change in benefits 2050 change
Glossy black-cockatoo	51	82	120	439	514	74	48	243
Brown treecreeper (eastern subspecies)	51	62	77	366	462	99	138	165
Dusky woodswallow	52	65	90	360	454	75	110	202
Hooded robin (south-eastern form)	54	65	88	370	478	96	127	183
White-bellied sea-eagle	56	69	81	447	520	67	76	227
Eastern quoll	56	69	96	294	434	98	94	297
Turquoise parrot	56	67	90	362	447	98	116	172
Booroolong frog	59	72	106	336	416	82	90	226
Southern myotis	63	71	101	412	501	86	93	217
Brush-tailed rock-wallaby	69	78	131	348	472	81	84	232
Spotted-tailed quoll	70	79	130	359	459	79	66	257
Eastern pygmy possum	75	81	122	368	461	78	53	257
Broad-toothed rat	76	84	146	263	343	78	52	386
Northern corroboree frog	76	84	131	303	357	80	52	332
Alpine tree frog	77	84	145	251	349	81	51	378
Mountain pygmy possum	78	85	144	249	326	77	44	396
Southern corroboree frog	78	85	153	237	315	79	45	415
Sooty owl	81	86	124	434	511	73	36	243
Smoky mouse	82	87	133	371	478	71	40	273
Alpine she-oak skink	83	87	156	236	308	84	39	415

3.7 Species occupancy modelled under climate change

The *Saving our Species* program includes the modelling of projected changes in habitat suitability, occupancy and species persistence expected under projected NARCliM simulations for landscape managed threatened species.

While currently in progress, this work will deliver products that will aid in understanding and addressing the long-term needs of landscape managed species (see link above) occurring in the Alpine region of New South Wales. Outputs will highlight areas predicted to currently be or become important for one or more species and help direct management towards areas most likely to benefit the greatest number of species, or towards areas that reduce the greatest extinction risks.

Draft species occupancy models for the eastern pygmy possum showing combinations of three RCMs and four GCMs for 2020 to 2039 and 2060 to 2079 are shown in Figure 12 to Figure 15. The 1990 to 2009 baseline map provides a comparison. The modified scenario (Figure 12 and Figure 13) simulates current and future occupancy given extant vegetation in its current condition, while the pristine scenario (Figure 14 and Figure 15) simulates potential occupancy as if no loss of habitat condition has occurred.

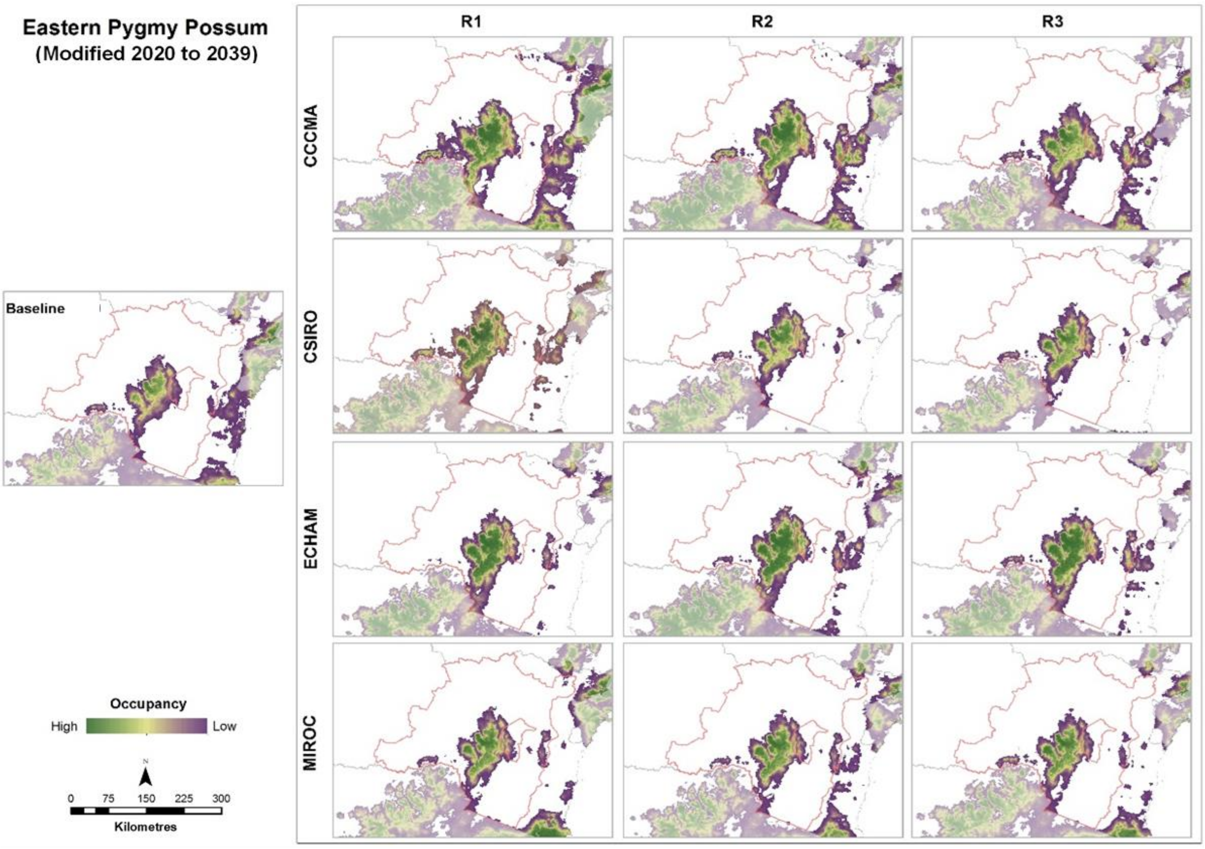


Figure 12 **Eastern pygmy possum occupancy modelled using modified (current) habitat for all NARCliM models (CCCMA3.1, CSIRO-Mk3.0, ECHAM5, MIROC3.2) for 2020 to 2039**

These early results project reductions in occupancy of eastern pygmy possum on the east coast in 2060 to 2079 when compared to the baseline and 2020 to 2039; however, the Alpine region is predicted to support higher levels of occupancy under all future scenarios. This model does not consider extreme events such as heatwaves and fire that could directly lead to high mortality, or indirectly through impacts on food resources.

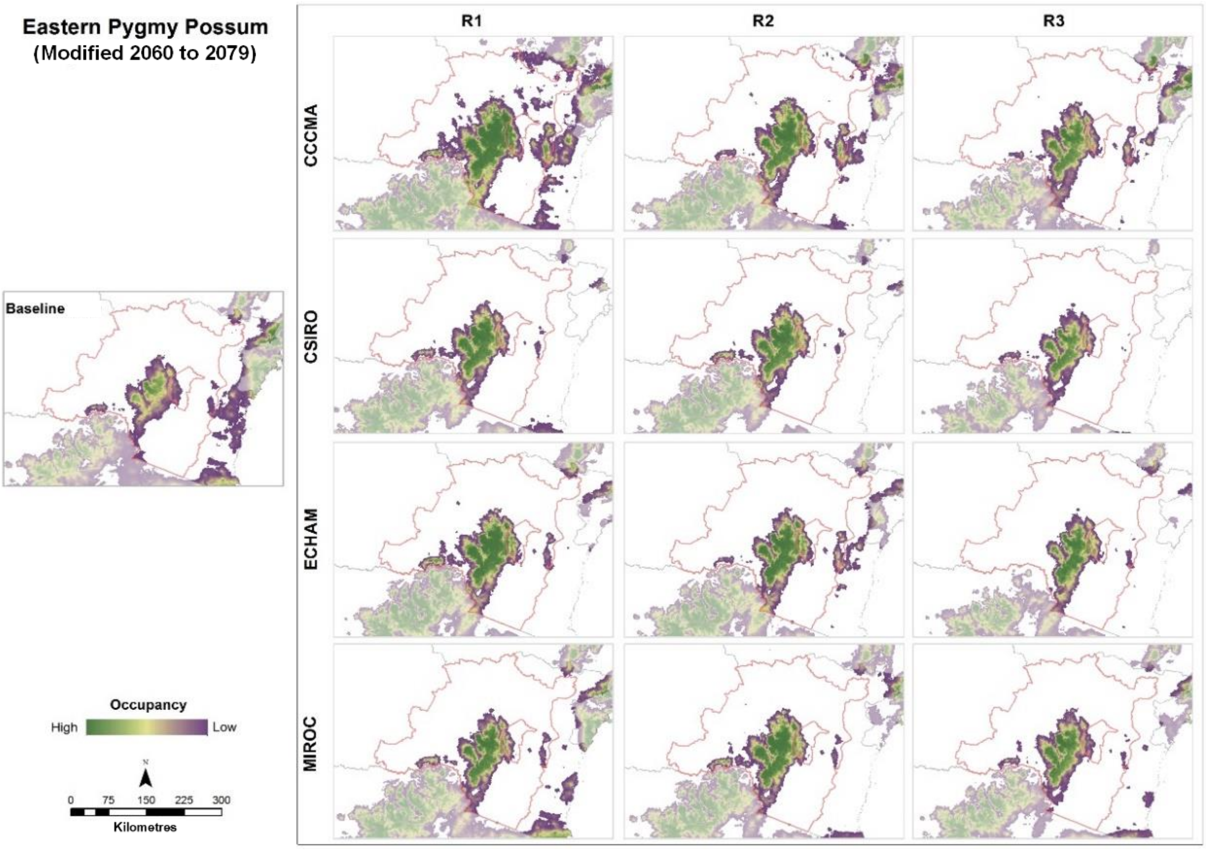


Figure 13 **Eastern pygmy possum occupancy modelled using modified (current) habitat for all NARCliM models (CCCMA3.1, CSIRO-Mk3.0, ECHAM5, MIROC3.2) for 2060 to 2079**

The comparison of modified and pristine scenarios allows areas to be identified that would likely support species populations now and into the future, if habitat condition had not been degraded. These are areas where environmental conditions are projected to be suitable for the species at some stage but where habitat has been fragmented or degraded beyond a threshold at which it’s capable of supporting viable populations. These potential habitat areas highlighted by the pristine mapping (Figure 14 and Figure 15), are places where links between isolated existing habitat would also be beneficial in supporting persistence.

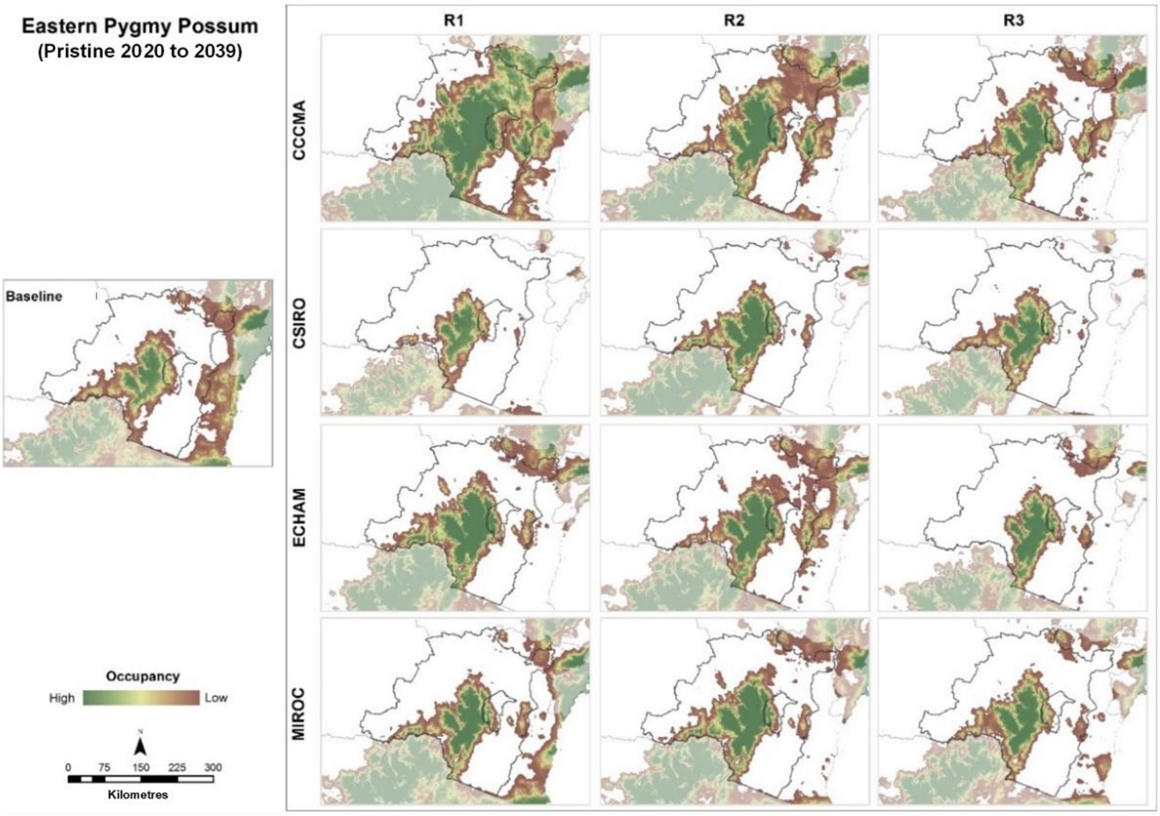


Figure 14 Eastern pygmy possum occupancy modelled using unmodified (pristine) habitat for all NARCliM models (CCCMA3.1, CSIRO-Mk3.0, ECHAM5, MIROC3.2) for 2020 to 2039

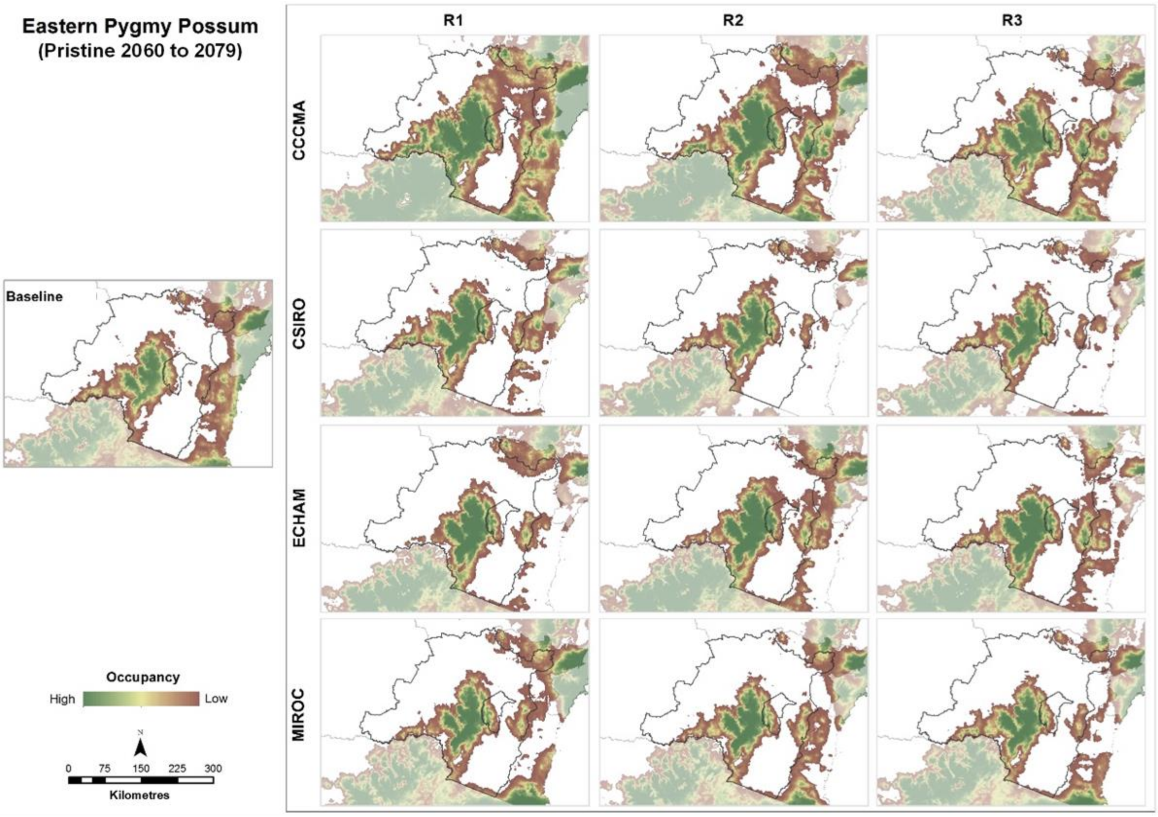


Figure 15 Eastern pygmy possum occupancy modelled using unmodified (pristine) habitat for all NARCliM models (CCCMA3.1, CSIRO-Mk3.0, ECHAM5, MIROC3.2) for 2060 to 2079

4. Discussion

Ecosystem change is expected and is a normal part of the functioning of ecosystems (Likens 1992). These changes are rarely simple or linear in nature because responses to drivers of change are mediated through a range of interactions and feedbacks between biotic and abiotic components and processes (Pickett & White 1985; Sutherland et al. 2013). Ecosystems are characterised by self-organisation, hysteresis, non-linear dynamics and the potential for multiple stable states (Holling & Gunderson 2002; Walker & Salt 2012). While projected climate model simulations are somewhat uncertain, from the NARCliM climate projections available for New South Wales we can reasonably expect average and extreme temperatures and heatwaves will continue to increase in the Alpine region of the state, forcing ecosystems to fluctuate beyond their natural self-supporting states.

The BIAP projected a decline in overall biodiversity across New South Wales in the near future, with continuing losses into the far future. This decline results from the modelled geographic shifts of bioclimatic envelopes and reduced suitability of habitats for existing species and ecosystems (Drielsma et al. 2015; OEH 2016; Drielsma et al. 2017). Envelope shifts vary, sometimes significantly, across the 12 NARCliM climate simulations BIAP assessed. Despite this variability, the BIAP work found that across different projection scenarios, NSW-wide biodiversity loss arising directly from climate change up to the 2060 to 2079 period could be comparable to the loss that has already arisen from land clearing and degradation post-European settlement (Drielsma et al. 2015).

The BIAP analysis found that the NARCliM simulations predominantly suggest an additional loss of biodiversity of around 8% by 2060 to 2079 resulting directly from bioclimatic shifts (OEH 2016). For 2060 to 2079, it is projected that some areas of New South Wales will be 30–60% less bioclimatically suitable for the species they currently support. Consequently, for populations to persist, species will need to either migrate or adapt, or otherwise rely on intervention (Aitken et at. 2008; Nogués-Bravo et al. 2018). The ability to persist depends on the viability of the existing populations, ongoing availability of suitable habitat and the capacity of landscapes to support change (Drielsma et al. 2015; OEH 2016; Drielsma et al. 2017).

Communities are expected to experience between a 21% to 70% change in their habitat’s bioclimatic suitability by the 2060 to 2079 period. The greatest impacts within this timeframe are expected to occur in the highly modified central parts of the broader study area, between Wagga Wagga and Griffith. Bioclimatic suitability in alpine areas is expected to change at a slower rate across the broader study area. Bioclimatic envelope shifts are predicted to be multi-directional, with shifts in the Alpine region and surrounding areas predominantly towards higher altitudes. In the western part of the study area between Wagga Wagga and Griffith, the shifts are mostly southwards, accompanied with more rapid and higher degrees of change (see Figure 6).

The 12 NARCliM GCM/RCM simulations show projected impacts to the distribution of BCC envelopes in the Alpine region differently and to varying extents; however, all project a decline in biodiversity resulting directly from changing climatic conditions (see Figure 20 to Figure 23). As dissimilarity increases (red tones), greater changes in species composition are expected to result. For 2020 to 2039 and 2060 to 2079, the most dramatic changes occur under the CCCMA3.1 (R1 to R3) hot/wet scenario (Figure 20). It is uncertain which, if any, of these models most accurately represents the future, but given the range of scenarios they cover and their general similarity in degree of impact, the importance of immediate and ongoing conservation actions is clear.

All 12 NARCliM GCM/RCM combinations assessed under BIAP show changes in every vegetation class across the full study region. The areas currently occupied by all 13 vegetation classes selected for reporting experience large changes in compositional suitability between the baseline and far future periods (see Figure 9). Vegetation classes as they're currently known are unlikely to support all the same species they're currently associated with, and as future vegetation types, may be quite compositionally dissimilar to what they are now. They may also occupy different spaces in the landscape, either by contraction, expansion, or latitudinal or altitudinal shifts (Wearne & Morgan 2001; Howden et al. 2003).

Additional to the impacts presented here, many weeds in the Alpine region are listed as Key Threatening Processes (KTPs). Pickering and Hill (2007) identified eight common weeds in and around the Snowy Mountains, including *Acetosella vulgaris, Hypocharies radicata, Trifolium repens, Taraxacum officinale, Agrostis capillaris, Dactylis glomerat, Anthoxanthum odoratum* and *Achillea millefolium* that are unlikely to be eradicated and may even become more abundant under climate change. South-eastern and south-western edges of KNP and surrounding areas are predicted to have more weed invasion with future climate change. Thus, management strategies must focus on reducing the current impacts to biological assets in these areas, as they are also likely to experience greater biodiversity change than other areas of the Alpine region.

Other species interactions are also expected to be negatively influenced by climate change. There may be increased predation by foxes and cats associated with warmer temperatures and decreasing snow cover (Hughes 2011). The impact of other feral animals, including pigs and horses may also increase with temperature as new areas become more environmentally suited to their habitat requirements. The management strategies currently in place for various threatened species, such as those under the nine SoS management streams, (see NSW SoS website) will need to be reviewed and adapted to reflect such changes as they unfold.

4.1 Key findings

The key findings of the study report that vegetation classes in the Alpine region are predicted to be significantly impacted by climate change. Vegetation classes in the Alpine region found to be most at risk from climate change are Montane Lakes, Alpine Herbfields, Wet Sclerophyll Forests (including Escarpment and Montane) and Dry Sclerophyll Forests, Grassy Woodlands, Montane Bogs and Fens, and Subalpine Woodlands. These vegetation types are those most likely to need direct intervention to ensure their persistence through near and far climate futures.

Large changes in species composition are predicted for vegetation communities between the baseline and far future projection periods; for example, by 2060 to 2079, Alpine Herbfields, Montane Bogs and Fens, Escarpment Wet Sclerophyll Forests, Montane and Southern Tableland Sclerophyll Forests are expected to decrease in area. It is predicted the geographic areas these communities currently occupy will transition to environmental conditions more suited to Subalpine Woodlands and Dry Sclerophyll Forests, which are predicted to expand accordingly.

Key flora species are predicted to be impacted by future changes in climate, including plants currently listed as critically endangered, including the black-hooded sun orchid (*Thelymitra atronitida*), Kelton's leek orchid (*Prasophyllum keltonii*) and *Prasophyllum bagoense*. These critically endangered species will be under increasing pressure as climate change proceeds.

Other threatened flora species predicted to be impacted by future climate change are: pale pomaderris, suggan buggan mallee, feldmark grass, anemone buttercup, austral pillwort, mauve burr-daisy, slender greenhood, Max Mueller's burr-daisy, shining cudweed, leafy anchor plant, Monaro golden daisy, slender greenhood, Kiandra leek orchid. These threatened flora species may need extra management interventions in the near future for them to maintain viable populations.

Threatened fauna species that are predicted to be impacted most from future climate change include southern myotis, hooded robin (south-eastern form), spotted-tailed quoll, sooty owl, southern bell frog, glossy black cockatoo, white-fronted chat, brush-tailed rock-wallaby, dusky woodswallow, booroolong frog, eastern pygmy possum, mountain pygmy possum, southern and northern corroboree frog, white-bellied sea eagle, broad-toothed rat, smoky mouse, Australian painted snipe, and turquoise parrot. Thus, these threatened species may need to be managed in new ways if they are to be preserved.

Subalpine Woodlands, Alpine Heaths and Herbfields, and Alpine Bogs and Fens are habitat for several species of frogs listed as critically endangered. These vegetation classes also provide habitat for the endangered alpine she-oak skink (*Cyclodomorphus praealtus*) and the Guthega skink (*Liopholis guthega*). It is predicted that the southern corroboree frog (*Pseudophryne corroboree*) and alpine tree frog (*Litoria verreauxii alpina*) will also be severely impacted.

4.2 Limitations and further research

Our understanding of how biodiversity will respond to future climate change is still developing. Uncertainty and future improvements in the climatic models will affect the results we present here; for example, changes in rainfall cannot be reliably predicted. Fires are likely to be a major agent of change, but fire events and their severity cannot accurately be predicted. New climate projections will continue to move the baseline forward as actual events supersede prediction. Rigorous long-term monitoring and research into the magnitude and velocity of change will allow us to better understand the biodiversity impacts in areas such as the Alpine region (Biggs et al. 2009; Lindenmayer & Likens 2010). Improved understanding of environmental trends together with ongoing physio-ecological observation will help direct efforts to restore and maintain overall functioning of alpine ecosystems. A range of mitigation and adaptation strategies are needed now and into the future to ensure that as new challenges become apparent, they can be addressed.

This study does not consider further degradation or modification of the landscape, or similarly, positive management actions, including ecological restoration that may be undertaken. Rather, vegetation condition is modelled as of 2012 and kept static to allow the impacts resulting directly from climate change to be assessed. Biodiversity is likely to face compounding pressures as influencing anthropogenic factors interact with emerging impacts resulting from climate change, such as fire, severe storms and erosion. As such, other factors that are likely to influence the persistence of biodiversity need to be taken into consideration, along with the results of this study. Collectively, impacts are likely to be much greater than those reported here, and ongoing work is needed to monitor changes and trends in habitat status, and to understand how best to manage biodiversity as emerging pressures arise.

5. Conclusion

This study assessed broad-scale impacts of climate change on alpine biodiversity in the context of the full study region, and for different vegetation classes and individual threatened flora and fauna. These findings add to existing research available for supporting effective monitoring and management of alpine biodiversity under climate change. In accordance with other literature, this study found that ecosystems in the Alpine region are predicted to be highly vulnerable to the impacts of climate change, as many species are endemic and depend on cold temperatures and adequate snow cover for their habitats. These habitats exist at the edge of environmental gradients that are likely to contract as climate changes, without new areas of environmentally suitable conditions emerging. However, this study finds alpine areas to be somewhat buffered from immediate impacts as the rate of change is expected to be slower than that in other parts of New South Wales, such as the western and central parts of the full study region. The relative intactness of alpine areas will also provide some opportunities for species to migrate in response to climate change, utilising higher altitude habitats where these exist. Although the pace of change in the higher altitude areas is predicted to be slower than in other parts of the state, the consequences are also expected to be greater, as ultimately, there is nowhere for biodiversity to migrate beyond mountain tops as temperatures increase. This will present unique challenges to the task of conserving alpine biodiversity.

As conditions are predominantly expected to become warmer and drier, the montane lakes, bogs and fens of the high country will be under increasing threat just from changes in climatic conditions alone. The same conditions are likely to place grassy woodlands and dry sclerophyll forests under greater threat from increasing severity and occurrence of bushfires. It is important these habitats are managed now with future conditions in mind as their maintenance will influence their utility as species move and adapt, or whether invasive colonisations occur, further altering their composition and structure, and consequently their capacity to persist. Ongoing monitoring of how ecosystems respond to change is needed to understand and address such challenges as they arise. How successful these responses are will depend on the adaptive capacity of ecosystems with some inherently less able to cope due to historic depletion, shrinking or rapidly changing climate niches, therefore more susceptible to transformation, whereas others, whether through greater intactness or tolerance, will be better equipped to absorb these impacts. Areas where habitats have suffered most to date from human modification, such as through the central part of the full study region, are predicted to be the same areas that experience the quickest and most severe effects of climate change.

Although the Alpine region is likely to be buffered from the most severe effects within the timeframe covered by this study, it is important to acknowledge that impacts will continue to unfold beyond this period, some of which may be managed or averted, while others will represent real and irreversible biodiversity loss, further reinforcing the need for immediate, ongoing and adaptive management, to ensure the best outcome we can for the unique, diverse and important biodiversity of the Alpine region.

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Appendix A Spatial data sources

Table 8 Spatial data sources used as inputs to the alpine biodiversity impacts analysis

Data source	Type	Figure	Reference	Retrieved from	Retrieval date
StudyAreaBND	Vector	Figure 1	NA	OEH Corporate (supplied)	29/05/2017
Southern Ranges NPWS Region Boundary	Vector	Figure 1	NA	OEH Corporate (supplied)	29/05/2017
Kosciuszko National Park	Vector	Figure 1	NA	OEH Corporate (supplied)	29/05/2017
BioClimatic_Class (BCC) envelopes	Grid	Figure 2, 3, 6	Drielsma et al. 2017	NARCLiM\9SecondAnalysis\Data\GDM\ClassGrids\ESRI\	6/07/2017
Keith vegetation classes	Grid	Figure 4, 5	Keith, D. 2002	Vegetation\VegClassification\ VegNSWMap_Keith_v3_E3848_VIS	18/09/2017
GDM_NARCliM climate models mean dissimilarity	Grid	Figure 8, 9	Drielsma et al. 2017	NARCLiM\9SecondAnalysis\Data\GDM\DissimilarityGrids\Calcs\dis_mean30	30/08/2017
Eastern pygmy possum occupancy	Grid	Figure 12–15	OEH unpub.	Currently unpublished	Currently unpublished
Statewide vegetation condition	Grid	Figure 16	Drielsma et al. 2017	3C\Products\DerivedProductsData\VegetationCondition2014	8/06/2017
Effective habitat area	Grid	Figure 17	Drielsma et al. 2017	3C\Products\DerivedProductsData\3c_eha	1/06/2017
Link benefits maps	Grid	Figure 18	Drielsma et al. 2015	3C\Products\DerivedProductsData\	20/09/2017
New3cMP	Grid	Figure 19	Drielsma et al. 2015	3C\Products\DerivedProductsData\	13/10/2017
GDM_NARCliM climate models	Grid	Figure 20–23	Drielsma et al. 2017	NARCLiM\9SecondAnalysis\Data\GDM\DissimilarityGrids\	6/07/2017
Conservation manage benefits	Grid	Figure 24	Drielsma et al. 2017	NARCLiM\9SecondAnalysis\3C_NARv2\ia_c	30/08/2017
Revegetation benefits	Grid	Figure 25	Drielsma et al. 2017	NARCLiM\9SecondAnalysis\3C_NARv2\ia_r	22/08/2017
Relative change benefits	Grid	Figure 26	Drielsma et al. 2017	3C\Products\DerivedProductsData\	13/07/2017
Threatened fauna	Vector	NA	NA	OEH Corporate Corporate\Themes\Biodiversity\Fauna\Fauna.gdb	5/09/2017
Threatened flora	Vector	NA	NA	OEH Corporate Corporate\Themes\Biodiversity\Flora\Flora.gdb	11/09/2017

Appendix B Spatial input details

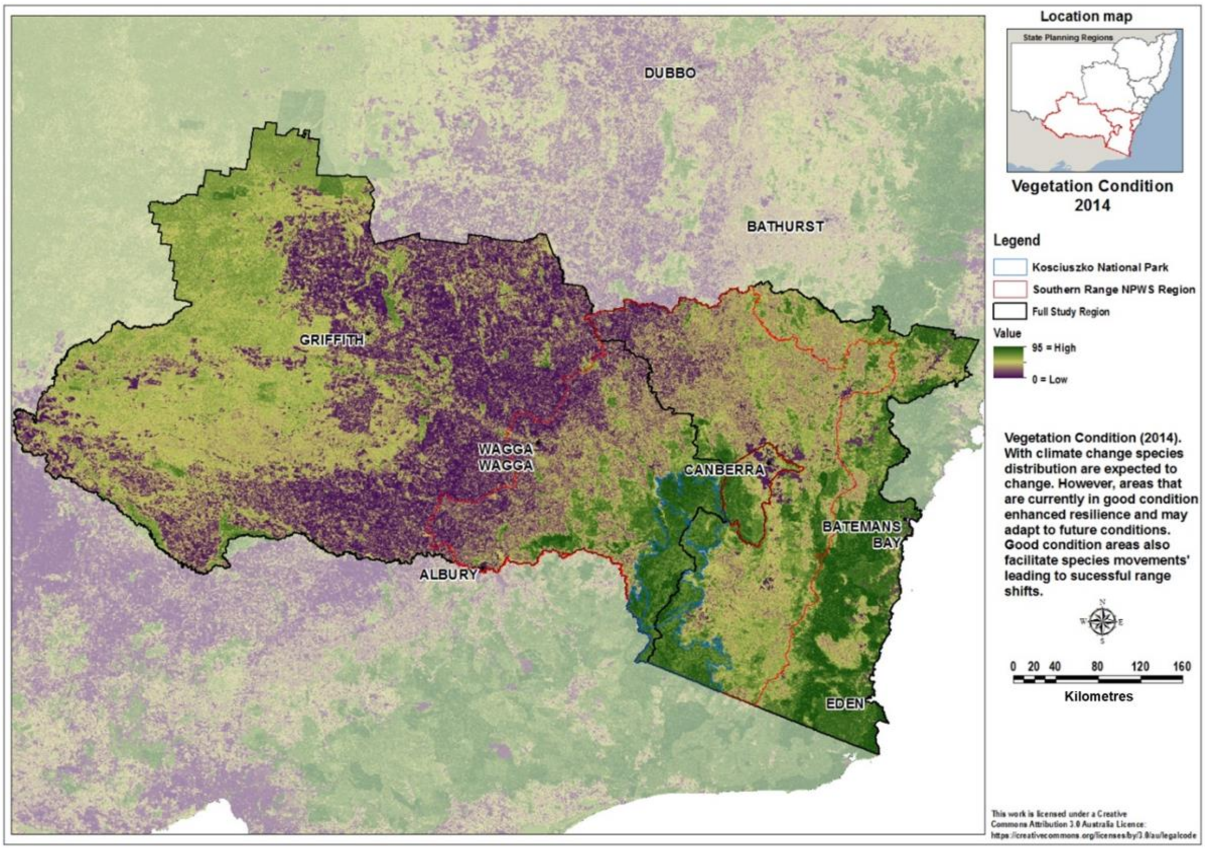
The following sections provide additional details and statistics for each of the spatial products used to develop reported measures.

B1. Current vegetation condition

Vegetation condition modelling provides continuous condition values ranging from zero (complete removal/alteration of native vegetation) to 95 (near pristine state, see Figure 16). The model used assumes condition is static (as of 2012) and does not account for future changes in management. Where the current condition layer is being used in analysis the actual results may be worse than modelled, unless land management practices undergo positive change in the future. This study used the vegetation condition model derived for the whole of New South Wales as part of BIAP (Drielsma et al. 2012, OEH 2016). Vegetation type modelling, remotely sensed foliage projective cover (FPC), land use, tenure and expert derived soil resilience were used as surrogates for estimating the current condition of native vegetation. Land use, tenure and soil resilience were used to inform the model about changes in condition resulting from different management regimes.

Table 9 **Vegetation condition statistics for the 13 selected vegetation classes with the mean values used for reporting shown in bold**

		Vegetation condition			
Vegetation class	**Area (ha)**	**Min.**	**Max.**	**Mean**	**Std dev.**
Alpine Bogs and Fens	40,431	32	95	**79**	11.55
Alpine Fjaeldmarks	175	61	95	**86**	9.61
Alpine Heaths	71,781	37	95	**77**	9.40
Alpine Herbfields	39,113	13	95	**74**	10.53
Montane Bogs and Fens	12,625	9	92	**68**	14.52
Montane Lakes	2,906	29	81	**50**	8.43
Montane Wet Sclerophyll Forests	78,119	14	95	**80**	7.75
Southern Escarpment Wet Sclerophyll Forests	195,275	9	95	**81**	9.68
Southern Montane Heaths	8,281	13	92	**77**	11.23
Southern Tableland Dry Sclerophyll Forests	692,644	6	95	**71**	14.58
Southern Tableland Grassy Woodlands	105,231	4	95	**63**	17.65
Southern Tableland Wet Sclerophyll Forests	197,288	6	95	**77**	12.01
Subalpine Woodlands	366,619	7	95	**75**	11.01



Vegetation Condition (2014). With climate change species distribution are expected to change. However, areas that are currently in good condition enhanced resilience and may adapt to future conditions. Good condition areas also facilitate species movements' leading to sucessful range shifts.

Figure 16 **Vegetation condition modelled for the NARCliM domain and shown for the full study region**

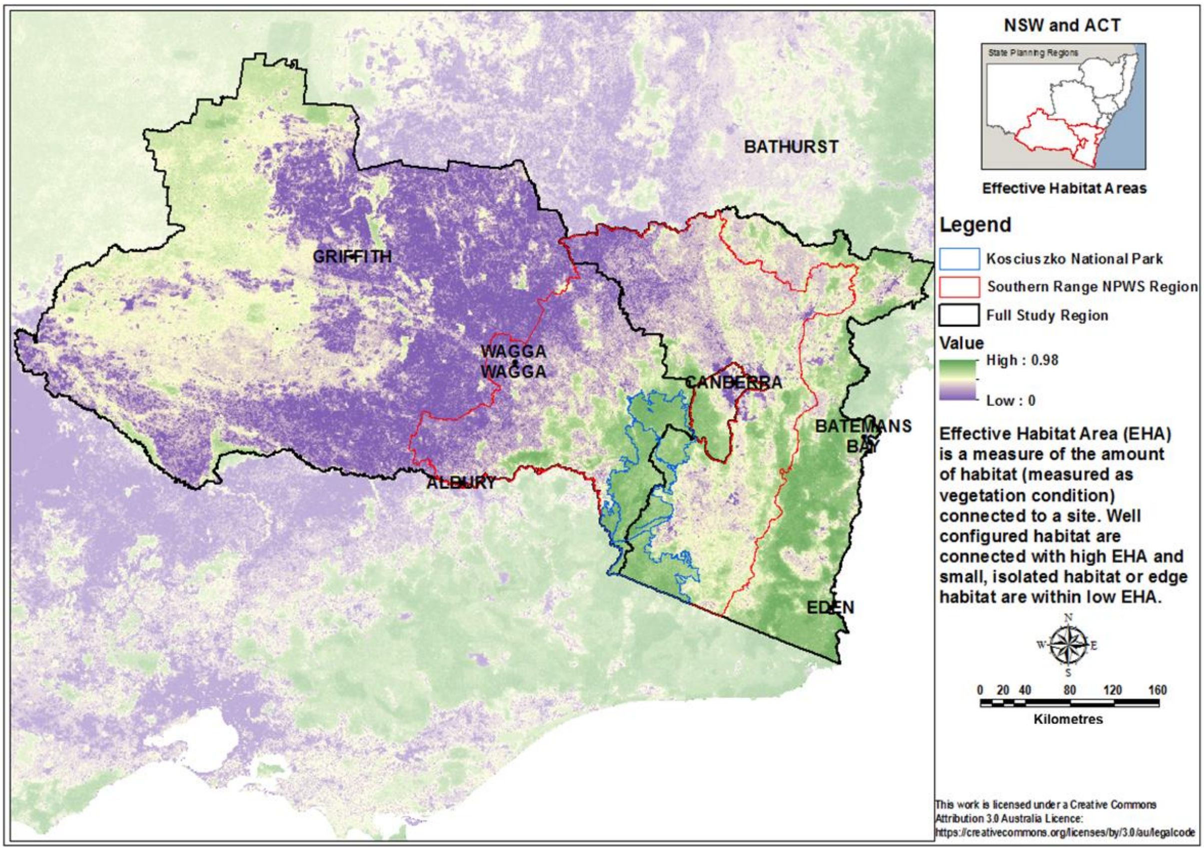
Condition values range from low (purple) to high (dark green).

B2. Effective habitat area

Effective habitat area (EHA) is a measure of habitat's spatial context (Figure 17), integrating ecological condition at each location (grid cell) with measures of its connectivity to, and the condition of, surrounding habitat. Maximum values are achieved in high condition habitat within large intact patches. Effective habitat area values are reduced through poorer condition at or within a five-kilometre radius of the site, or where degraded habitat reduces connectivity to neighbouring high condition areas.

Table 10 **Effective habitat area statistics for the 13 selected vegetation classes with the mean values used for reporting shown in bold**

		Effective habitat area			
Vegetation class	**Area (ha)**	**Min.**	**Max.**	**Mean**	**Std dev.**
Alpine Bogs and Fens	40,431	55	94	**85**	5.63
Alpine Fjaeldmarks	175	81	94	**90**	3.20
Alpine Heaths	71,781	66	94	**84**	3.76
Alpine Herbfields	39,113	51	94	**83**	4.92
Montane Bogs and Fens	12,625	39	92	**77**	8.51
Montane Lakes	2,906	53	89	**63**	4.01
Montane Wet Sclerophyll Forests	78,119	45	93	**86**	3.62
Southern Escarpment Wet Sclerophyll Forests	195,275	41	93	**86**	5.16
Southern Montane Heaths	8,281	44	92	**84**	6.53
Southern Tableland Dry Sclerophyll Forests	692,644	29	93	**78**	8.88
Southern Tableland Grassy Woodlands	105,231	28	91	**72**	10.27
Southern Tableland Wet Sclerophyll Forests	197,288	34	93	**83**	7.21
Subalpine Woodlands	366,619	38	93	**82**	6.24



Effective Habitat Area (EHA) is a measure of the amount of habitat (measured as vegetation condition) connected to a site. Well configured habitat are connected with high EHA and small, isolated habitat or edge habitat are within low EHA.

Figure 17 **Effective habitat area for the full study region**

Effective habitat area values range from low (0, purple) to high (98, dark green).

B3. Habitat connectivity

The links habitat connectivity map shows where the placement and structure of habitat is most likely to facilitate the movement of biodiversity through the landscape. Connectivity is modelled across a wide range of ecological scales to provide an unbiased evaluation of habitat connectivity independent of specific taxa, movement processes or timeframes. In this case, connectivity between habitat has been measured across spatial scales ranging from a few hundred metres to hundreds of kilometres.

Areas with higher connectivity are more likely to support propagation, migration or colonisation as species shift in response to changes in habitat suitability resulting from climate change. In contrast, lower connectivity areas are more likely to impede ecological movement as species and ecosystems respond to change. Areas having higher connectivity do not directly imply they have higher habitat condition. These areas can also include degraded locations that may not be colonised but will allow biodiversity to move through them to more suitable habitat due to their relative locality. Restoring or improving lost and degraded habitat in such areas is likely to help facilitate successful responses to climate change. Further loss of intact habitats that also provide connectivity should be avoided to prevent further impeding the capacity to respond.

Links habitat connectivity mapping (Figure 18) highlights areas where it is important to maintain or improve habitat connectivity to allow biodiversity to remain viable across the region.

Table 11 Habitat connectivity statistics for the 13 selected vegetation classes with the mean values used for reporting shown in bold

		Habitat connectivity			
Vegetation class	Area (ha)	Min.	Max.	Mean	Std dev.
Alpine Bogs and Fens	40,431	91	201	**153**	18.29
Alpine Fjaeldmarks	175	122	177	**150**	15.53
Alpine Heaths	71,781	107	199	**147**	15.00
Alpine Herbfields	39,113	94	193	**145**	13.71
Montane Bogs and Fens	12,625	58	205	**128**	24.60
Montane Lakes	2,906	62	156	**95**	15.11
Montane Wet Sclerophyll Forests	78,119	72	208	**140**	13.15
Southern Escarpment Wet Sclerophyll Forests	195,275	72	211	**150**	17.60
Southern Montane Heaths	8,281	70	193	**144**	16.14
Southern Tableland Dry Sclerophyll Forests	692,644	34	229	**128**	25.97
Southern Tableland Grassy Woodlands	105,231	24	184	**111**	27.06
Southern Tableland Wet Sclerophyll Forests	197,288	59	210	**139**	19.96
Subalpine Woodlands	366,619	58	218	**141**	18.83

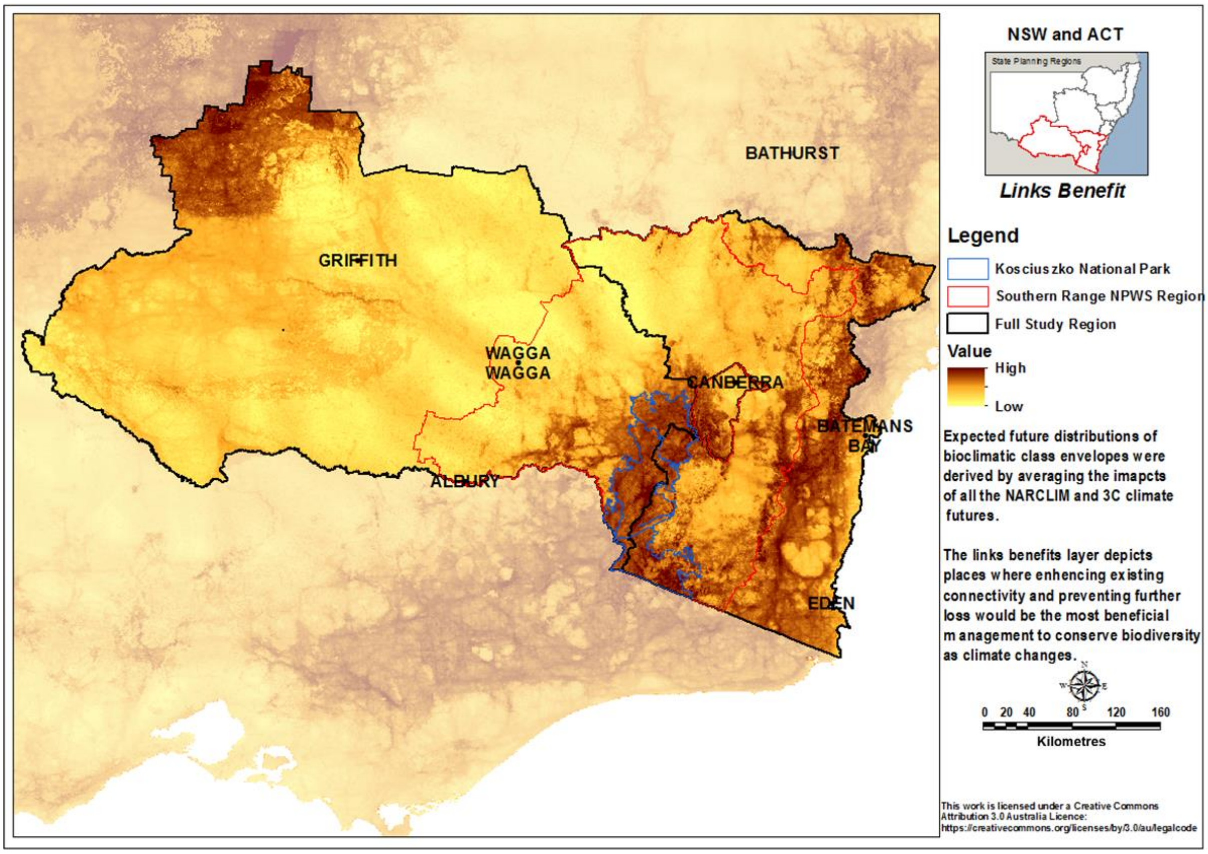


Figure 18 **Links habitat connectivity map depicting places where enhancing existing connectivity and preventing future loss will most benefit biodiversity conservation**

B4. Climate ready metapopulation analysis

Climate ready metapopulation analysis (3CMP) performed as a prototype under the 3C project (Drielsma et al. 2015) shows areas that will be able to support ecosystem diversity under predicted future climate change scenarios (Figure 19). Areas shaded green are either 1) relatively stable through climate change, supporting depleted (cleared or degraded) ecosystems; or 2) by their connectivity can passively transition between depleted ecosystems. Maintaining appropriate connectivity is an increasingly important component of effective conservation strategies, as species adapt to the impacts of climate change. The ability to move across the landscape to more suitable habitat as environmental conditions change will be vital to the persistence of many species.

3CMP is broadly based on the REMP methodology (Drielsma & Ferrier 2009). Consistent with that approach, occupancy is mapped across the region subject to the suitability, amount, quality and spatial pattern of habitat. In the context of climate change modelling, the 3CMP model is an early attempt at this style of modelling and was only performed using the MPI (RCP8.5) climate future from 2000 to 2050. The results at this stage are preliminary; therefore, these results have been given less focus here when reporting.

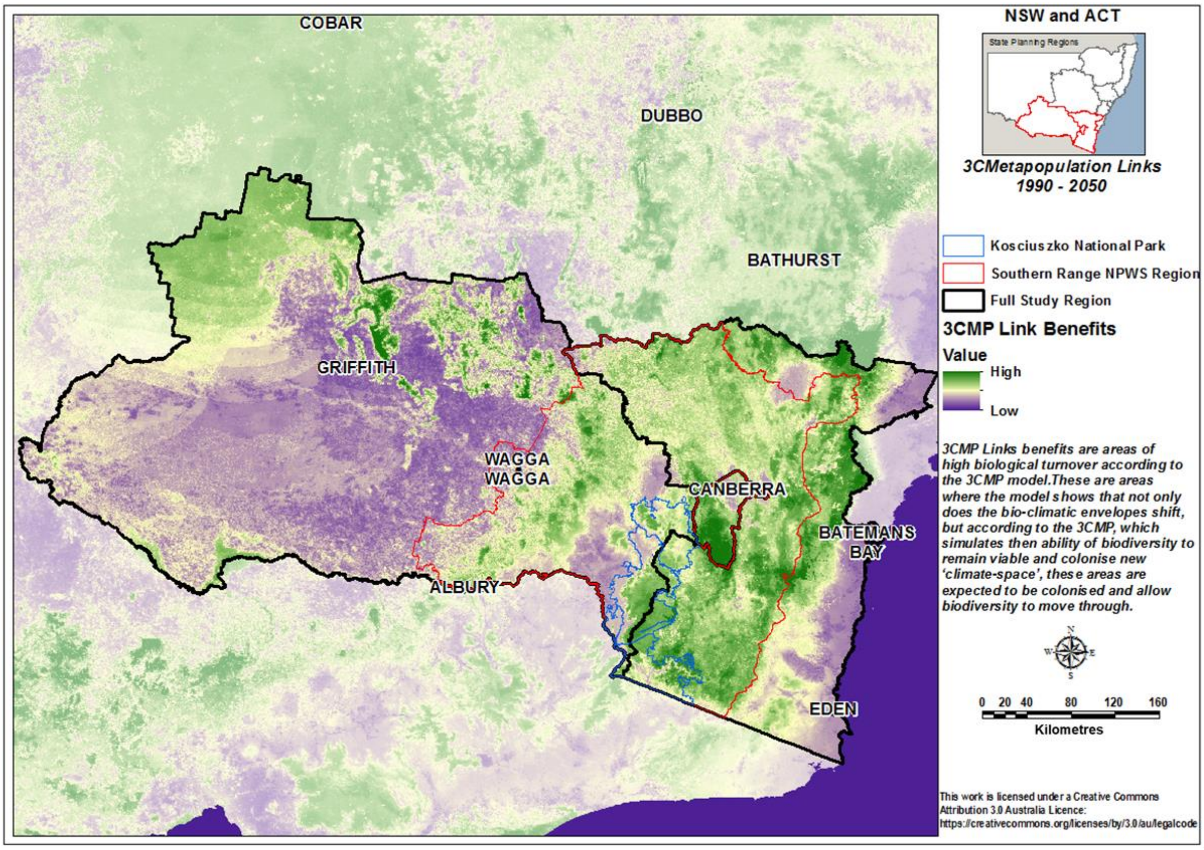


Figure 19 **3C metapopulation links, showing areas of expected migration, colonisation and temporal compositional turnover**

Greener areas support ecosystem diversity through expected future climate and are either stable through climate change or by virtue of their connectivity are able to passively transition to alternative ecosystems.

B5. Climate impacts – dissimilarity with baseline biodiversity

As climatic conditions change, species unable to tolerate or adapt to prevailing conditions are less likely to persist in situ and will more frequently be replaced by those better equipped and more able to colonise under future conditions, whether native or exotic. Species that can tolerate changing conditions will persist in situ for longer, forming the basis of novel emerging communities.

Future climate projections were used to estimate the dissimilarity in species composition between current and future climate projections at each location (grid cell). This provides a measure of how unsuitable each location will become for the composition of species it currently supports and how dissimilar the composition of species best suited to future conditions is, to that which currently occurs.

The dissimilarity in species composition was averaged for each location (grid cell) across each of the individual NARCliM GCM/RCMs (Figure 20 to Figure 23) using a multi-model mean for 2020 to 2039 relative to 1990 to 1990, and 2060 to 2079 relative to 1990 to 2009. Potential values can range from 0, indicating no compositional change (no dissimilarity), to 1 where no species are expected to be shared between the two time periods. These values have been multiplied by 1000 for reporting.

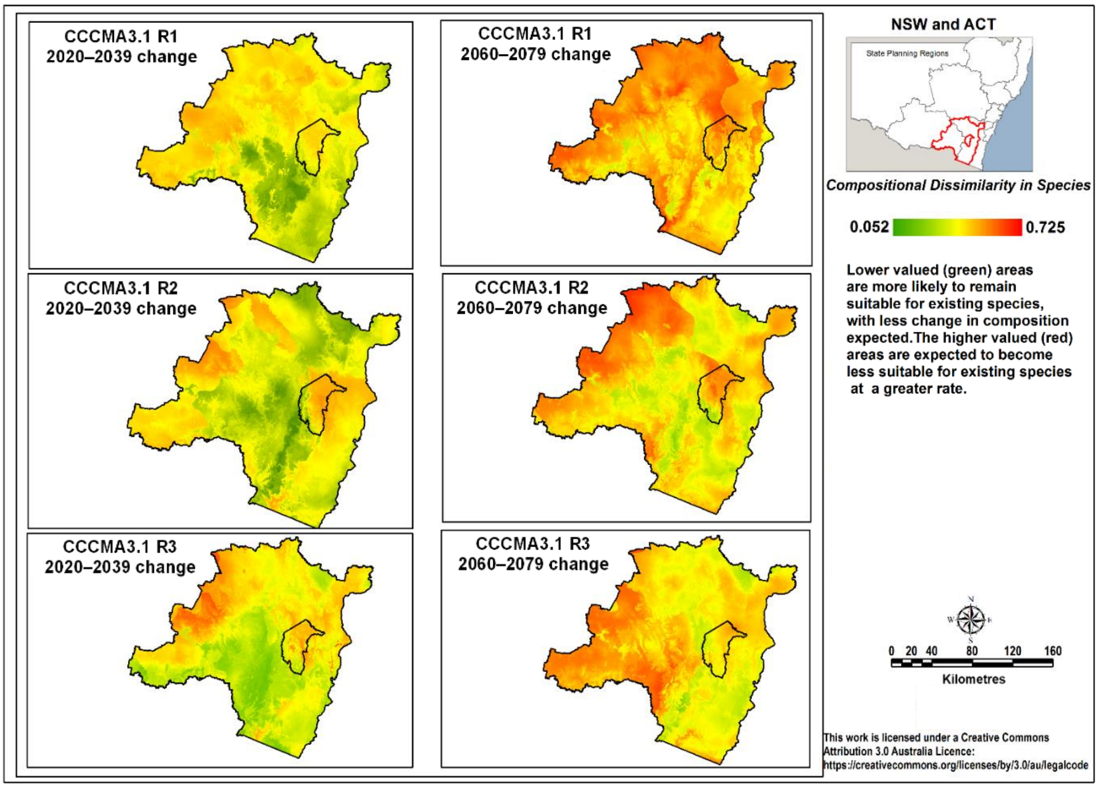


Figure 20 Compositional dissimilarity between transformed environmental variables for 2020 to 2039 relative to 1990 to 2009 (left column), and 2060 to 2079 relative to 1990 to 2009 (right column), at each location (grid cell) for the NARCliM CCCMA3.1 GCM and R1 (top), R2 (middle) and R3 (bottom) RCMs

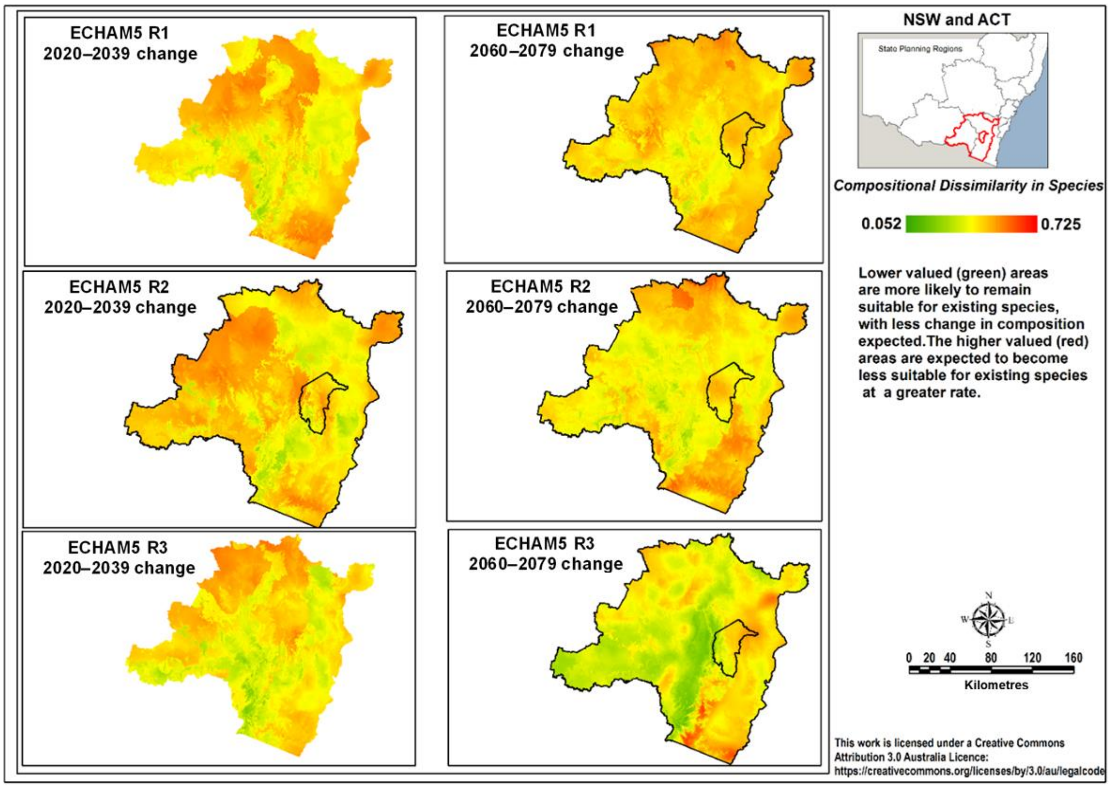


Figure 21 Compositional dissimilarity between transformed environmental variables for 2020 to 2039 relative to 1990 to 2009 (left column), and 2060 to 2079 relative to 1990 to 2009 (right column), at each location (grid cell) for the NARCliM ECHAM5 GCM and R1 (top), R2 (middle) and R3 (bottom) RCMs

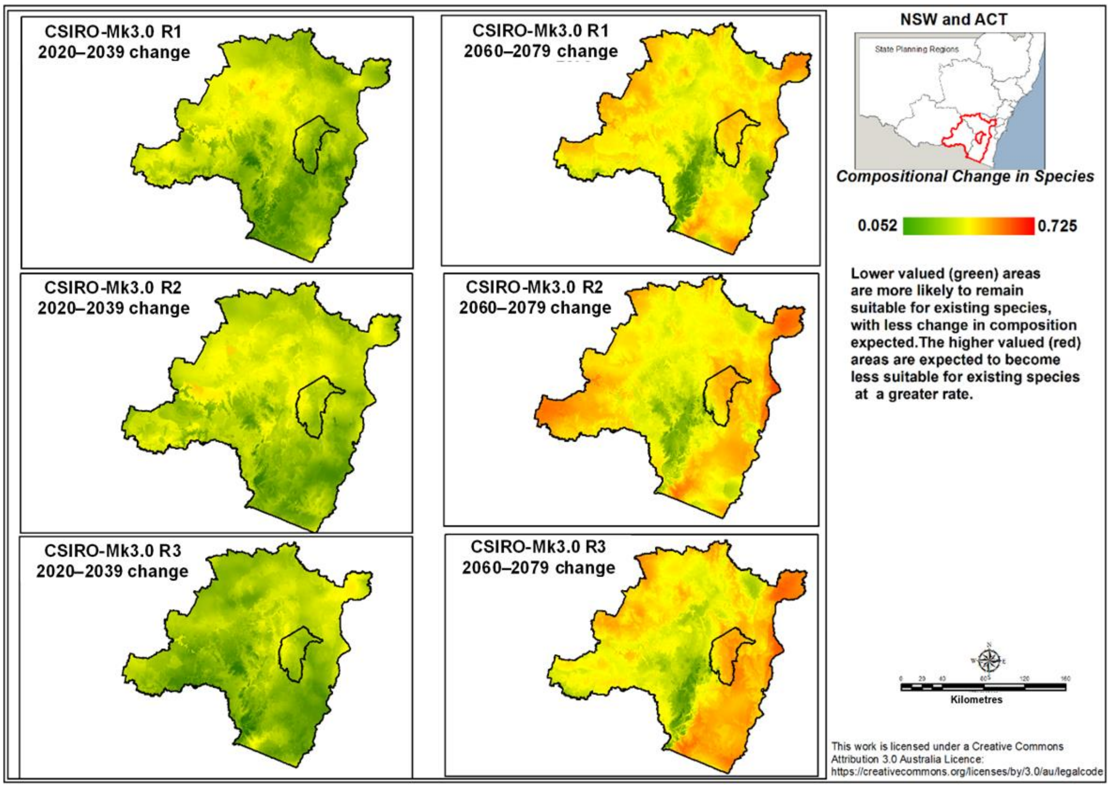


Figure 22 Compositional dissimilarity between transformed environmental variables for 2020 to 2039 relative to 1990 to 2009 (left column), and 2060 to 2079 relative to 1990 to 2009 (right column), at each location (grid cell) for the NARCliM CSIRO-Mk3.0 GCM and R1 (top), R2 (middle) and R3 (bottom) RCMs

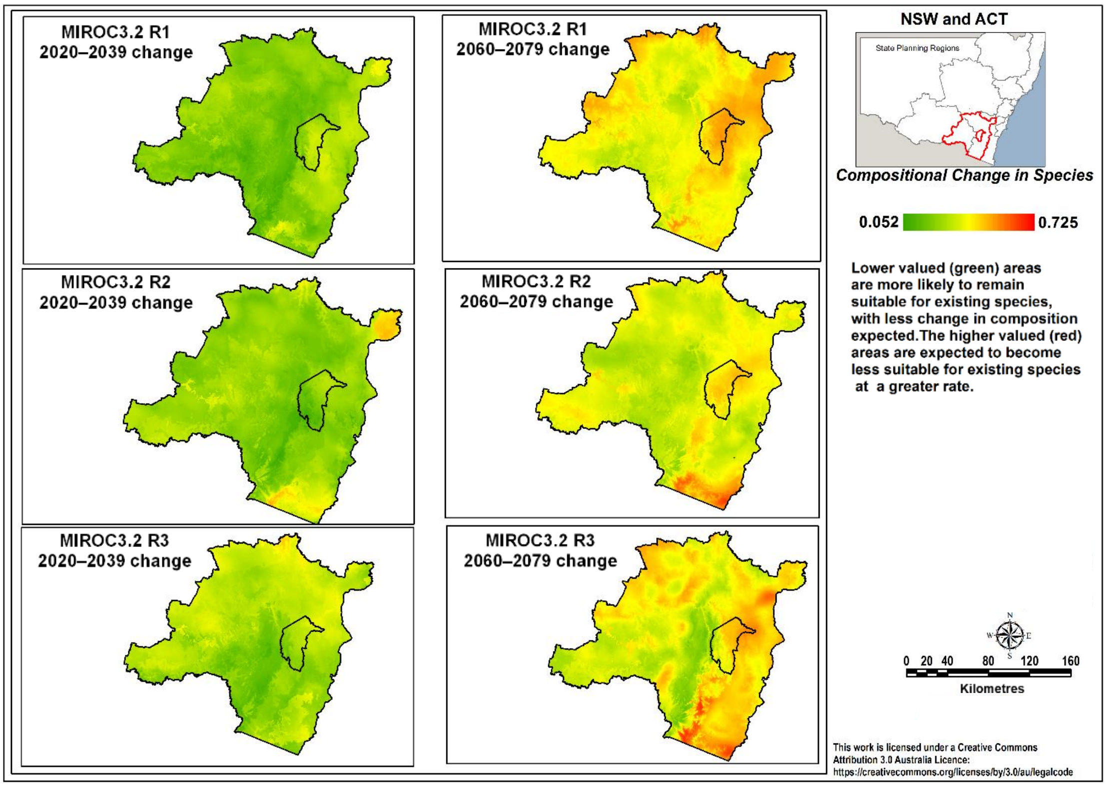


Figure 23 Compositional dissimilarity between transformed environmental variables for 2020 to 2039 relative to 1990 to 2009 (left column), and 2060 to 2079 relative to 1990 to 2009 (right column), at each location (grid cell) for the NARCliM MIROC3.2 GCM and R1 (top), R2 (middle) and R3 (bottom) RCMs

B6. Conservation manage benefits

Conservation manage benefits (Drielsma et al. 2014) measure the benefit to regional biodiversity persistence that occurs if existing intact habitat is retained at each location (grid cell), proportional to the avoided loss that would result from its removal. These benefits consider the representativeness and condition of habitat at each location (grid cell) and how well connected it is to other surrounding habitat (up to a 5 km radius).

Conservation manage benefits are most relevant to conservation efforts aimed at retaining relatively intact well-connected examples of habitat types that are not well represented in the contemporary landscape. These are often habitat types that have been largely cleared or degraded through past management; therefore, retain a lower proportion of their original extent and condition. Conservation manage benefits are designed to inform management actions such as reserve establishment and private land conservation that promote the maintenance of intact and well-connected habitats to protect remaining diversity.

Conservation manage benefit values for this study are scaled between 0 (low), where habitat has been completely degraded, to a maximum possible value of 255 (high), where less-well represented habitat types remain intact and well connected with surrounding habitat (Figure 24).

Table 12 **Conservation manage benefits (1990 to 2009 to 2060 to 2079) statistics for the 13 selected vegetation classes with the mean values used for reporting shown in bold**

		Conservation manage benefits			
Vegetation class	Area (ha)	Min.	Max.	Mean	Std dev.
Alpine Bogs and Fens	40,431	39	111	**81**	11.51
Alpine Fjaeldmarks	175	64	98	**87**	8.77
Alpine Heaths	71,781	42	111	**77**	8.90
Alpine Herbfields	39,113	23	108	**77**	10.49
Montane Bogs and Fens	12,625	16	127	**79**	16.20
Montane Lakes	2,906	48	103	**73**	10.25
Montane Wet Sclerophyll Forests	78,119	15	120	**80**	9.60
Southern Escarpment Wet Sclerophyll Forests	195,275	14	154	**82**	16.83
Southern Montane Heaths	8,281	21	129	**87**	13.69
Southern Tableland Dry Sclerophyll Forests	692,644	9	158	**93**	19.29
Southern Tableland Grassy Woodlands	105,231	12	159	**85**	23.10
Southern Tableland Wet Sclerophyll Forests	197,288	9	152	**87**	16.73
Subalpine Woodlands	366,619	13	130	**83**	12.92

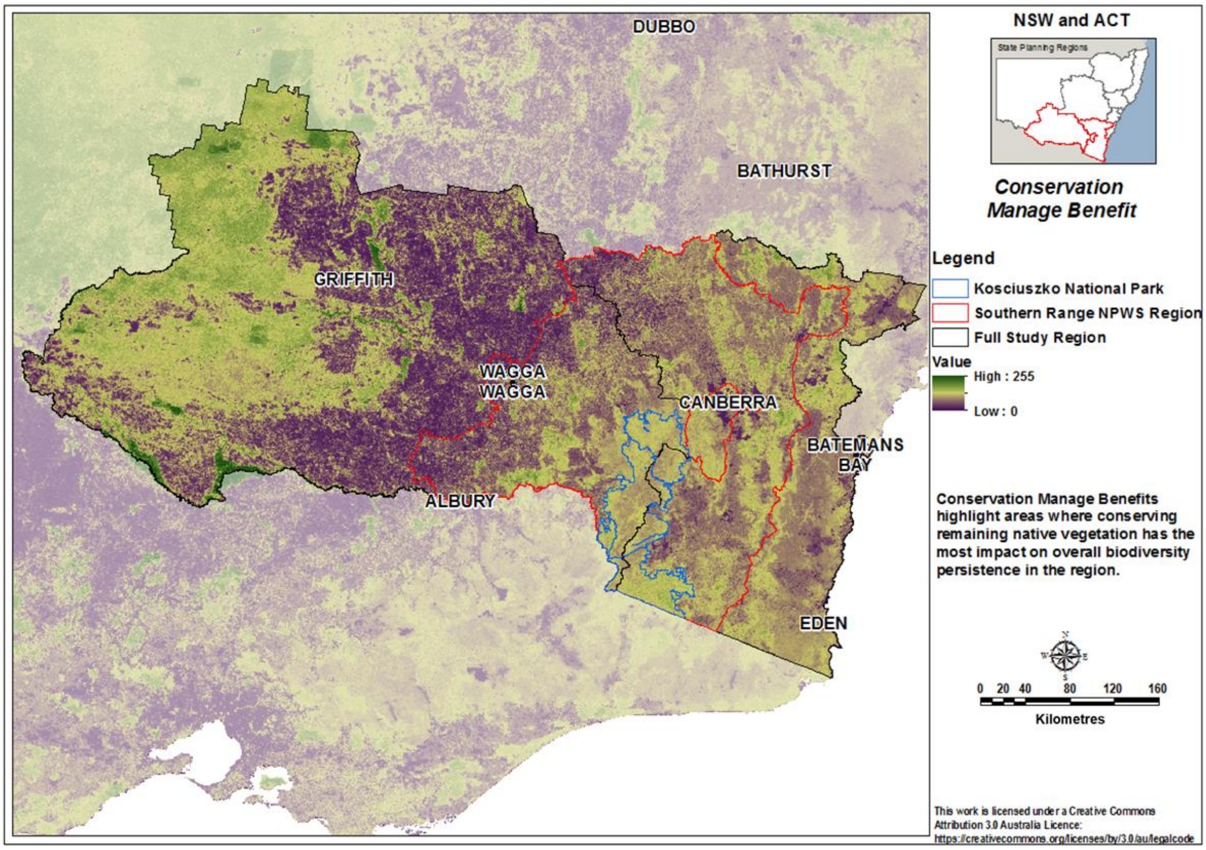


Figure 24 **Conservation manage benefits highlight areas where conserving remaining native vegetation has the most impact on overall biodiversity persistence in the region**

B7. Revegetation benefits

Revegetation benefits identify degraded areas where replanting or the natural regeneration of species previously occurring (or expected to occur under future climate) will have the greatest positive influence on regional biodiversity persistence by increasing the representativeness of species and restoring lost neighbouring connectivity (Drielsma et al. 2014). Revegetation benefits are derived by simulating changes in habitat condition at each location (grid cell) from its current state to a pristine state, then measuring the effect on regional biodiversity persistence. Revegetation benefits aim to direct restoration and revegetation efforts towards degraded areas where important habitat types have been lost (or could persist under future climate) but where good context through proximity and connectivity to other intact habitats remain.

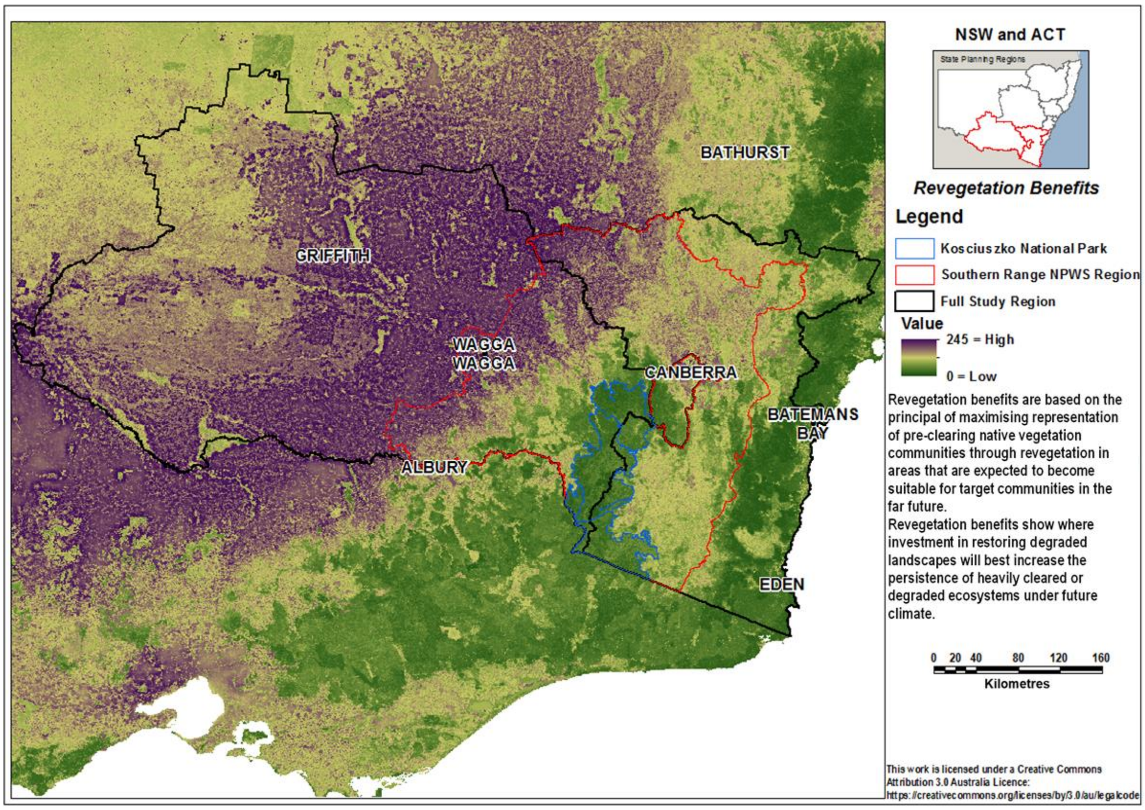
The revegetation benefits map (Figure 25) identifies areas where restoring lost or degraded habitat will have the greatest contribution to biodiversity persistence averaged across the 12 NARCliM GCM/RCM combinations for the 1990 to 2009 baseline and two future periods. Revegetation benefit values occurring in the full study region range between 0 (low) and 245 (high, out of a possible 255) (Figure 25 and Table 13).

Benefits have been averaged across current and all future climate scenarios to account for the uncertainty associated with future climate and highlight areas that are of high value across the potential range of climate outcomes. Irrespective of how climate may change, these are the areas where the greatest benefits from investment in revegetation or restoration is most certain.

Table 13 **Revegetation benefits statistics for the 13 selected vegetation classes with the mean values used for reporting shown in bold**

Results are averaged across the three NARCliM periods (1990 to 2009, 2020 to 2039, and 2060 to 2079) for all 12 GCM/RCM combinations.

		Revegetation manage benefits			
Vegetation class	**Area (ha)**	**Min.**	**Max.**	**Mean**	**Std dev.**
Alpine Bogs and Fens	40,431	10	124	**43**	17.99
Alpine Fjaeldmarks	175	10	45	**25**	8.72
Alpine Heaths	71,781	10	109	**46**	11.19
Alpine Herbfields	39,113	10	102	**56**	17.10
Montane Bogs and Fens	12,625	27	133	**76**	22.82
Montane Lakes	2,906	26	153	**124**	9.35
Montane Wet Sclerophyll Forests	78,119	17	110	**46**	11.05
Southern Escarpment Wet Sclerophyll Forests	195,275	15	125	**47**	18.04
Southern Montane Heaths	8,281	19	145	**58**	22.67
Southern Tableland Dry Sclerophyll Forests	692,644	21	170	**78**	28.06
Southern Tableland Grassy Woodlands	105,231	27	169	**92**	27.72
Southern Tableland Wet Sclerophyll Forests	197,288	16	150	**57**	23.19
Subalpine Woodlands	366,619	16	166	**59**	19.52



Revegetation benefits are based on the principal of maximising representation of pre-clearing native vegetation communities through revegetation in areas that are expected to become suitable for target communities in the far future.

Revegetation benefits show where investment in restoring degraded landscapes will best increase the persistence of heavily cleared or degraded ecosystems under future climate.

Figure 25 **Revegetation benefits show where investment in restoring degraded landscapes will best increase the persistence of degraded ecosystems under future climate**

Results are averaged across the three NARCliM periods (1990 to 2009, 2020 to 2039, and 2060 to 2079) for all 12 GCM/RCM combinations.B8. Relative change in benefits

The relative change in biodiversity benefits between 2000 and 2050 provides a perspective on how climate change is expected to influence the way in which habitat at each location (grid cell) is best managed across the region (Figure 26). This relative change in biodiversity benefit values shows how actual conservation and revegetation benefit values, which are intended to inform investment decisions (Figure 24 and Figure 25), change over time.

Benefit values only increase, not decrease, across the full study region, indicating increasing pressure on biodiversity from climate change; therefore, an increasing need to undertake management actions that benefit biodiversity persistence. Important alpine habitats, with biodiversity benefits already in the upper range, are increasing disproportionally in relation to habitats in lower slopes and the plains to the west. This highlights an increasing role for alpine areas in biodiversity conservation. As BCCs shift altitudinally in response to increasing temperatures, these areas will need to accommodate retreating climate refugees from other areas, while also remaining the last refuge of species already dependant on alpine environments.

Table 14 Change in biodiversity benefits from 2000 to 2050 for the 13 selected vegetation classes with the mean values used for reporting shown in bold

Vegetation class	Area (ha)	Relative change in benefits Min.	Max.	Mean	Std dev.
Alpine Bogs and Fens	40,431	235	435	**409**	24.50
Alpine Fjaeldmarks	175	395	414	**405**	5.34
Alpine Heaths	71,781	253	435	**407**	21.22
Alpine Herbfields	39,113	303	434	**384**	33.42
Montane Bogs and Fens	12,625	165	401	**281**	46.66
Montane Lakes	2,906	193	409	**249**	21.19
Montane Wet Sclerophyll Forests	78,119	190	427	**348**	34.10
Southern Escarpment Wet Sclerophyll Forests	195,275	151	401	**297**	38.79
Southern Montane Heaths	8,281	192	370	**279**	41.93
Southern Tableland Dry Sclerophyll Forests	692,644	136	398	**248**	43.33
Southern Tableland Grassy Woodlands	105,231	124	367	**226**	39.30
Southern Tableland Wet Sclerophyll Forests	197,288	134	401	**280**	51.20
Subalpine Woodlands	366,619	170	435	**333**	48.96

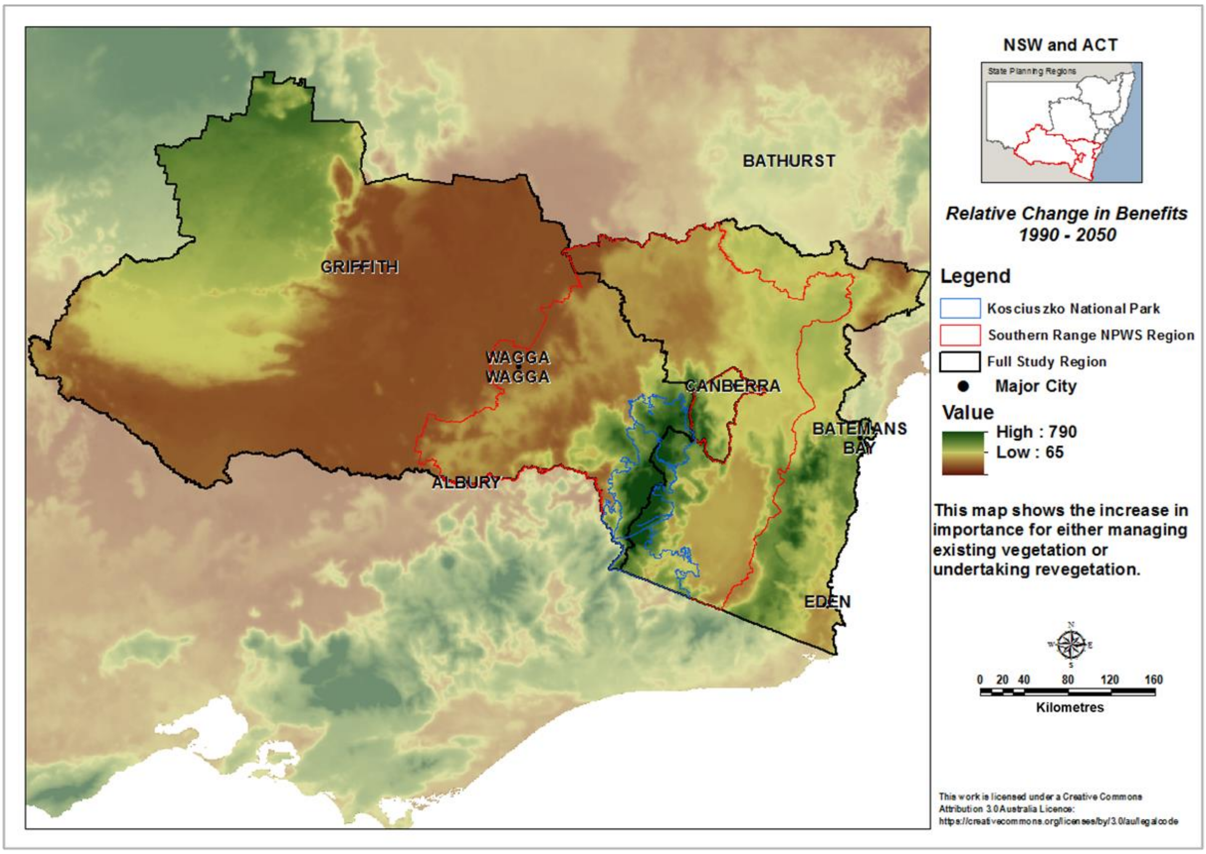


Figure 26 Relative change in benefits shows the increase in importance for either managing existing vegetation or undertaking revegetation by 2050