3C Modelling for Biodiversity under Future Climate

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Abbreviations

3C – refers to the three NRM clusters included in the study area

3CLINKS – the assessment methodology for deriving climate corridors

3CMP – the assessment methodology for modelling occupancy based on metapopulation modelling

AdaptNRM – the National NRM Impacts and Adaptation project led by CSIRO (www.adaptnrm.com)

ANHAT – Australian Natural Heritage Assessment Tool

BCC – bioclimatic class

BDI – biodiversity index, calculated by the Biodiversity Forecasting Toolkit

BFT – the Biodiversity Forecasting Toolkit assessment methodology

CAN – the Canadian Earth System Global Climate Model (CAN-ESM2)

CS – Conservation Status (index of the proportion of species expected to persist in a BCC)

ED – environmental distance

FPC – foliage projective cover

GCM – global climate/circulation model

GDM – generalised dissimilarity modelling

IBRA – Interim Biogeographic Regionalisation for Australia

MAR – mean annual rainfall

MAT – mean annual temperature

MIR – the MIROC5 Climate Simulation Global Climate Model

MPI – the Max-Plank-Institute Earth System Global Climate Model (MPI-ESM)

NARCLiM – NSW/ACT Regional Climate Modelling project

NRM – natural resource management (agency)

OEH – Office of Environment and Heritage NSW

RCP – representative concentration pathways (IPCC emissions scenario)

REMP – rapid evaluation of metapopulation persistence

Summary

Short description

The 3C modelling for biodiversity under future climate project is part of the Australian government's Regional Natural Resource Management Planning for Climate Change, Stream 2. The 3C study area comprised the East Coast, Central Slopes and Murray-Basin NRM cluster regions and was extended to include all of NSW, totalling approximately one quarter of the Australian continent (approx. 2M ha)(see Figure 1).

The 3C project evaluated the impacts of climate change on biodiversity up to 2050 and mapped where conservation actions will provide the greatest benefits. Impacts on 100 ecosystems were modelled for six alternative climate futures using a range of spatial-analytical approaches. Natural resource management agencies can now incorporate this information into their planning.

Novel methodologies were developed to integrate climate impacts with other key considerations – representation of distinct vegetation classes, vegetation condition and habitat connectivity – into a framework for evaluating scenarios in terms of overall biodiversity persistence; and for mapping the biodiversity benefits of applying conservation measures and revegetation across a region.

The 3C provides a big-picture perspective to natural resource management agencies (NRMs), the people who are well-placed to make decisions at a local scale. The 3C biodiversity evaluation warns of significant changes and general depletion of biodiversity in the region arising from climate change. Map products help NRMs to minimise climate impacts to biodiversity through their biodiversity conservation activities.

Visualisation products arising from the work have been designed to engage people in creative thinking and learning in relation to biodiversity in a changing climate.

A detailed list of products is provided in this report [see section 4 entitled **Products**]. This report and all the 3C spatial data and visualisation products are stored and archived on the TERRA NOVA portal (www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection) where they are searchable online and freely available for download.

OEH context

The OEH Knowledge Strategy 2013–17 is a targeted approach to identify priority knowledge needs within the organisation to strengthen the alignment of our science, research and knowledge exchange activities to best meet organisational priorities. By establishing a system of ongoing review, priorities and progress towards achieving objectives are regularly documented and reported. The 3C project is specifically mentioned as a high priority knowledge need for OEH in both the Climate Change Impacts and Adaptation knowledge theme and the Landscape Management knowledge theme of the Knowledge Strategy.

This report describes the first stage of a broad-scale biodiversity and climate change modelling program undertaken by the NSW Office of Environment and Heritage (OEH) and its collaborators. The NARCLiM biodiversity modelling project (2014–2015) will build on the 3C work throughout 2015. The interim finding of the NARCLiM project have been compiled (Office of Environment and Heritage NSW 2015).

Methods in brief

The 3C approach synthesises spatial habitat predictors and topographically down-scaled (9-second, approximately 250 m grid cell resolution) climate modelling at interpolated time-steps from 1990 to 2050. The modelling undertakes biodiversity assessment across time-steps taking into account emergent environmental conditions and landscape connectivity. The 3C comprises well-developed biodiversity assessment tools that consider: representation of original pre-European ecosystems (Biodiversity Forecasting Toolkit); habitat connectivity at the scale of migrations (Spatial Links Tool); and metapopulation persistence.

To inform the modelling, relatively high resolution continuous raster surfaces (250 m grid cells) were developed of:

- bioclimatic vegetation class distributions (based on vascular plant survey data and spatially complete predictor surfaces) for 1990 and projected up to 2050 using a Generalised Dissimilarity Model, and
- habitat condition of the current landscape.

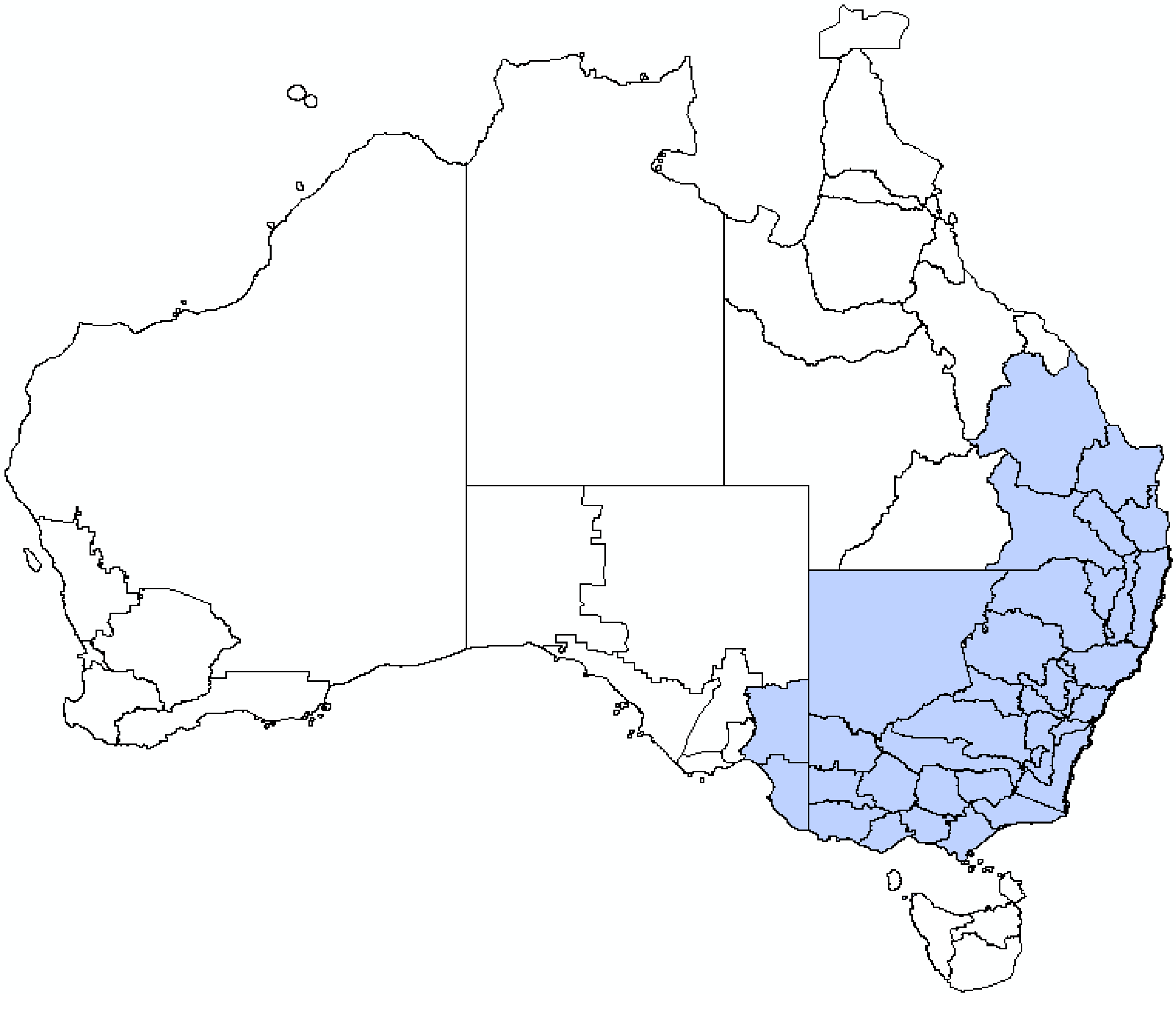

Figure 1: The 3C study area (shaded), based on NRM boundaries

The analysis also included a 50 km buffer around the inland boundaries in order to negate any edge effects within the areas shown here.

3C involved two broad steps:

1. **Deriving bioclimatic suitability** – forecasting the distribution of areas suitable to support each of 100 bioclimatic classes under alternative futures
2. **Climate-informed biodiversity assessment** –
   a) evaluating spatial distributions of the 100 bioclimatic classes as outcomes of interaction between landscape condition, connectivity and alternative future climates, and
   b) mapping the expected benefits of undertaking conservation actions across the 3C region.

Outputs include:

1. a Biodiversity Forecasting Toolkit evaluation of climate change induced impacts on broad-scale biogeographic patterns across the 3C region
2. spatial layers depicting conservation benefit: the relative benefits to the region's biodiversity of investing in a variety of conservation actions across the region
3. aggregated map products, highlighting convergence and synergies arising from the project's outputs
4. interactive visualisation tools to assist in the exploration of outputs, and
5. a scenario evaluation framework for quantifying biodiversity impacts (positive and negative) arising from complex suites of land-use changes and environmental changes.

Relationship to AdaptNRM

AdaptNRM, the CSIRO led National NRM project, aims to support NRM groups in updating their plans to include climate adaptation planning (www.adaptnrm.com). Information and materials are made accessible through a series of five easy-to-understand learning modules which deliver simple, synthesised guidance for planning. The two AdaptNRM modules on biodiversity (Williams et al. 2014; Prober et al. 2015) focus on description and illustration across four biological groups: vascular plants, mammals, reptiles and amphibians.

The 3C project and the AdaptNRM modules on biodiversity share a common basis in community-level modelling and build on the same data (Williams et al. 2015). AdaptNRM is delivering high resolution data continent-wide while the 3C project is focused on eastern Australia. Creating linkages to national initiatives promotes consistent information and guidance to regional NRM planners for climate change adaptation options and also improves understanding of the biophysical, ecosystem, social, economic and cultural drivers that influence land-management change under a changing climate.

At the beginning of both projects the two biodiversity teams, who have a history of working together, agreed on how they would share software and data to ensure consistency in this first iteration of outputs for NRMs. The 3C project uses the biodiversity models and climate scenarios developed at 9-second resolution by CSIRO (outlined in Williams et al. 2014), and both teams contributed across the two projects. While both teams also develop benefit mapping for biodiversity conservation action (Prober et al. 2015), 3C develops more detailed vegetation condition information and uses more explicit landscape-limited movement processes, leading to biodiversity evaluations as well as map products.

Collectively, the two projects provide, for the region over which they intersect, complementary perspectives on climate impacts and possible management scenarios. In this sense, the two projects can be viewed as comprising a broad assessment framework of Biodiversity Pattern and climate impacts (see Figure 4).

In this document we refer to AdaptNRM on a number of occasions. The AdaptNRM biodiversity modules at www.adaptnrm.com provide a more detailed explanation of many of the shared underpinning concepts and approaches, such as compositional similarity, and novel and disappearing ecological environments.

1 Introduction

1.1 The world is complex. But do read on …

Biodiversity is an intrinsically complex variable composed of numerous biological entities and processes, interacting individually and collectively at multiple levels of organisation, with abiotic exchange and flow of materials and energy, and biotic propagule dispersal over time and space (Hartvigsen et al. 1998; Noss 1990). Climate change adaptation planning for biodiversity evokes even higher levels of complexity (taxonomic, ecological, spatial, socio-economic, temporal dynamics) and uncertainty – i.e. the future trajectory of emissions; what will happen to the climate; when it will happen (temporal); changes to the economy, to society, and to society's aspirations. Yet there is a compelling need for effective decision-making in the coming years as the impacts of climate change add to already significant pressures on biodiversity.

Understandings of future conditions are central to effective planning. Yet high levels of complexity and uncertainty renders conventional positivist approaches (getting to *the* truth) to planning impotent (Funtowicz et al. 1999; Saloranta 2001). Although we cannot fully anticipate future conditions under climate change, we can be certain that a trajectory of significant change is already upon us. For natural resource management (NRM) to be as effective as possible, risks to biodiversity must be recognised and acted upon, even if the future is somewhat obscured from view.

The complex nature of biodiversity, together with uncertain future climate, make it challenging for us to anticipate future impacts and to plan effectively for biodiversity conservation (Rissik et al. 2014). Nonetheless, an ability to anticipate, however imperfectly, how a changing climate intersects with our current landscapes, enables us to re-examine our present-day priorities and strategies for conservation action; for instance by maximising the condition and extent of natural environments that aid natural adaptation, and by maintaining or enhancing connectivity in places that will be critical to facilitating climate-induced migrations and range-shifts.

The following work is constrained by an obscured view into the workings of biodiversity and its interactions with a changing climate. We have therefore adopted a simplified representation of a complex phenomenon that we trust has produced fit-for-purpose tools.

The 3C project was designed specifically to provide big-picture perspective relevant to NRM at a strategic level. All that follows in this report should be seen in that light. We expect that end users will temper our results with local information and knowledge, and with an appreciation of any exceptions not captured by our analysis.

The 3C findings are primarily *to inform current decision-making* and forward planning (for the next 5–10 years), based on modelled future environmental conditions, as we currently understand them. The findings of the 3C project will need to be updated in time as projections are improved and as modelling and assumptions are progressively superseded by realisations.

For more discussion on the nature of planning for climate change adaptation we suggest reading *The NRM Adaptation Checklist: Supporting climate adaptation planning and decision-making for regional NRM* by Rissik et al. (2014), available at http://adaptnrm.csiro.au/adaptation-planning/.

1.1.1 What follows

The 3C modelling presented in the following sections intersect climate futures with landscape and biogeographical information in order to evaluate biodiversity persistence across the 3C region, and to highlight areas, viewed at a broad scale, that warrant attention for NRM investment. Naturally, this work will need to be augmented by more local information and planning.

We continue in this **introduction** by outlining the understandings that underpin the 3C modelling. The section entitled **3C analysis** at times descends into complex technical descriptions of the modelling process, which readers may wish to selectively dabble into. The **discussion** section addresses the significance and key messages arising from the work which should be generally useful.

The 3C products (other than interactive tools) are stored and can be accessed from www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection. Appendix 4 lists and provides links to the 3C products including spatial data and larger format versions of the maps in this report. Interactive tools are available on request from the authors.

1.2 Linking habitat to the physical environment

Habitat suitability can be linked to a range of spatial predictors such as lithology, soil type, topography, and past disturbances – all of which can be assumed static over planning horizons[1] – as well as future land use and climate which must be considered dynamic (Ostberg et al. 2015). Over the coming decades (and with no foreseeable end) generally increasing temperatures and changing precipitation will progressively shift, expand or contract the bioclimatic envelopes which primarily govern the spatial distribution of biodiversity. Higher temperatures will generally push envelopes towards the poles, to higher elevations, towards the coast and towards areas with suitable moisture levels. In many regions of Australia the direction of changes to precipitation are uncertain, not following any discernible trend or pattern other than to become more variable and extreme. In some regions long-term drying trends are evident (Delworth et al. 2014), but this provides limited guidance to medium-term forecasting (i.e. decadal).

For detailed information on climate projections go to the Australian climate projections website (www.climatechangeinaustralia.gov.au).

1.2.1 Climate and biodiversity, they go back!

Climate is a key factor influencing the spatial distribution of biological communities observed across Australia and the world (Austin et al. 2011). Many species are known to survive and persist within specific ranges of temperature and precipitation regimes or are dependent on other species that do (Aitken et al. 2008). Outside of these tolerances there is lower colonisation, increased mortality, impaired reproduction and reduced ability to compete with species better adapted to the prevailing conditions. Over time this process manifests as transitions between community types (Gaston 2009; Wiens 2011).

During past climate change, species and whole communities have needed to adapt to changing conditions, producing continental-scale migration of species ranges, as well as extinction and speciation. At the continental scale and over millennia, through exposure to repeated episodes of climate fluctuation, the biota that has survived retains a legacy of adaptive capacity in relation to climate change (Taylor et al. 2007; Pitelka 1997; Graham et al. 2010).

Adaptive capacity has developed through a range of natural biological mechanisms (Hoffmann et al. 2011). Thus, to varying degrees, species can cope with limited shifts in environmental conditions in situ. Mechanisms include the ability to draw on genetic variability

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[1] This has been the assumption in this project; however, work is currently underway in various science institutions to understand how climate change will affect soil qualities, through scenario modelling. This information can be included in future iterations of the 3C modelling approach.

contained within their collective gene-pool, a process that allows relatively rapid (over a number of generations) responses to environmental change (Franks et al. 2012; Franks et al. 2014). For some species, through vector- or wind-assisted pollination and propagule dispersal, adaptation-enabling genetic information can be exchanged within populations relatively rapidly (Kremer et al. 2012).

Alternatively species can, if necessary, permanently or successively relocate through dispersals (as individuals, seeds, or pollen) to follow favourable climatic conditions. This can involve migrating to and colonising new areas that become more suitable. There is already clear evidence that this process has begun in response to recent climate change (Vos et al. 2008; Parmesan et al. 2003; Heller et al. 2009).

During periods of stable climate, some animals, and some plants (e.g. see Pitelka 1997) still move between habitats, seasonally and opportunistically to access food and other resources. This process is often driven by weather events or climate variability. With climate change in the mix this short to medium-term flux in habitat conditions will continue, superimposed over shifts to long-term average habitat conditions. With the likelihood of increased frequency of extreme events, such as storms, flooding rain, droughts and heatwaves, seasonal movements will become more critical to species survival (Smith 2010).

Climate change challenges, but also underlines the role of reserves in conserving biodiversity. Until now ecosystems within reserves were considered relatively stable, albeit within a dynamic equilibrium. Despite the disruptive influence of shifting climatic envelopes, reserves will continue to play a central role, albeit not necessarily in the ways originally envisioned. By virtue of their size and generally excellent condition, reserves are well equipped to re-organise, providing new habitats for species displaced from their former distributions; as well as provide corridors and stepping stones for climate migrations (Dunlop et al. 2012; Dunlop et al. 2008; Heller et al. 2009; Mackey et al. 2010; Thomas et al. 2004; Skøien et al. 2013).

Integrated ‘whole-of-landscape’ biodiversity conservation is increasingly seen as the logical way to pursue biodiversity conservation (Ferrier et al. 2010; Alpert 1996; Scott et al. 2001; Bengtsson et al. 2003). This approach seeks to build resilience through systems of functionally connected habitat networks across all tenures and land uses (Doerr et al. 2013; Drielsma et al. 2009; Bennett 1998; Fahrig et al. 1985; Merriam 1984; Taylor et al. 1993).

1.2.2 Will biodiversity persist through current climate change?

Anthropogenic reductions to the extent and connectivity of natural environments now limit biodiversity’s ability to adapt to future climate change, especially for adaptation through migration (Pitelka 1997). As a result, significant depletion of biodiversity, including species extinctions, is expected over coming decades (Thomas et al. 2004; Wake et al. 2008). There is evidence that this process has already begun (Heller et al. 2009). Carefully considered, concerted intervention aimed at building resilience and facilitating adaptation can minimise this loss.

Hopefully many species will persist in situ, utilising suitable habitats near or within their past distributions; other species will need to migrate to new areas that become suitable in the coming decades. Species’ ability to passively ‘range-shift’, unassisted by human agency, relies on whether new environments actually emerge within range of each species’ migration ability. This will not occur when species habitats disappear in one place but do not emerge nearby as the climate changes (e.g., cool climate species on mountain tops) (Chen et al. 2011; Burrows et al. 2014). Range-shifts will also depend on whether species have the mobility to keep pace with the velocity of change and on whether migration pathways of suitable and sufficient habitat are available to them, even temporarily (i.e. habitat corridors, or stepping stones of suitable habitat) (Taylor et al. 2007; Vos et al. 2008). Species persistence may be jeopardised when range-shifting strategies are blocked by natural barriers, such as water bodies, mountain ranges; by unsuitable habitats; or by areas permanently cleared of native habitat for urbanisation, mining or agriculture, for example (Hoegh-Guldberg et al. 2008). The persistence of a proportion of species will also depend on changing interspecific relations (between species), including competition with other species, in their current or newly colonised areas (Sinclair et al. 2010).

1.3 General approach of 3C

The 3C project utilised spatial modelling to discern drivers of change to the distribution of biodiversity and to inform possible NRM responses to the risks to biodiversity persistence. The aims of the 3C project are to provide:

- a coarse-scale evaluation of the impacts of climate change on the persistence of biodiversity
- guidance on which parts of the region would provide the greatest benefit to overall biodiversity persistence from undertaking conservation actions, considering the degree and pattern of past disturbances (e.g. site-based condition and landscape-based connectivity) and anticipated future climate change
- learning tools to help build understandings of climate change impacts
- evaluation, reporting and forecasting capabilities in relation to past, proposed or possible land-use changes, and
- information to integrate big-picture biodiversity management with other domains (carbon sequestration, hydrology, salinity, agricultural production), and with finer-scale information, available to NRMs and others.

This was achieved by:

1. establishing a framework for undertaking **whole-of-landscape biodiversity assessment** across the Central Slopes, East Coast and Murray-Basin NRM cluster regions, resulting in spatial information suited for inclusion into integrated landscape-scale decision-making and cross-border planning
2. providing broad-scale **forecasts on impacts of climate change on biodiversity** based on multiple, plausible future climate scenarios (MPI, CAN, MIROC, RCP 4.5 and 8.5) between 1990 and 2050, and
3. deriving **conservation benefit mapping –** the relative benefits of undertaking conservation action across the 3C region. Benefit mapping was derived by integrating bioclimatic envelope shifts of 'vegetation communities' with modelling of vegetation condition and habitat connectivity process modelling.

1.3.1 More on complexity and uncertainty

In this project we recognised that tackling big-picture processes like climate change is beyond the reach of NRMs who are otherwise well positioned to integrate a range of issues at the regional scale. Understanding broad continental-scale processes is only part of what is needed for effective decision-making. Other, finer-grained, place-specific issues, sometimes social in nature and highly dynamic – require the expertise of people skilled at working at that scale. A key strategy of this project was therefore to foster a meeting of top–down with bottom–up scales.

The 3C project addressed complexity and uncertainty by:

- viewing biodiversity through the lens of 100 bioclimatic vegetation-derived classes, which we used to represent biodiversity as a whole [see below and section 2.3 entitled **Bioclimatic envelopes**]

- considering a range of alternative climate futures – a combination of global climate model (GCM) projections and representative concentration pathways (RCPs) [see section 2.3.2 entitled **Climate futures**] (Coreau et al. 2009), and
- undertaking a range of assessment methodologies (see Table 3)
- combining outputs to highlight commonality across alternative model runs – places where synergistic conservation actions are appropriate.

Effective engagement of end users is essential to the success of the 3C. Another way to manage complexity and uncertainty is by providing visualisations that enable people to explore and to build understandings; to interactively compare alternative futures, to assess risks and opportunities through their individual lens (Balram et al. 2009; Frame et al. 2008). [Examples of engagement tools, developed as part of 3C are shown in sections 2.3.7 entitled **The Time Series Viewer** and 2.4.6 **Combined benefits mapping]**.

1.4 Deriving bioclimatic classes

The majority of the 3C analysis was undertaken using bioclimatic classes (BCCs) as a surrogate for biodiversity as a whole [see section 1.4.1, below]. The process of BCC derivation is unsupervised, i.e. an algorithm defines the classes automatically. The method involved extracting training data from the vascular plants observation data using a set of sample points, equally placed within modelled environmental space based on a generalised dissimilarity modelling (GDM). A hierarchical clustering algorithm was used to partition the training data into 100 classes based on their environmental distance. This classified training data was then used in a nearest neighbour algorithm that assigned to each cell in the analysis extent, the class of its nearest neighbour in the training data.

As BCCs were not developed as end products for management purposes we have not described them in detail other than by their distributions, a species list for each (see the BCC class profiles product), and compositional similarities to each other, expressed in a class by class two dimensional matrix containing similarity values ranging from zero (no species overlap) to one (identical species composition). No explicit modelling or comparisons with other vegetation community classifications, individual species distributions, or interspecific interactions was undertaken. Added nuance and detail was captured by mapping class distributions probabilistically.

For vegetation type and condition, each 250 m by 250 m cell is assessed individually. Each cell is attributed with a probability of each BCC occurring at any point within that cell; and each cell is given a condition score ranging between zero (poor) and one (excellent), reflecting the degree of degradation arising through past clearing, land use, weed invasion, and so forth [see section 2.2 entitled **Vegetation condition**].

We expect range-shifts of BCCs to be a process over time whereby a proportion of species leave or enter each location, while others remain, reflected in the modelling by gradual, incremental shifts in probabilities, some falling, others rising over time. The apparent replacement of one BCC by others does not signify a complete or sudden turnover of all species. At least in the short term, a change in identity will initially be to a class of similar composition (see Figure 9 and Figure 11).

When we consider the lack of a suitable 1990 analogue class for some areas in the future, as well as the limitations on 1990 classes reaching and successfully colonising new climate spaces, significant proportions of the region may develop novel ecological communities (see Figure 24); however, at this time 3C is unable to fully evaluate novel ecosystems' contribution to biodiversity conservation (only inasmuch as they resemble past ecosystems). More in-depth discussion of the array of potential realisations for biodiversity under climate change is provided by Dunlop and Brown (2008).

1.4.1 Bioclimatic classes are the unit of biodiversity in 3C

It was not feasible to undertake analysis of each species separately[2] or even major groupings of species[3]. The 3C approach involved employing coarse biological surrogates, which are referred to as bioclimatic classes (BCCs). BCCs are hypothetical communities (or assemblages) derived from vascular plant records using generalised dissimilarity modelling (GDM) (Ferrier et al. 2007). The approach is not intended for or suited to informing individual species conservation, but rather is a tool for finding broad landscape and regional-scale trends, leading to identifying generally beneficial management options for biodiversity as a whole.

We know that species operate both individualistically and synergistically within similar or nested environments, as described by the continuum concept (Austin et al. 1989), resulting in continuous variation in plant community assemblages along multiple environmental gradients, that can be surveyed and mapped into recognisable units that occupy distinct environmental domains (Franklin 1995).

Each species has unique traits governing its tolerance to climate change, as well as its movement abilities (Garcia et al. 2014); and each exhibits individual modes of interaction with other species. Although it is often useful to work with species collectively at the level of communities (as we do for the 3C project), we know that individual species will also respond independently to climate change, including undergoing range-shifting as independent agents, reconfiguring with new sets of species to alter the composition of existing interactions. New configurations of species are expected – as each species moves at different rates, possibly in different directions, some will persist in situ, while others will die out altogether. Over time, changing species composition at a location will result in a shifts to different recognised communities (a different BCC) or in other cases the new composition will not align with any recognised community and a novel biological communities will result (Hobbs et al. 2006). In a sense this is a natural process (which may mirror adaptive responses to past climate change) that must be embraced and facilitated to some degree. It also compromises the utility of familiar pre-industrial distribution patterns as benchmarks or building blocks for biodiversity conservation.

However, in the 3C it is assumed that future habitat compositions will be constrained to the 100 classes based on 1990 environmental conditions. 3C modelling fits future environments to current BCCs. This is a limitation of the methodology as it stands.

New species from outside the 3C region can also be expected to enter the mix, either from other parts of the Australian continent or from elsewhere. As we enter a time of environmental flux, new configurations of species will need to be embraced. We will be challenged by increased levels of invasive pest and weed species as these species are likely to be the most readily able to colonise emerging climate space. The reason for this can be that they escape from consumers and pathogens in their native range, and some will also benefit from increased concentrations of carbon dioxide (Vos et al. 2008; Taylor S et al. 2012; Scott et al. 2014).

1.4.2 Timeframe

For this analysis we are using ‘projections’ and not ‘predictions’. Even if all projections agreed on the direction of climate change (as they mostly do), we cannot know about the precise timing of changes or exactly how they will play out through complex biological interactions. Although changing climate creates the underlying driver or pressure for

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[2] Australia is one of 12 megadiverse countries. It is estimated that Australia is home to over one million species of plants and animals (see www.environment.nsw.gov.au/animals).

[3] AdaptNRM considered four broad classes of terrestrial biodiversity (mammals, reptiles, amphibians and vascular plants)

changes to biodiversity, the trigger for change may be a secondary, more haphazard event or series of events, involving drought, storms and wildfire.

The timeframe of the 3C project's scenarios, in relation to climate change modelling, is from 1990 to 2050 (Figure 2). This window provides a good balance between capturing changes already begun and changes yet to emerge; however, climate change will continue well beyond this period and therefore ongoing assessment will be needed.

The baseline used in 3C for gauging the direction and magnitude of changes to biodiversity is the pre-industrial state (circa 1750). Since then biodiversity levels in Australia have fallen significantly, largely due to habitat destruction associated with land-use changes, and the introduction of exotic plants and animals (Mackey et al. 2008; Department of Environment 2011; Common et al. 1992). Apart from limitations due to irreversible species extinctions, the pre-industrial species inventory serves as a baseline, representing a theoretically achievable aspiration and a useful monitoring gauge across the board.

In terms of BCCs, which we use as a surrogate for the species they support, past disturbances have disproportionally impacted on classes associated with fertility from an agricultural perspective, and classes that have been subject to urban development and mining. From a conservation planning perspective these classes are already more important to conserve and restore. As an example, grassy woodlands in south-eastern Australia and the woodland birds they support have been in decline for some time due to historical clearing and fragmentation of their habitat due to agricultural land uses (Ford et al. 2001). The 3C incorporates these legacy impacts with expected climate impacts which can also disproportionally impact on certain BCCs. In order to maximise the persistence of the original biodiversity we focus conservation efforts into communities depleted in the past, such as grassy woodlands, and those likely to be adversely affected by future climate change. Climate changes the way we do biodiversity assessment, bringing directional change into the already complex dynamics of the system. To reach our conservation objectives we need to anticipate additional, climate-driven environmental changes that will affect conservation priorities and opportunities.

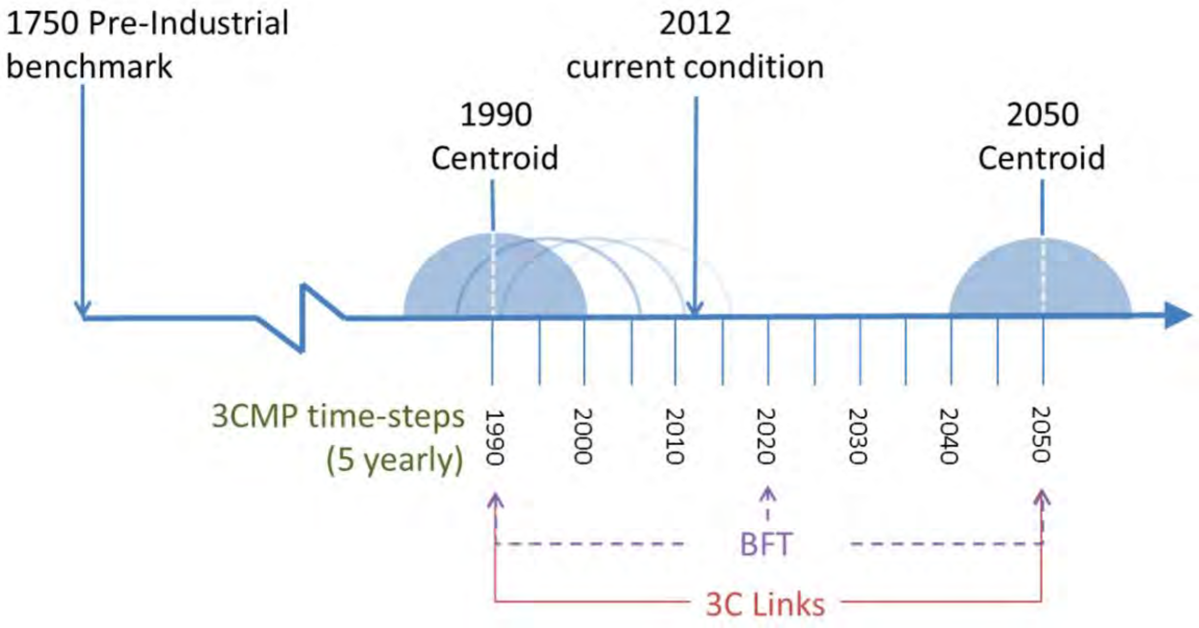

Figure 2: Timeline illustrating the temporal aspects of the 3C project

1.5 Envelopes and bioclimatic class distribution

BCCs were developed to help manage the complexity and scale of the modelling task. BCCs are a very broad classification of biodiversity developed by biotically-scaling environment using vascular plant records. The suite of 100 BCCs represents a simplification of the full diversity of native environments in the study area; from alpine ecosystems to rainforest, arid dune fields, coastal swamps, and everything in-between. They were used in the 3C as coarse surrogates for the thousands of species and the biological relationships they represent. Spatially, BCCs broadly align with the distribution of IBRA subregions (Department of Environment 2014). They were derived using known distributions of vascular plants in combination with spatially complete environmental predictors.

Each BCC can be characterised by its species composition and species density. Any single species can occur in a number of BCCs in different combinations and densities (see Figure 3).

Each location (250 m grid cell) was allocated a probability of finding each BCC within it, based on that location’s environmental similarity to that class, calculated using the abiotic variables as ‘predictors’ (see methods for more detail).

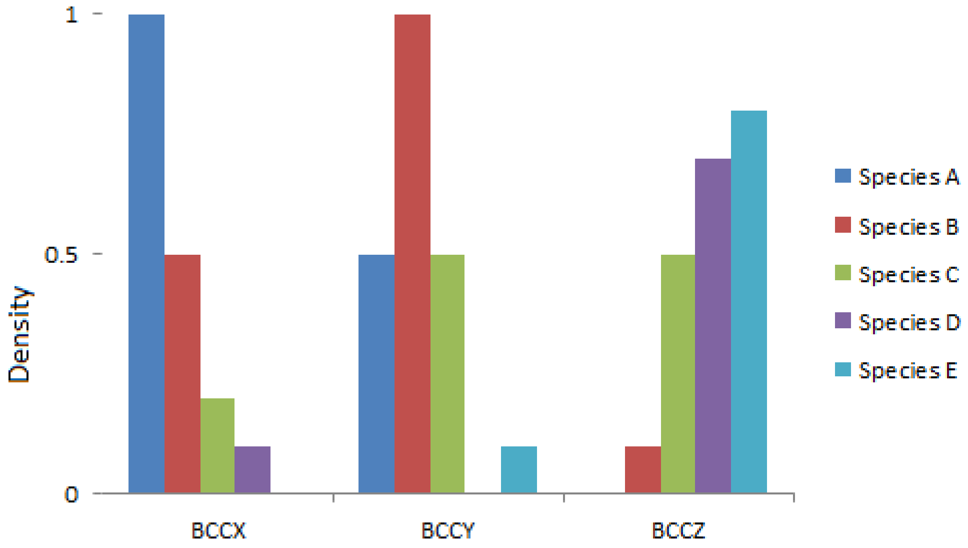

Figure 3: Conceptual relationship between species and BCCs

For illustrative purpose only. Each class is characterised by the species present and the density at which they occur.

Our first step was to model the distribution of BCC environmental envelopes, which govern the environmental *potential* of any given location to support each class. In the future, these envelopes, while still bound to some degree by substrate and topography, are expected to spatially reconfigure (shift, expand and/or contract) as current climate attributes are replaced with alternative climate futures.

The second step in the process determined the *suitability* of each location to support each bioclimatic class once the condition of habitat is considered; areas of high condition (areas where the native vegetation is intact, as it would have been in pre-industrial times) are considered capable of more fully supporting and transmitting (through species dispersal and reassembly) current and future BCCs.

Once the bioclimatic suitability of the locations had been ascertained a number of biodiversity assessment approaches were applied, each of which attempts to anticipate in some way the realisation of BCC distributions after the spatial configuration of habitat (affecting viability) and dispersal ability (affecting colonisation) is also considered.

2 The 3C analysis

Essentially, the 3C methodology involves comparing original (pre-clearing), current and future climate scenarios in terms of broadly assessed outcomes for biodiversity. Outputs address the three measurable facets of biodiversity (Noss 1990):

- COMPOSITION – development of a GDM model of compositional turnover and the distributions of bioclimatic classes (ecosystems)
- STRUCTURE – a dynamic model of vegetation condition, and
- FUNCTION – Landscape Value (connectivity) mapping, enhanced to include feasible climate-induced migrations by species to emerging habitats.

Spatial products and tools developed through 3C include:

- distribution models of bioclimatic classes across all climate projections
- assessments of expected changes in composition and suitability
- biodiversity evaluations measuring the impacts of climate scenarios
- conservation benefits mapping which provides direct input to NRM and strategic planning, and
- visualisation tools designed to promote engagement and learning throughout the community.

The 3C approach builds on the work from the national AdaptNRM Project (led by CSIRO, as outlined above in **Relationship to AdaptNRM**) which was responsible for the first two steps shown in Figure 4 (top left boxes). Each step in the 3C process (other than those undertaken as part of AdaptNRM) is described in more detail in the following sections. Several of the boxes in Figure 4 are expanded into more detailed flow diagrams (Vegetation condition modelling – Figure 5; 3CMP model – Appendix 2; 3CLINKS model – Appendix 3).

2.1 Study area

3C was run over an area of approximately 2 million hectares, or one quarter of the land surface of Australia. It represents what can be described as a continental-scale analysis, appropriate for considering the broad-scale impacts of climate change. The 3C region incorporates 30 NRM regions, includes all of NSW, Victoria and the ACT, as well as south-eastern Queensland and the eastern part of South Australia (see Figure 1).

This scale of analysis was made possible due to the availability of continental bioclimatic datasets, provided by CSIRO, topographically down-scaled to 250 m grid cell resolution, adopted as the spatial analysis unit (for a discussion of topo-climate concepts, see Slavich et al. 2014). All inputs and products were developed according to a common grid (ESRI grid format) template. The 3C analysis comprises over 27 million 250 m by 250 m grid cells projected to GDA94 geographic Spheroid.

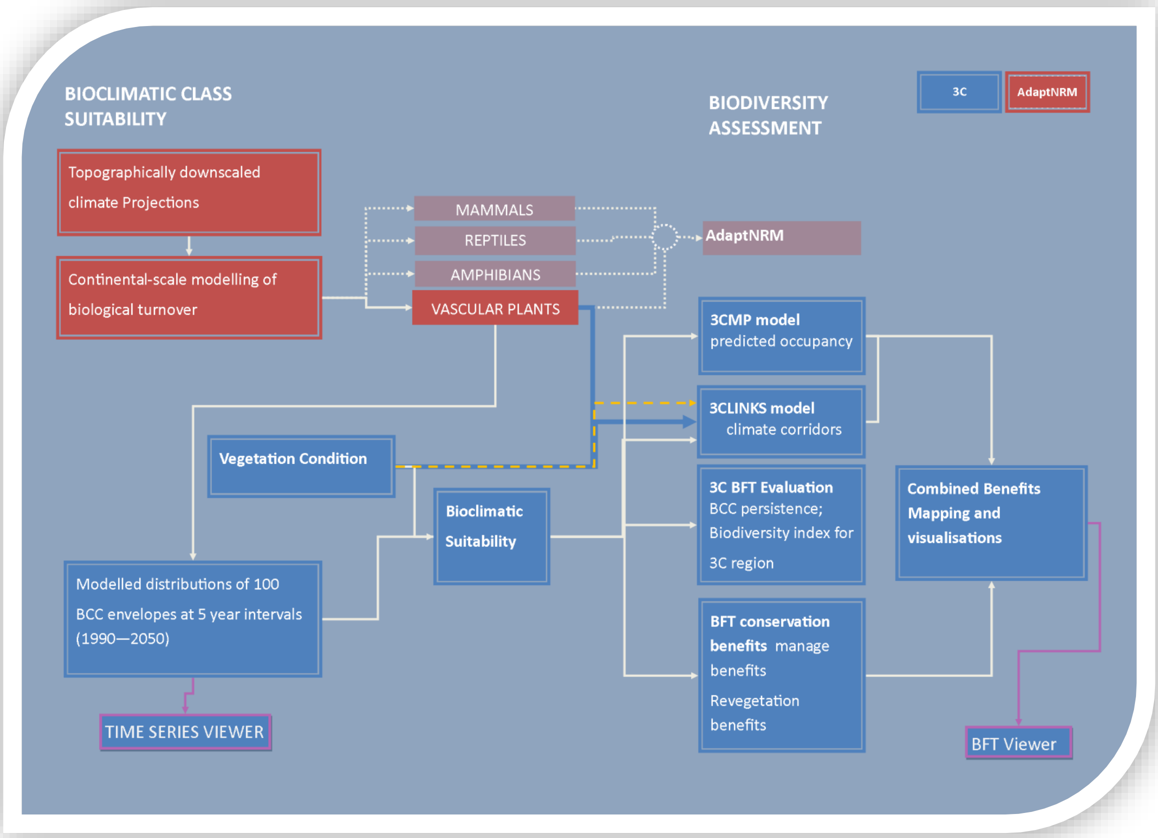

Figure 4: The overall 3C framework (in relation to AdaptNRM)

The left-hand side of the chart is essentially concerned with defining the suitability of conditions to support a bioclimatic class, based on the distribution of bioclimatic envelopes and landscape conditions. The right-hand side represents a range of biodiversity assessment methodologies based on the suitability modelling, representation of pre-clearing diversity, and habitat connectivity.

2.2 Vegetation condition

2.2.1 Background

For the 3C analysis, vegetation condition is a measure of the intactness of native vegetation and habitat of each site in relation to its pre-industrial benchmark. It is also a measure of the site’s ability, viewed in isolation (not considering spatial processes such as migrations and patch dynamics[4]) to support its original, pre-industrial biodiversity.

In the 3C analysis we used a current condition layer to inform later assessment of the current state, extent and spatial configuration of native vegetation. In the Biodiversity Forecasting Toolkit (BFT), current condition combined with the distributions of BCCs, is the basis for assessing the conservation status of each BCC.

We have derived an index of vegetation condition to reflect the actual ‘current’ state at 2014, at the time of the 3C modelling. We reasoned that current condition, should it be maintained, is a major determinant of the resilience and adaptability of natural systems. In the 3C, areas in good condition are better able to support current species, they produce greater numbers of

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[4] Spatial dynamics are considered in later stages of the 3C, by the BFT and Links methodologies.

propagules to colonise new areas, are better able to accept new colonisers from other areas, and are better able to facilitate migrations between other source and destination areas.

The 3C modelling framework allows for scenarios of changing condition over time (arising from factors such as land-use change, revegetation, and natural disasters) to be included. But for now, the impacts and adaptation conclusions from 3C are solely due to anticipated climate change.

2.2.2 Deriving current condition

Vegetation condition as an input to biodiversity assessment is routinely modelled at spatial scales and levels of detail relevant to analysis requirements. Condition indices range from site-based empirical data providing accurate measures of vegetation condition at one or more geographically distinct locations, through to continental or even global-scale models where a measure of vegetation condition is inferred from coarser and often less descriptive surrogates. Historically surrogates at these scales have been as simple as the presence/absence of woody vegetation (Department of the Environment Water Heritage and the Arts 2014), direct linking to land-use mapping (Drielsma et al. 2006) or inferred from remotely sensed data (Drielsma et al. 2010; Newell et al. 2006).

Continental-scale condition models cannot answer the question of precisely what state a particular location is in, and it is impractical to accurately measure the state of every location across the continent. Error can arise due to inaccuracies in the input data and data gaps. Even without errors, the values attributed to each grid cell are at best an average value for the 250 m x 250 m area it represents. Any given (average) condition value for a cell could result from consistent conditions across the cell or a mix of high and low condition. This highlights the need to carefully consider the limits of what information can be drawn from available surrogates in terms of meeting analysis requirements when evaluating the feasibility, suitability and efficiency of condition modelling approaches (Lawley et al. 2015).

Existing techniques were evaluated in terms of their data and processing requirements and suitability for this project. These approaches included a technique currently under development that employs site data as the dependant variable in a neural network to identify relationships between vegetation condition and independent spatial variables (e.g. see Newell et al. 2006). While promising results are being realised across smaller catchment-scale regions, the approach was not considered feasible within our project constraints. Also considered was a composition of existing surrogate products, though data gaps and inconsistencies reduced the likelihood of developing a usable integrated product. It was decided that an existing condition model (Drielsma et al. 2013) could be extended to include the entire 3C region by classifying and attributing relevant spatial layers with complete coverage of the region.

Condition has been systematically modelled across the whole of NSW (Drielsma et al. 2010; Drielsma et al. 2013). This process employed vegetation type modelling, remotely sensed foliage projective cover (FPC), land use, tenure and expert derived soil resilience (D. Robson, pers. comm.) as surrogates for estimating the condition of native vegetation. For woody vegetation, condition at each 250 m grid cell was derived from its FPC value in relation to a minimum threshold for which vegetation cover is expected to occur naturally. This was further modified using land use, tenure and soil resilience to characterise the expected reduction in lower strata development and ground cover, including non-woody vegetation, resulting from different management regimes.

We extrapolated this NSW data across the 3C analysis region (see Figure 7). We used a 100 class unsupervised ISO clustering of 2012 MODIS annual fractional cover metrics (Guerschman et al. 2009) and an intersection of land use (Australian Bureau of Agricultural and Resource Economics and Sciences 2012) to produce land cover (Lymburner et al. 2011) classifications. Using the NSW model, individual classes within these classifications were attributed with the mean condition score from their extents within NSW. These scores were applied to the extent of each class across the analysis region and the two re-attributed classification layers were then averaged on a per cell basis.

This approach assumes that:

- locations of similar vegetation structural type and annual variability under similar management regimes are likely to be of similar condition
- management actions associated with each particular land-use practice impacts on similar vegetation types with similar consequence
- the degradation of native vegetation resulting from historic land-use practices predicted across NSW is representative of that occurring across the broader study area.

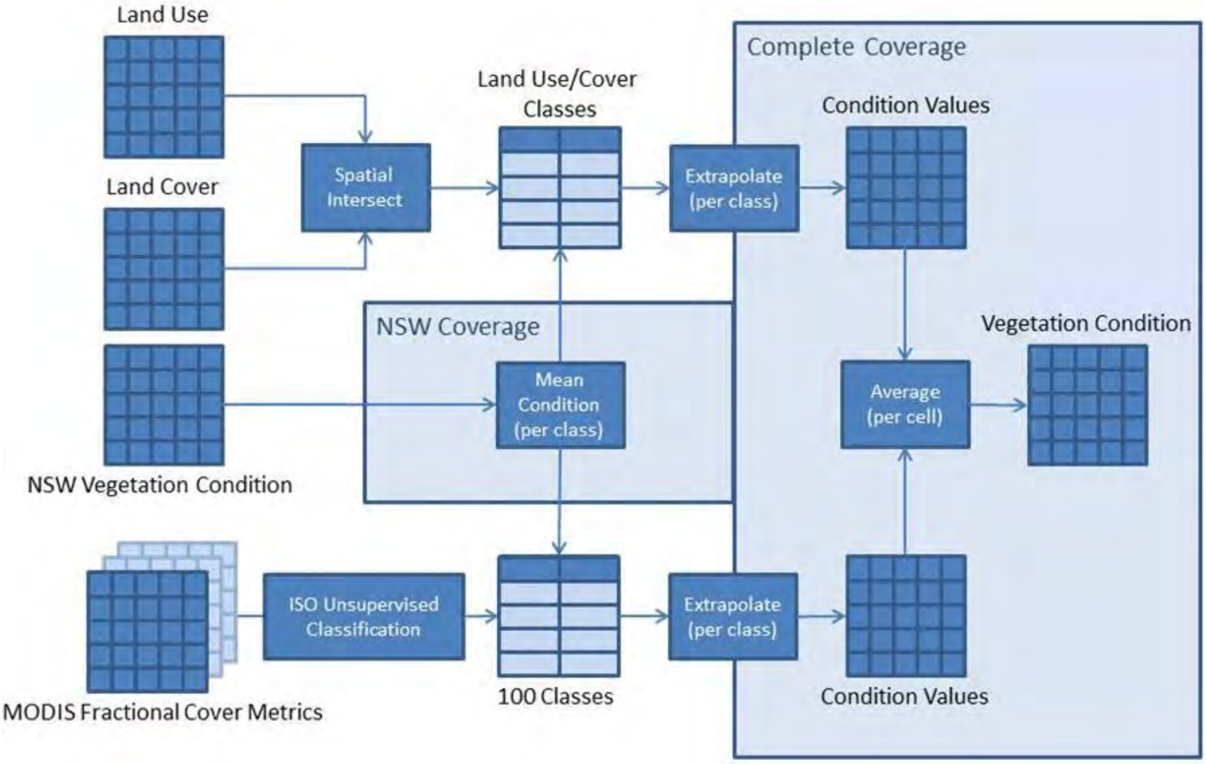
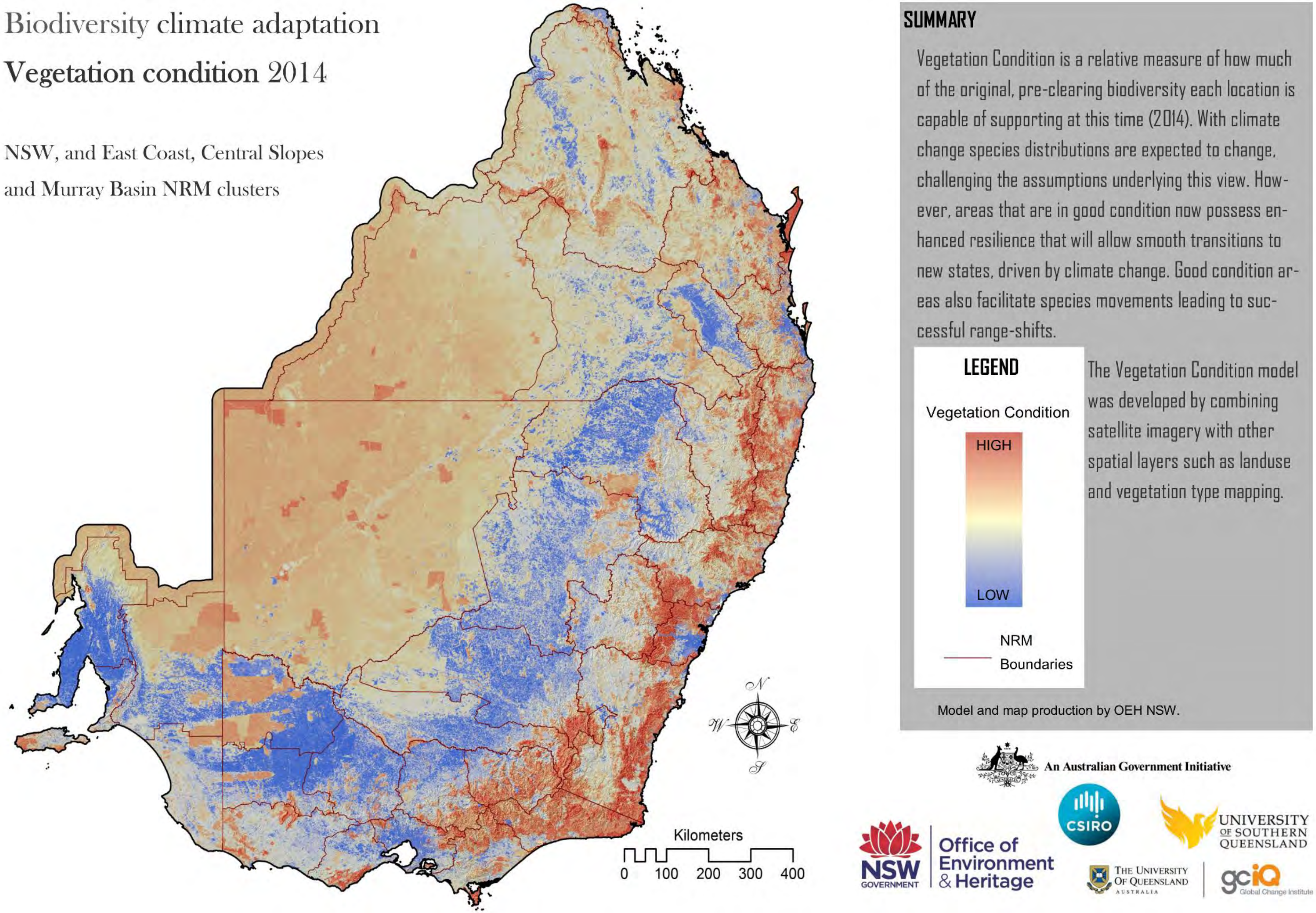


Figure 5: Workflow for the derivation of vegetation condition for the 3C project



SUMMARY

Vegetation Condition is a relative measure of how much of the original, pre-clearing biodiversity each location is capable of supporting at this time (2014). With climate change species distributions are expected to change, challenging the assumptions underlying this view. However, areas that are in good condition now possess enhanced resilience that will allow smooth transitions to new states, driven by climate change. Good condition areas also facilitate species movements leading to successful range-shifts.

The Vegetation Condition model was developed by combining satellite imagery with other spatial layers such as landuse and vegetation type mapping.

Model and map production by OEH NSW.

An Australian Government Initiative

Figure 6: **Vegetation condition mapping for the 3C region**

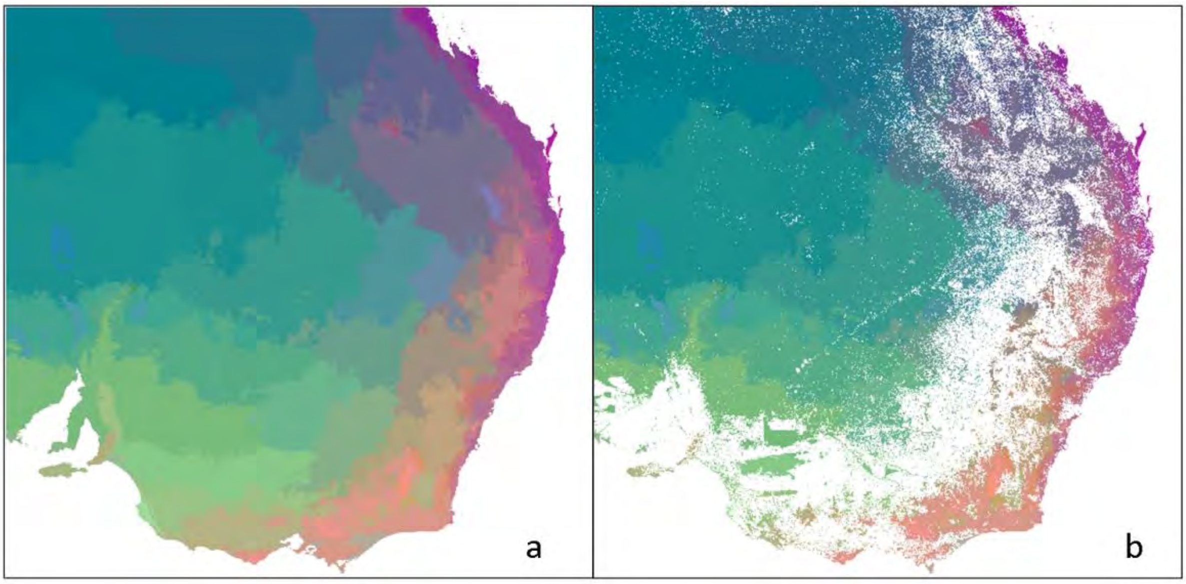


Figure 7: 1990 BCC envelope distributions
Showing class with highest probability at each location at 1990 (a), and same information for areas with condition scores greater than 0.5 (out of a possible 1.0) (b).

2.3 Bioclimatic classes

2.3.1 Deriving bioclimatic classes

The majority of the 3C analysis was undertaken using BCCs as a surrogate for biodiversity as a whole. The process of BCC derivation is unsupervised, i.e. an algorithm defines the classes automatically. The method involved taking an equally placed sample point subset (training data) of the GDM modelled environmental space and apply a hierarchical clustering algorithm to partition the training data into 100 classes based on their predicted environmental distance (ED). This classified training data was then used in a nearest neighbour algorithm that assigned to each cell in the analysis extent to the same BCC as its nearest neighbour in the training data. BCCs are a tool for subsequent biodiversity assessment. As BCCs were not developed as end products for management purposes we have not described them in detail other than by their distributions, a species list for each (see the BCC class profiles product), and compositional similarities to each other, expressed in a class by class two dimensional matrix containing similarity values ranging from zero (no species overlap) to one[5] (identical species composition). No explicit modelling or comparisons with other vegetation community classifications, individual species distributions, or interspecific interactions was undertaken. Added nuance and detail was captured by mapping class distributions probabilistically.

For vegetation type and condition, each 250 m by 250 m cell was assessed individually. Each cell was attributed with a probability of each BCC occurring at any point within that cell; and each cell is given a condition score ranging between zero (poor) and one (excellent), reflecting the degree of degradation arising through past clearing, land use, weed invasion, and so forth [see section 2.2 entitled **Vegetation condition**].

We expect range-shifts of BCCs to be a process over time whereby a proportion of species leave or enter each location, while others remain, reflected in the modelling by gradual,

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[5] A similarity of one does not occur as this would mean the two BCCs are in fact the same class

incremental shifts in probabilities, some falling, others rising over time. The apparent replacement of one BCC by others does not signify a complete or sudden turnover of all species. At least in the short term, a change in identity will initially be to a class of similar composition (see Figure 11 and the Time Series Viewer in Figure 9).

When we consider the likely lack of a suitable 1990 analogues for some biological communities in the future, as well as the limitations on 1990 classes reaching and successfully colonising new climate spaces with suitable climates, significant proportions of the region may develop novel ecological communities (see Figure 24); however, at this time 3C is unable to fully evaluate novel ecosystems' contribution to biodiversity conservation (only inasmuch as they resemble past ecosystems). More in-depth discussion of the array of potential realisations for biodiversity under climate change is provided by Dunlop and Brown (2008).

2.3.2 Climate futures

Three global climate models (GCMs) were used for this analysis and each one was applied with both a conservative emission control policy and a 'business as usual' high emissions policy. These representative concentration pathways (RCPs) are radiative forcing values derived from increasing emissions relative to pre-industrial levels. The RCP of 4.5 is a gradual stabilisation of emissions leading to the equivalent of ~650 ppm CO_2 at stabilisation after 2100. The RCP of 8.5 is a do-nothing high emissions policy that leads to a rising radiative forcing pathway of ~1370 ppm CO_2 by 2100.

Three divergent, yet individually plausible GCM projections were included as climate futures in the Australian context based on CSIRO climate change studies (P. Whetton, pers. comm.). These are the Max-Plank-Institute Earth System Model (MPI-ESM) (Giorgetta et al. 2013), the MIROC5 Climate Simulation Model (Watanabe et al. 2010) and the Canadian Earth System Model (CAN-ESM2) (Chylec et al. 2011). The six models and the abbreviations we use are listed in Table 1.

Table 1: Climate models used in 3C

Climate future models	Abbreviation
Canadian Earth System Model (CAN-ESM2) RCP 4.5	CAN45
Canadian Earth System Model (CAN-ESM2) RCP 8.5	CAN85
MIROC5 Climate Simulation Model RCP 4.5	MIR45
MIROC5 Climate Simulation Model RCP 8.5	MIR85
Max-Plank-Institute Earth System Model (MPI-ESM) RCP 4.5	MPI45
Max-Plank-Institute Earth System Model (MPI-ESM) RCP 8.5	MPI85

In terms of comparability, the three GCMs (MIR, MPI, and CAN) encompass a variety of future scenarios. For example, in the Central Australian Rangelands the CAN8.5 model projects a much drier and much hotter future climate (17.8% reduction in mean annual rainfall (MAR) and 3.22°C rise in mean annual temperature (MAT) by 2050), whereas the MIR8.5 model projects a slight rise in MAR of 3.3% and a hotter MAT by 1.88°C. The MPI8.5 is situated between these scenarios, projecting a fall in MAR of 19.9% and a rise in MAT of 2.6°C. Further details about these climate futures can be explored using CSIRO's Climate Futures Tool (http://www.climatechangeinaustralia.gov.au/en/climate-projections/climate-futures-tool/introduction-climate-futures/).

The forecasts for the Eastern Australian Region in 2050 are slightly different for the same models. The MPI8.5 model has the most extreme change of –32.6% MAR and a rise of

2.69°C MAT. The CAN8.5 model is next with –13.7% MAR and a rise of 2.86°C MAT. The MIR8.5 model has –6.8% MAR and a rise of 1.96°C MAT.

The CSIRO AdaptNRM project provided the down-scaled climate scenario data, matched to the ~250 m grid resolution of the data used in the GDM model of vascular plant compositional similarity. Coarse GCM patterns were re-scaled on 9-second grids using 1990-centred (30 year average) monthly gridded climate data derived from using ANUCLIM software (Xu et al. 2013) with an accurate land surface model (Hutchinson et al. 2008). The climate scenario data were summarised into matching 30-year monthly averages centred on 2050. The resulting future climate scenario data therefore captured some of the fine-scale land surface patterns that are important drivers of biodiversity response. The data were further processed to capture the radiative exposure effects of mountainous terrain (slope, aspect and shading) on temperature and evaporation; applying the CSIRO-component methods described in Reside et al. (2013).

These climate scenarios were used in projections of vascular plant compositional turnover using GDM, provided through the National NRM project (AdaptNRM) and as described in the following sections (the resulting model and data is available from data.csiro.au – see Williams et al. 2015).

2.3.3 The generalised dissimilarity model

Generalised Dissimilarity Modelling (GDM, Ferrier et al. 2007) is a statistical method for assessing variation in the magnitude and rate of change in observations of species occurrences along environmental gradients. The community-level dissimilarity index used in this model is calculated from the counts of similarities and differences in the presence of distinct assemblages of species at pairs of locations. The index is bound between 0 and 1, where 0 means the two locations share all species, and 1 means they do not share any species. Dissimilarity is directly related to similarity between the same two locations by the equation: similarity = 1-dissimilarity.

Biological data for this analysis were derived in April 2013 from the Australian Natural Heritage Assessment Tool (ANHAT) Database, courtesy of the Australian Department of the Environment. Taxonomic checking occurs before species are included in ANHAT. The vascular plants represented in this dataset comprise over 13,250 species, represented by 258 families in six taxonomic classes (Cycadopsida – 2 families, Liliopsida – 71, Lycopodiopsida – 3, Magnoliopsida – 177, Pinopsida – 4, Psilotopsida – 1). All taxa were grouped at the species level of taxonomic determination and unknown/unmatched taxa excluded. Introduced and cultivated plant specimen locations were excluded. Locations with a geoaccuracy > +/– 2000 m were excluded; although locations that lacked a geoaccuracy estimate were included.

To minimise the effect of under-sampling due to non-systematic survey methodologies, only sites with more than 10 species, aggregated to a 9-second grid cell, were used. Furthermore, to minimise the effect of sampling bias towards populated, accessible regions, the site-pairs were randomly sampled equally within and between the 85 bioregions characterising the environmental heterogeneity of the Australian continent; developed using Biodiverse software (Laffan et al. 2010), coupled with site-pair sampler software (Rosauer et al. 2014). In addition, three under-sampling covariates were defined from the number of unique species, the number of original unique locations, and the number of unique observation records, per grid cell. These covariates helped partial-out the effect of under-sampling of occurrence, as far as could be explained. Due to computation and processing time limitations, the number of site-pairs used was approximately 1.5 million. These site-pairs encompass 28,527 grid cells where vascular plants have been sampled continent-wide.

The .NET GD Modeller software version 2.7 (Manion 2012) was used to develop fitted models of species compositional turnover. It has been developed by the NSW Office of Environment and Heritage to support in-house applications and research. Many of the functions have now been incorporated into an R-package (Manion et al. 2015).

The GDM model fitting process follows the procedure outlined in Williams et al. (2012). Each variable group (baseline climate, substrate, and landform) was initially tested to identify which are likely to be used for predicting species composition in the model. The remaining variables were combined into a single model and tested for redundancy. The final subset of candidate variables was further screened for excessive correlation using a backward stepwise variable elimination procedure. Variables were retained in the model if they contributed at least 0.05% partial deviance explained when each was tested by removal. This procedure significantly reduces the number of predictors retained in the model. The potential for a 4th spline to better define the shape of the retained predictors was tested selectively for those with the highest relative contribution, using the model fit criterion of at least 0.05% additional partial deviance explained. The combined significance of the predictors was again tested using the backward elimination criterion. In this version of the GDM fitted model, coarser resolution substrate variables derived from national soil and geology mapping (used in previous CSIRO modelling), were excluded from the set of candidate environmental variables presented to the model.

The final GDM model comprised 17 environmental predictors (listed in Table 2). Substrate variables were kept constant across the 1990–2050 timeframe to the ‘current’ state. Topo-climate variables were subject to the climate futures at 2050. The GDM transformed predictors were interpolated (linearly) to each five year interval between 1990 and 2050.

Table 2: The eleven topo-climate and six substrate predictors used in GDM for the 3C

Topo-climate group:
WDI: Atmospheric water deficit (precipitation minus potential evaporation) – monthly minimum (Williams et al. 2012) (topographically-scaled[6] with evaporation)
TNX: Minimum temperature – monthly maximum[7]
TXI: Maximum temperature – monthly minimum (topographically-scaled[6])
TXX: Maximum temperature – monthly maximum (topographically-scaled[6])
TRA: Annual temperature range (topographically-scaled by TXX[6])(TXX – Minimum temperature – monthly minimum[6])
PTI: Precipitation – monthly minimum[7]
PTRX: Precipitation seasonality – maximum of differences between successive months (Williams et al. 2012)
PTS1: Precipitation – solstice seasonality composite factor ratio (Williams et al. 2012)
EPI: Potential (pan) evaporation – monthly minimum (topographically-scaled[6])
EAA: Annual total actual evapotranspiration terrain-scaled using MODIS[6]
EAAS: Annual modelled total actual evapotranspiration modelled using topographically-scaled and CTI-adjusted water holding capacity[6]
Substrate group:
WII: Weathering intensity index (Wilford 2012)
PC1_20: Spectra of surficial topsoils 0–20 cm – Principal Component 1 (Viscarra-Rossel et al. 2011)
PC2_80: Spectra of surficial topsoils 60–80 cm – Principal Component 2 (Viscarra-Rossel et al. 2011)
PC3_80: Spectra of surficial topsoils 60–80 cm – Principal Component 3 (Viscarra-Rossel et al. 2011)
SME80: Relative abundance of smectite clay minerals in subsoil (60–80 cm) (Viscarra-Rossel et al. 2011)
ELVFR1000: Elevation focal range within 1000 m (Gallant et al. 2011).

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[6] The CSIRO-component methods described in Reside et al. (2013)

[7] Variable is effectively equivalent to a bioclimatic predictor derived when using the BIOCLIM module of the ANUCLIM software (Xu & Hutchinson 2011).

2.3.4 Creating the 1990 baseline GDM bioclimatic classification

The outputs from the baseline 1990 GDM model include a set of modified raster surfaces resulting from transforming the original environmental predictors by a set of fitted coefficients determined by the statistical model (henceforth GDM transformed grids). The output grids can be used to derive an environmental distance between any pair of sites by calculating the sum of absolute distances across the GDM transformed grids. This ecological distance acts (when inversed) as a similarity metric for the nearest neighbour classification function, described below.

The first step in this nearest neighbour classification is to subsample all the GDM space. This was done by deriving a sample mesh of approximately 25,000 sites evenly distributed over the analysis region. A table of cell values was extracted with columns representing sites and rows representing GDM predictor (transform) grids. A hierarchical classification was applied to this table data to generate an ‘unsupervised’ classification of 100 classes. We chose a classification with 100 classes in order to approximate the IBRA bioregional classification (Department of Environment 2014). IBRA regions were selected as an analogy because they are well described and familiar to many people and because they are nationally consistent (whereas the specification for subregions may vary between jurisdictions). The classes were then associated with each site in the sample mesh data to create a training data set for the classification of each grid cell probabilistically to each of the 100 BCCs. Thus for the biodiversity assessment process a probability stack of 100 grids was produced for the 1990 baseline and for each combination of climate future and time-step [see section 2.3.8 entitled **Creating bioclimatic envelope probability grids from the continental-scale GDM for five year incremental time-steps from 1990 to 2050**].

2.3.5 Creating coloured maximum probability grids

In addition to the stacks of probability grids for each of the 100 BCCs that were used in the biodiversity assessment phase, for each combination of climate future and time-step a single ‘maximum probability grid’ was produced (i.e. highest probability BCC to each cell in the 3C region).

A colour legend was derived for the resulting grid to best represent the estimated number of species shared between the BCCs. This was achieved through a classical metric multi-dimensional scaling process to represent in multi-dimensional space the similarities between a group of objects – in this case the group of 100 BCC classes. For the BCCs the final dimension space has three axes. After re-scaling between 0 and 255 these axes are used as RGB values for the final classification grid.

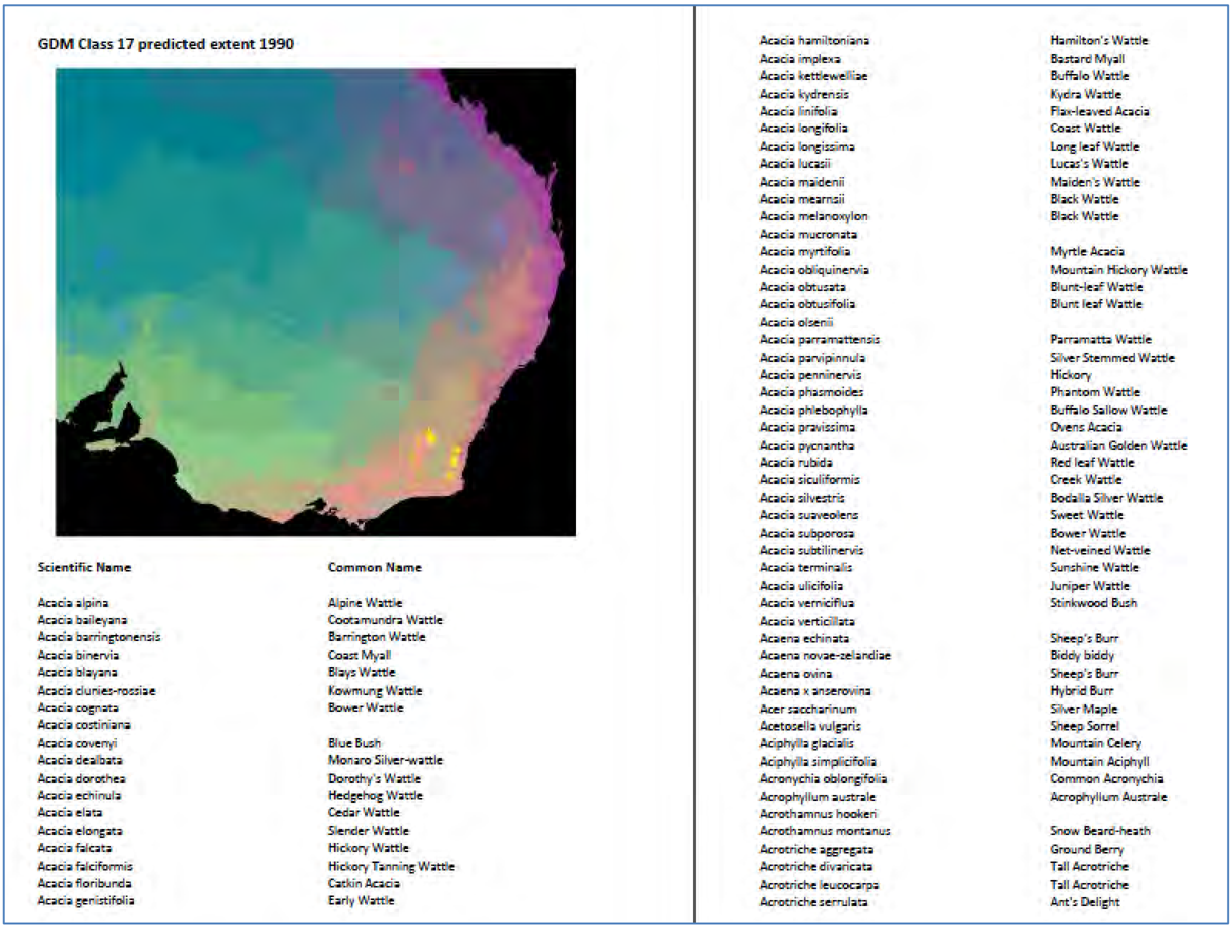
The relative RGB colouring with the classification is a good visual representation of the estimated extents and the ‘closeness’ (compositional similarity) between the individual classes predicted by the GDM model. This classification is shown in Figure 11. The colour legend is shown in Figure 15.

The maximum probability grids were converted into jpeg files and used as imagery for the Time Series Viewer [see section below entitled 2.3.7 **The Time Series Viewer**]. Figure 11 shows the expected change in vegetation structure as a response to the MIROC5 model with an 8.5 RCP for the 1990 baseline, 2020 and 2050. The same RGB colouring is applied as derived for the 1990 baseline classification, so that the change in classification boundaries and colour are synonymous with predicted shifts in plant community composition (see Figure 15).

Profiles were prepared for each of the BCCs (as PDF files) which include a map of where the BCC is dominant (has the highest probability), and a species list (see Figure 8). These are available from: www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/3c-modelling-gdm-bioclimatic-class-profiles.

2.3.6 Creating the incremental GDM climate change projections of the bioclimatic classifications

In the 1990 baseline classification, the topo-climate and substrate predictors used in the continental-scale GDM vascular plant model were used in their original transformed mode. In order to assess the spatial shift in these classes over a number of climate change scenarios, the topo-climate predictors used in the GDM model were 'projected' from the 1990 baseline to each of six scenarios that were considered likely under current mitigation policies and emission levels (Table 1). Only the topo-climate predictors were projected according to the climate change scenarios; the substrate predictors were held the same as the 1990 baseline model (see Table 2).



GDM Class 17 predicted extent 1990

Scientific Name	**Common Name**
Acacia alpina	Alpine Wattle
Acacia baileyana	Cootamundra Wattle
Acacia barringtonensis	Barrington Wattle
Acacia binervia	Coast Myall
Acacia blayana	Blays Wattle
Acacia clunies-rossiae	Kowmung Wattle
Acacia cognata	Bower Wattle
Acacia costiniana	
Acacia covenyi	Blue Bush
Acacia dealbata	Monaro Silver-wattle
Acacia dorothea	Dorothy's Wattle
Acacia echinula	Hedgehog Wattle
Acacia elata	Cedar Wattle
Acacia elongata	Slender Wattle
Acacia falcata	Hickory Wattle
Acacia falciformis	Hickory Tanning Wattle
Acacia floribunda	Catkin Acacia
Acacia genistifolia	Early Wattle
Acacia hamiltoniana	Hamilton's Wattle
Acacia implexa	Bastard Myall
Acacia kettlewelliae	Buffalo Wattle
Acacia kydrensis	Kydra Wattle
Acacia linifolia	Flax-leaved Acacia
Acacia longifolia	Coast Wattle
Acacia longissima	Long leaf Wattle
Acacia lucasii	Lucas's Wattle
Acacia maidenii	Maiden's Wattle
Acacia mearnsii	Black Wattle
Acacia melanoxylon	Black Wattle
Acacia mucronata	
Acacia myrtifolia	Myrtle Acacia
Acacia obliquinervia	Mountain Hickory Wattle
Acacia obtusata	Blunt-leaf Wattle
Acacia obtusifolia	Blunt leaf Wattle
Acacia olsenii	
Acacia parramattensis	Parramatta Wattle
Acacia parvipinnula	Silver Stemmed Wattle
Acacia penninervis	Hickory
Acacia phasmoides	Phantom Wattle
Acacia phlebophylla	Buffalo Sallow Wattle
Acacia pravissima	Ovens Acacia
Acacia pycnantha	Australian Golden Wattle
Acacia rubida	Red leaf Wattle
Acacia siculiformis	Creek Wattle
Acacia silvestris	Bodalla Silver Wattle
Acacia suaveolens	Sweet Wattle
Acacia subporosa	Bower Wattle
Acacia subtilinervis	Net-veined Wattle
Acacia terminalis	Sunshine Wattle
Acacia ulicifolia	Juniper Wattle
Acacia verniciflua	Stinkwood Bush
Acacia verticillata	
Acaena echinata	Sheep's Burr
Acaena novae-zelandiae	Biddy biddy
Acaena ovina	Sheep's Burr
Acaena x anserovina	Hybrid Burr
Acer saccharinum	Silver Maple
Acetosella vulgaris	Sheep Sorrel
Aciphylla glacialis	Mountain Celery
Aciphylla simplicifolia	Mountain Aciphyll
Acronychia oblongifolia	Common Acronychia
Acrophyllum australe	Acrophyllum Australe
Acrothamnus hookeri	
Acrothamnus montanus	Snow Beard-heath
Acrotriche aggregata	Ground Berry
Acrotriche divaricata	Tall Acrotriche
Acrotriche leucocarpa	Tall Acrotriche
Acrotriche serrulata	Ant's Delight

Figure 8: **Class profile for BCC17.**
BCC17 is highlighted as yellow in the map and a species list is provided

A suite of nearest neighbour classifications were then produced for each of the six future climate scenarios in five year time-steps over the period from the 1990 baseline to 2050. This started with two probability grid stacks of the 100 BCCs, one for 1990 and one for 2050.

The differences between the 2050 projected transformed predictor values and the 1990 baseline transformed predictor values were interpolated linearly in five yearly increments. These interpolated values were used as cell values for the nearest neighbour classifications (resulting in 100 probability grids for each series of five year time-steps).

The process at this point produces BCC envelopes, representing the region as uncleared and unaltered from its pre-European state. In the biodiversity assessments [see section 2.4 **Assessment methodologies**] vegetation condition is introduced to represent historical post-European impacts.

Given that the training data was the same as that used for the 1990 baseline classification; we effectively mapped the change in the 1990-derived class values and their spatial shift, through the 60 year period. In all the models, a visible trend was the desertification of western and central NSW and northern Victoria due to the bioclimatic shifting in a broad south-easterly direction. The primary difference between the models was the speed and magnitude of change.

2.3.7 The Time Series Viewer

The production of the time series classifications resulted in 13 images, one from each of the six climate change models. The Time Series Viewer application (available from authors MD, JL) was developed to enable the quick visual analysis of the comparative bioclimatic envelope models over 13 five year time-steps from 1990 to 2050. The resulting grids from the time series classification were all converted into jpeg images for quick display without the need for an accompanying GIS. The application is shown in Figure 9.

A longitudinal time series view of any model is achieved by moving the slider gadget from 1990 through to 2050. The respective classification for the selected model at the currently selected year will be displayed.

A transverse view can be obtained by setting the slider bar to the desired year and then clicking on any of the six radio buttons in the lower left corner to display the model differences in any given five year interval.

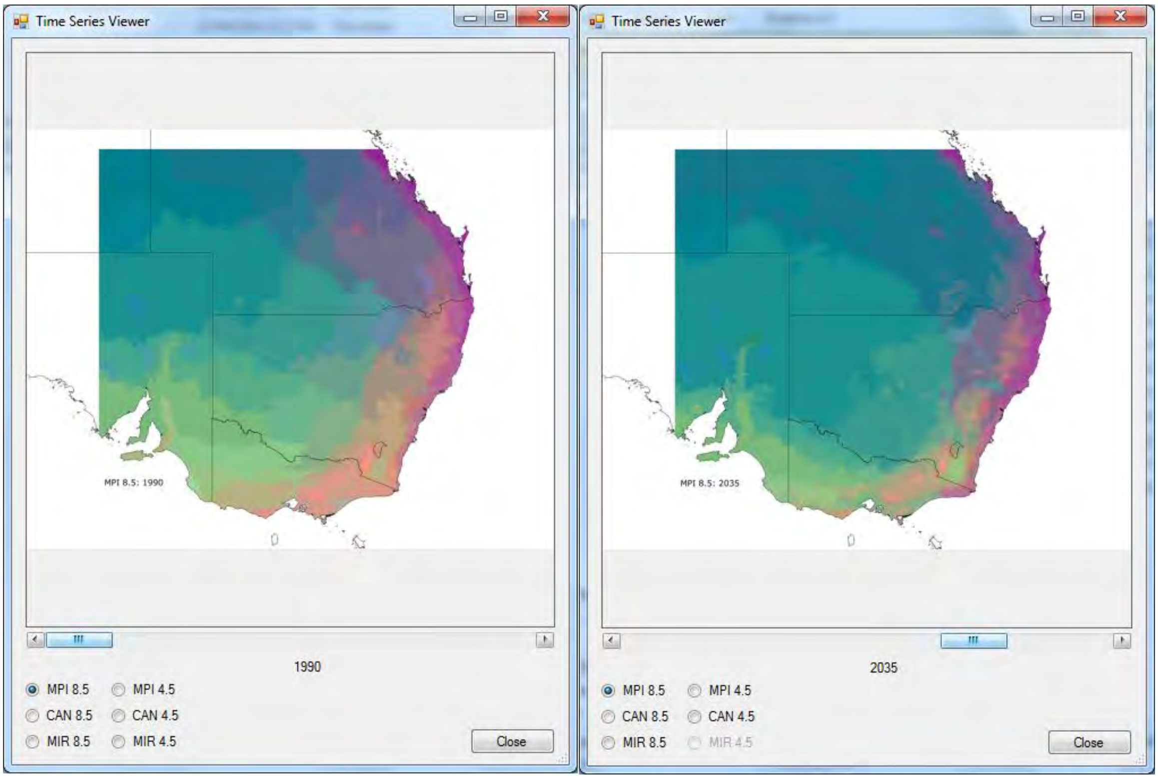


Figure 9: Screenshot of the Time Series Viewer at 1990 and MPI8.5 at 2035

The tool allows interactive comparisons of BCC envelopes across time and between climate futures

2.3.8 Creating bioclimatic envelope probability grids from the continental-scale GDM for five year incremental time-steps from 1990 to 2050

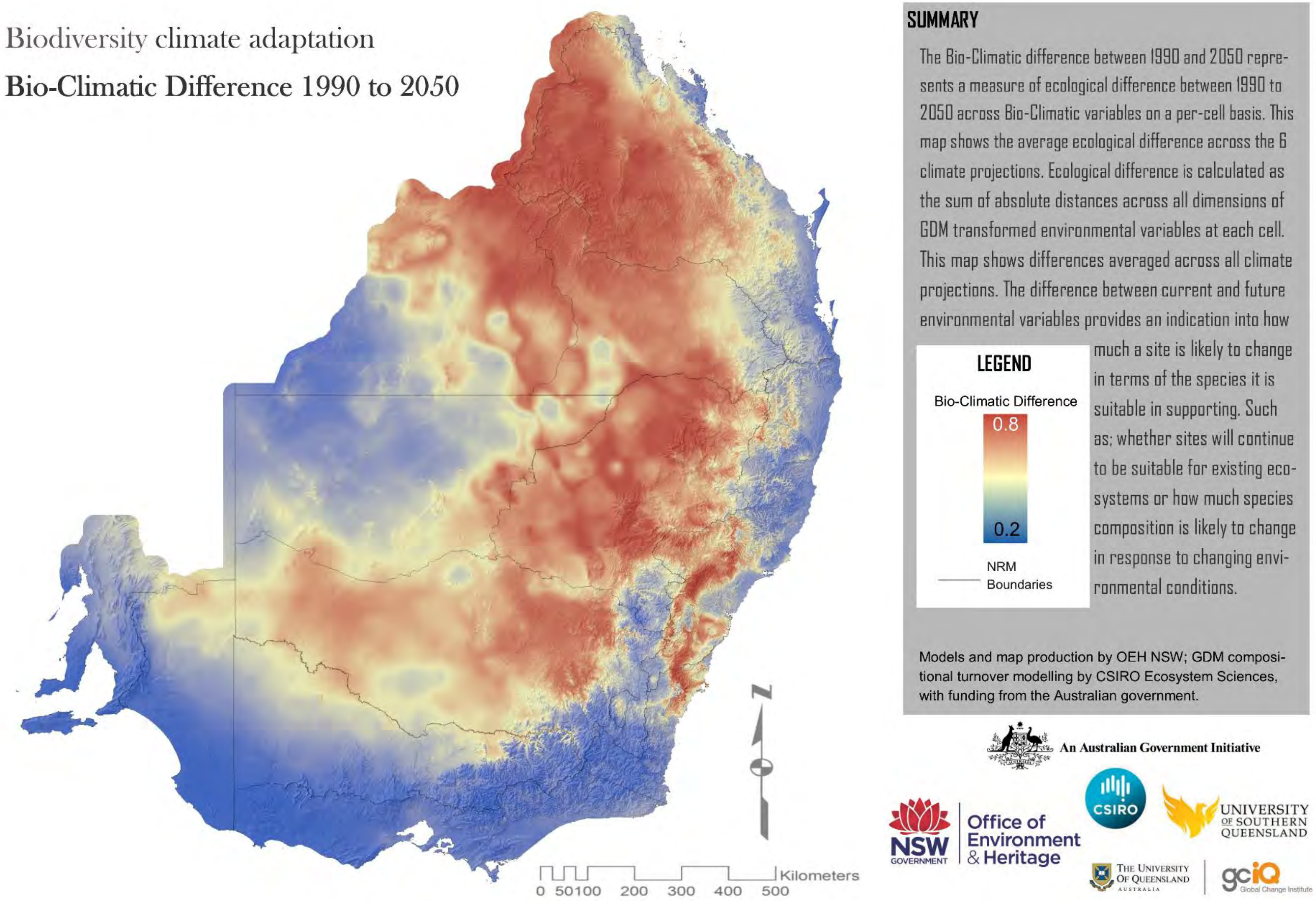
One of the inputs to the time series BFT, detailed below, is a set of probability grids for the 100 bioclimatic classes. Unlike the classification, every data cell in the analysis area will have a probability of belonging to each of the 100 derived bioclimatic classes. A suite of 100 probability grids is created for each five year time-step.

These probability grids are created via a kernel regression algorithm that not only looks at the nearest neighbour but the nearest J-neighbours (kernel) with a decay function R applied to each J-sized kernel. The J and R parameters are determined by experimentally testing a range of J and R parameters that best reduce the sum of squares in the training data. The training data is the same table that is used for the 1990 baseline GDM classification discussed earlier. The results for the time-step grids are all relative to the 1990 baseline model.

The time series probability grids are created for each five year time-step from 1990 to 2050, for each of the six climate change models used in the 3C analysis. Whereas the maximum probability grids are single grids (for a single time-step) that map the predicted spatial extent of the most likely BCC envelope, the probability grids provide a measure of uncertainty (or competing spatial positions) as the projected envelopes of the individual classes shift in response to a given climate change scenario.

An example of the probability of a particular BCC envelope (class number 35) moving in a south-easterly direction as a result of the CAN8.5 climate model projection is shown below (Figure 12) for 1990, 2020 and 2050. The interpretation is light pink for zero probability to dark red for high probability. This class originates in the Channel Country bioregion and the eastern part of the Mitchell Grass Downs.

Forecasted bio-climatic changes for the 3C region, or how much each location is expected to change in terms of its biota, is presented in Figure 10. Bio-climatic change was calculated as the average absolute differences between GDM transform girds (i.e. the average dissimilarity) between the 1990 baseline and the 6 climate futures.



Biodiversity climate adaptation

Bio-Climatic Difference 1990 to 2050

SUMMARY

The Bio-Climatic difference between 1990 and 2050 represents a measure of ecological difference between 1990 to 2050 across Bio-Climatic variables on a per-cell basis. This map shows the average ecological difference across the 6 climate projections. Ecological difference is calculated as the sum of absolute distances across all dimensions of GDM transformed environmental variables at each cell. This map shows differences averaged across all climate projections. The difference between current and future environmental variables provides an indication into how much a site is likely to change in terms of the species it is suitable in supporting. Such as; whether sites will continue to be suitable for existing ecosystems or how much species composition is likely to change in response to changing environmental conditions.

LEGEND

Bio-Climatic Difference

0.8

0.2

NRM Boundaries

Models and map production by OEH NSW; GDM compositional turnover modelling by CSIRO Ecosystem Sciences, with funding from the Australian government.

Figure 10: Average bio-climatic difference between 1990 and 2050

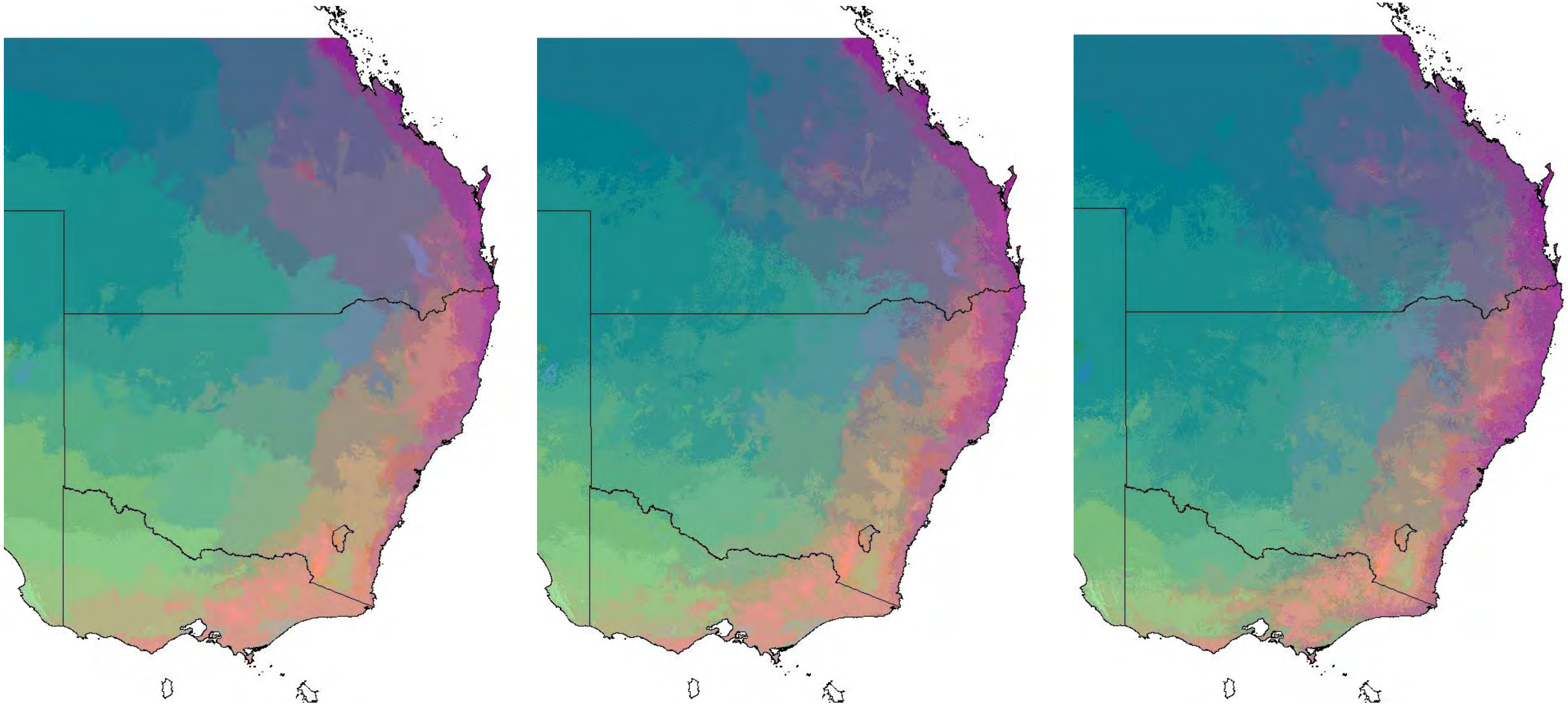


Figure 11: Predicted bioclimatic envelopes for CAN8.5 climate future at 1990 (left), 2020, and 2050 (right)

Each BCC is represented by a single colour. Colours of similar hue represent BCCs with similar species composition

2.4 Assessment methodologies

Biodiversity assessment is a way of removing the vagueness associated with the term 'biodiversity' by providing actual measures of outcomes (Ferrier et al. 2010; Noss 1990). The ability to quantify biodiversity outcomes allows biodiversity to be considered equally alongside other considerations without the need to assign a dollar value to species persistence.

Even when considering biodiversity at a coarse level of classification, there is no single assessment methodology that can encompass all aspects of biodiversity conservation, let alone with the added factor of climate change. Our approach was to modify and develop existing approaches that in some way overlap, but also exhibit complementary strengths and weaknesses (see Box 2).

In the subsections below we describe the suite of biodiversity assessment methods that were employed for the 3C. These were also combined into aggregate products, described in the latter part of this section. Logically, it would be ideal to integrate these analyses as much as possible, rather than combine their separate results at the end; however, for the 3C we were limited to only minor modifications of existing assessment tools and partial application of new ones. The approach we took does allow further integration and combining of more methods as they become available.

2.4.1 The Biodiversity Forecasting Toolkit

The Biodiversity Forecasting Toolkit (BFT) helps answer three important questions relating to regional biodiversity persistence: 'how much' biodiversity can persist for a given land-management scenario; 'what' habitats (in this case BCCs) to focus conservation effort on; and 'where' in the landscape to undertake conservation action (Drielsma et al. 2014). The tool integrates fine-scaled variability in vegetation composition and structure, with spatial context, which is critical for ensuring the viability of populations. Thus, a raster data framework is employed which deems each location or grid cell in a landscape as contributing to biodiversity benefits to various degrees.

The primary criterion in BFT biodiversity assessment is the representation and complementarity of vegetation communities or ecosystems (Margules et al. 2000). Representation is determined from three lower-level criteria:

- vegetation condition
- neighbourhood connectivity, or the spatial context of habitat, which influences the viability of an area to support organisms and populations
- the compositional distinctiveness of BCCs, (this differs from representation, which refers to the degree to which the BCC persists), by taking into consideration the compositional (species) overlap between BCCs, so that a loss of a distinctive BCC is likely to lead to greater loss of diversity than a BCC which shares many species with less impacted BCCs.

The 3C BFT analysis adheres to these criteria with a modification that allows these established criteria to change through time as they are impacted by, and respond/adapt (as is possible) to climate change. For example, a BCC may contract in its historical extent, while also shifting, subject to available landscape connectivity, to habitat patches that are becoming suitable. This can mean that the BCC is reduced in extent, its condition with regard to matching environments may become poorer, and its neighbourhood connectivity could be diminished through shifting to smaller patches.

The impact on the distinctiveness criterion will depend on the fate of compositionally similar BCCs over the same period. Generally, deteriorating suitability of environmental conditions will decrease the degree to which the BCC is represented in the region, making its conservation more critical.

In the 3C, the BFT methodology was extended to report on the persistence of the original, pre-industrial biodiversity of the 3C region at future times subject to shifting distributions of bioclimatic envelopes as a consequence to projected climate change. By translating the predicted GDM model (of continuous compositional turnover) into the BCC classes, we were able to apply the BFT (see Section 2.4) with minor modification.

The representation (or complementarity) component of the BFT gives greater conservation significance to BCCs that have been more cleared, degraded or fragmented in the past or are forecasted to be in the future, based on a benchmark state. Typically for Australian assessments, the benchmark is the state prior to European settlement, which was modelled for this project. The results of the BFT analysis will be governed by this benchmark and by the spatial extent of the region upon which the benchmark levels (areas; or Effective Habitat Areas, where spatial configuration or fragmentation is considered, see Drielsma et al. (2014)) are calculated. In this case the biodiversity evaluations and benefits are calculated in relation to the pre-industrial extent of BCCs across the 3C region.

The BFT evaluation produces an overall biodiversity index (BDI), which incorporates the four criteria set out above, extended to consider shifts in environmental envelopes due to climate change. The BDI is a measure of expected persistence of the original pre-industrial biodiversity of the 3C region, using BCCs as a biodiversity surrogate. Although substrate patterns factor in to the BFT, changes to biodiversity from the 1990 baseline are due solely to climate change. Other factors, including interspecific effects (Sinclair et al. 2010) and the impacts of extreme events (Verboom et al. 2010) are not explicitly considered in the 3C project. Land use is assumed to remain constant. The BFT evaluation presented below therefore may underestimate the impacts to biodiversity, although a robust program of conservation-focused land-use changes could also lead to positive impacts not considered in the current model.

2.4.2 BFT evaluation

Evaluations were undertaken for each of the six futures considered in the project, at 1990, 2020 and 2050. For each time-slice, the BDI was calculated for the region (Figure 16 and Figure 17) as well as a measure of conservation status for each BCC, equivalent to one minus the Marginal Biodiversity Benefit (Drielsma et al. 2014), times 100. Given 100 classes, the factor of 100 transforms conservation status values to a range between zero (completely lost) and one (completely intact). Figure 14 presents the results for CAN8.5.

The evaluation indicates the degree and direction of change; not a management tool unless undertaken as part of a scenario planning exercise, whereby alternative management actions are assessed in order to guide decision-making (Bennett et al. 2003).

Figure 16 and Figure 17 show the forecasted BDI levels for the 3C region from 1990 to 2050. All futures drive a decline in the index, representing an acceleration of decline from the pre-industrial benchmark and a sharp drop from recent historical levels. For each projection the RCP 8.5 futures show a marked decrease in BDI compared to their RCP 4.5 counterparts. MPI produces the most severe impact followed by CAN and then MIROC. Despite the linear interpolation between 1990 and 2050 levels (see Section 2.3) the declines in BDI are not linear, due to non-linear future decreases in available suitable space for many BCCs as they contract into relatively cooler areas. Also, because the BDI is governed by the species–area relationship, thereby accounting for an acceleration of species loss as available area for a community decreases.

The BFT does not fully consider the ability of species to relocate and may therefore underestimate biodiversity loss.

Figure 14 suggests that BCCs that have declined most in the past (blue-green colours) are most at risk of further decline from climate change.

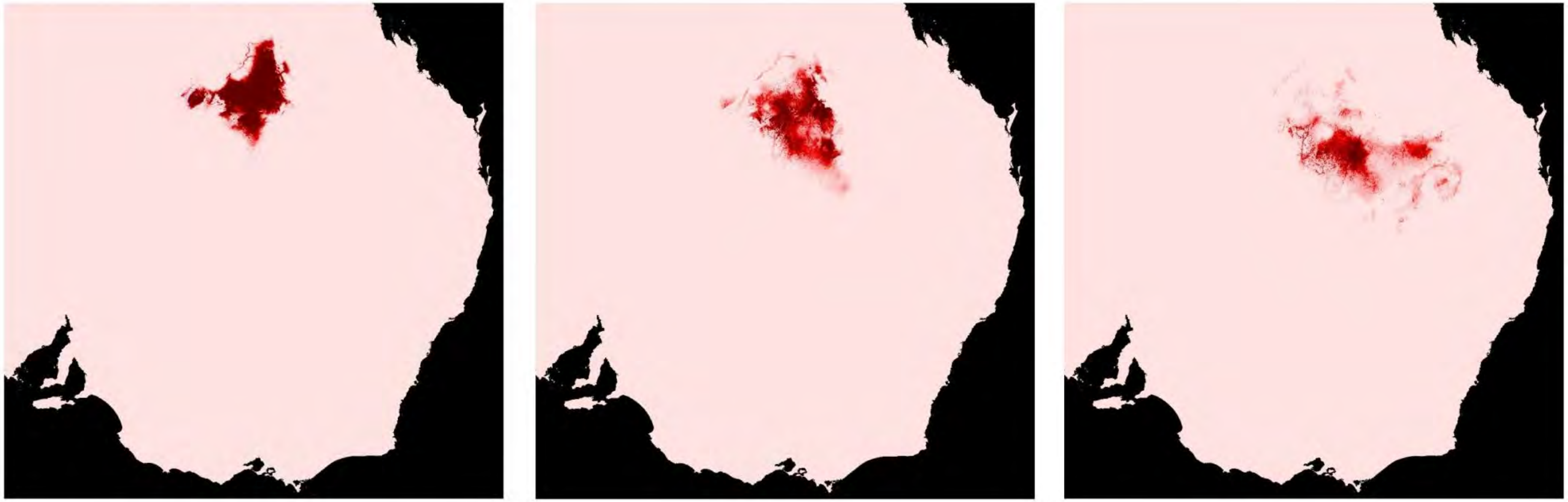


Figure 12: Predicted extent of bioclimatic class number 35 in 1990, 2020, and 2050 with the CAN8.5 model

The 1990 predicted extent for this class is primarily contained in the Mitchell Grass Downs bioregion of Queensland. The 2020 image shows this same class moving in a SSE direction into the Mulga Lands bioregion, a region that already has suffered ~3.8% loss of woody vegetation cover from 1993 to 2003. By 2050 this class has intruded into parts of the Southern Brigalow Belt and even extending further into the upper reaches of the Darling Riverine Plains on the NSW border.

Table 3: Comparison of the approaches employed in the 3C project

All approaches utilise the continuous vegetation condition surface and the bioclimatic class envelopes.

Approach	Purpose	Complem-entarity	Corridors	Dispersals	Spatial context	Spatial scale	Competition for space	Products
BFT Evaluation	Scenario evaluation in terms of each habitat class and overall biodiversity outcome	Yes	No	No	Yes	5 km radius	No	6 climate futures 1990–2050 at 5 year intervals
BFT Benefits Mapping	Map the relative benefits of undertaking conservation actions across a region	Yes	No	No	Yes	5 km radius	No	1990 and 6 climate futures at 2020; and 2050
3CLINKS	Map climate corridors to facilitate dispersals and migrations based on 1990; and between 1990 and 2050	No	Yes	Yes	No	2.5 km – 800 km cross-scale dispersals	No	Links calculated between 1990 & 2050 for MPI with RCP 8.5 only
3CMP	Model persistence of biodiversity entities (BCCs) through a process of climate change	No	Yes	Yes	Yes	7.625 km radius (per 5 year time-step)	Yes	1990–2050 at 5 year intervals MPI with RCP 8.5 only

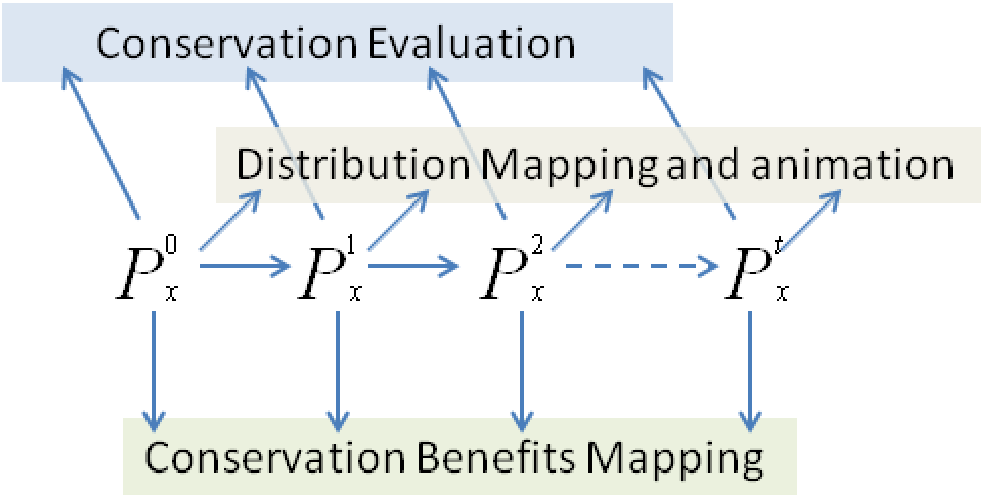


Figure 13: The BFT as a time-series

At each time-step from 0, 1, 2 and finally, t, a probability of the BCC, say class x, being present across the region is shown as P0x. The probabilities themselves are useful information that can be represented by distribution maps and animations of change through time (via the Time Series Viewer). At any time-step the conservation status (relative to the pre-industrial benchmark) of biodiversity is evaluated using the BFT. Also, the benefits (in terms of biodiversity persistence across the 3C region) of undertaking conservation actions at any point in time can be mapped across the region.

2.4.3 BFT conservation benefit mapping

Conservation benefit mapping was derived for 1990 and for each of the six futures at 2020 (interpolated time point) and 2050. In each case two benefit maps were derived:

- ‘Manage Benefits’ indicating the relative benefits across the region to overall biodiversity of managing existing vegetation to maintain its existing condition. Areas with high ‘manage’ benefit are intended to highlight the best remaining examples of vegetation communities (here we use BCCs) that address all criteria (representativeness of depleted species of vascular plants, good condition, good connectivity to adjoining native vegetation). The analysis assigns a higher benefit to sites that are in ‘better’ condition; however, once other attributes are taken into account in the analysis, high manage benefit areas can range in condition from ‘moderate’ to ‘very good’
- ‘Revegetation Benefits’ indicating the relative benefits across the region to overall biodiversity of revegetation and restoration. Areas with high ‘revegetation’ benefit are predominantly cleared or highly degraded examples of BCCs that score highly across the other criteria (representativeness of depleted species of vascular plants and good connectivity to adjoining native vegetation).

Overall, the 3C BFT benefit mapping considers both past depletion (clearing, degradation and fragmentation) and future, climate-induced depletion of BCCs. Benefits were derived for 1990 in which only past depletion was considered, and for:

- 2020 benefits which considered past and climate-induced depletion up to 2020, and
- 2050 benefits which consider past and climate-induced depletion up to 2050.

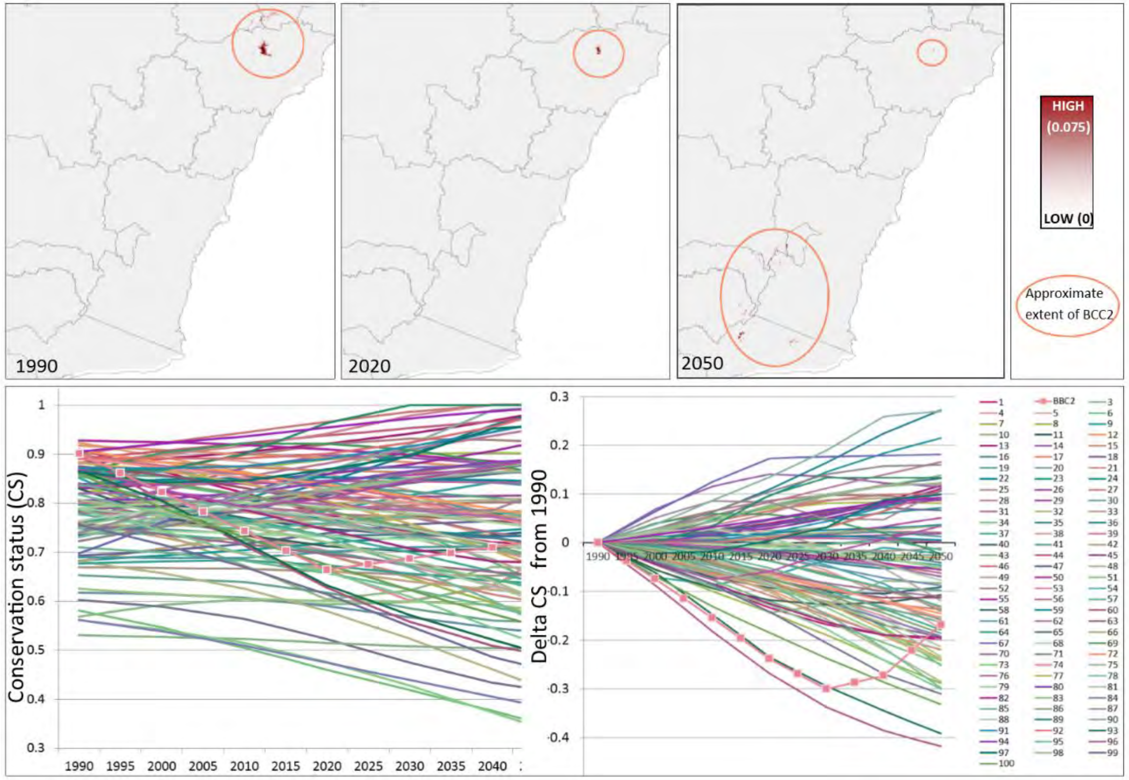
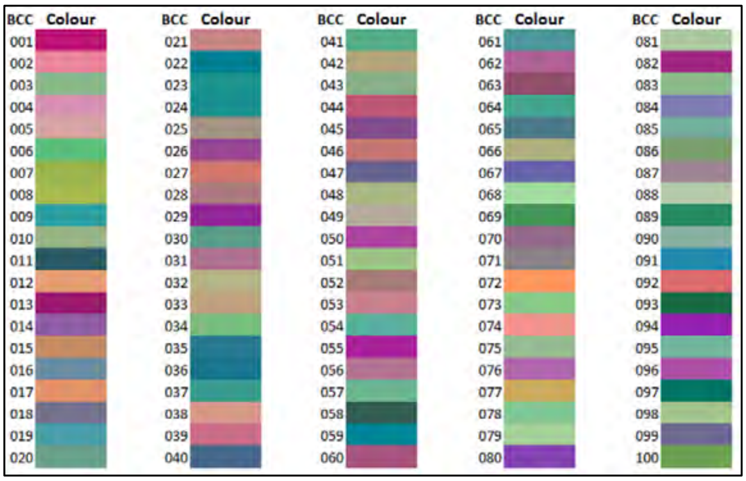


Figure 14: Trends in conservation status from the BFT evaluation, with a focus on BCC2 using CAN8.5, to illustrate

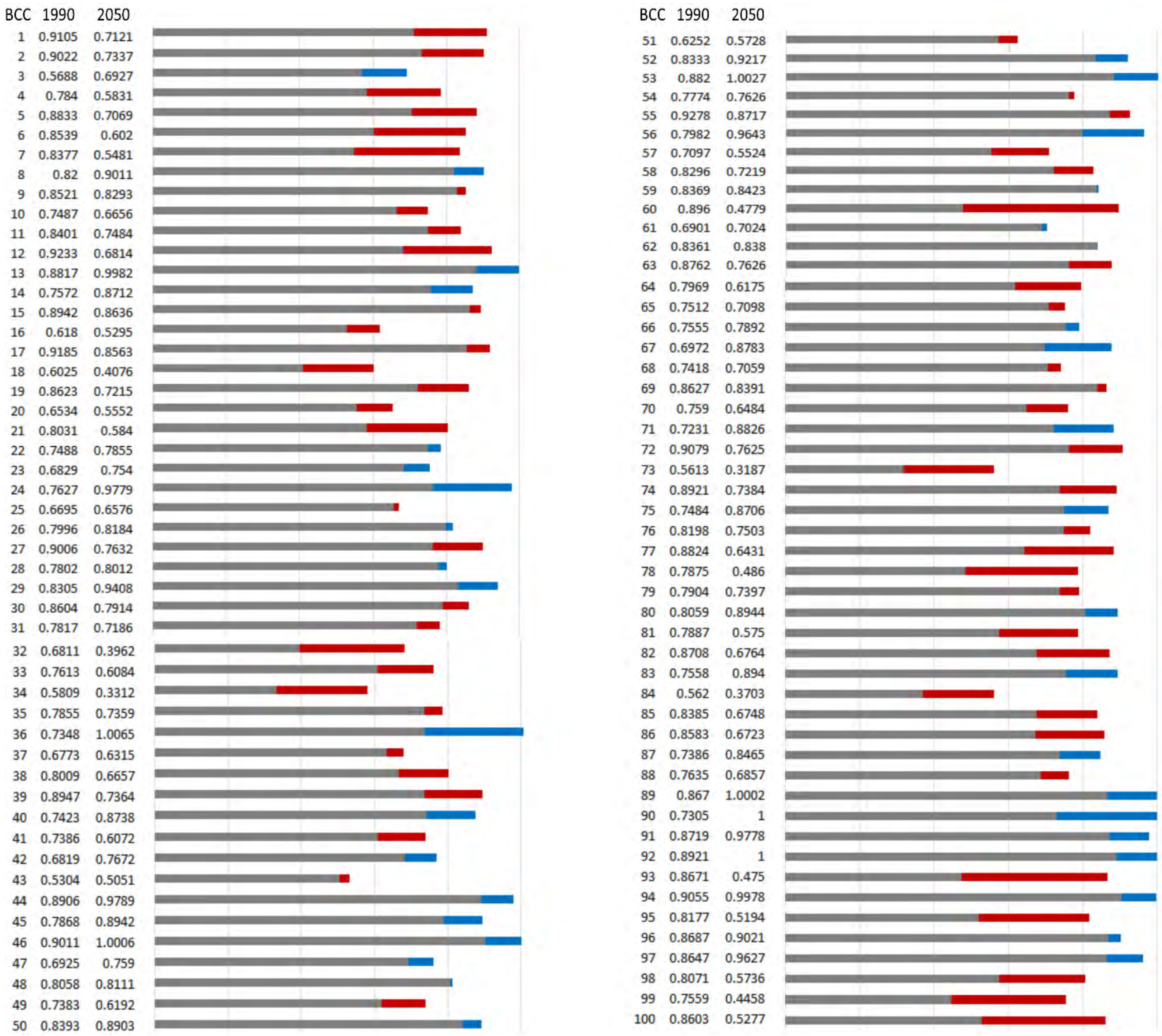
Maps on the top row show the distribution of suitable habitat for BCC2 at 1990, 2020 and 2050. Changing conservation status for each is shown in the bottom row with BCC2 highlighted (pink line and square markers). The bottom left chart shows conservation status in absolute values, where the 1990 level is determined by past clearing and degradation. The bottom right chart shows forecasted changes to 1990 levels, solely due to climate change. Colours map directly to those used in Figure 11 and Figure 15. BCC2 is a high-elevation disappearing class in its past distribution (Barrington Tops), but recovers climate space after 2030 as new areas far to the south (Australian Alps) become suitable. The BFT does not consider migration ability. Because of the geographic gap, species within BCC2 are candidates for assisted migration.



BCC	Colour	BCC	Colour	BCC	Colour	BCC	Colour	BCC	Colour
001		021		041		061		081	
002		022		042		062		082	
003		023		043		063		083	
004		024		044		064		084	
005		025		045		065		085	
006		026		046		066		086	
007		027		047		067		087	
008		028		048		068		088	
009		029		049		069		089	
010		030		050		070		090	
011		031		051		071		091	
012		032		052		072		092	
013		033		053		073		093	
014		034		054		074		094	
015		035		055		075		095	
016		036		056		076		096	
017		037		057		077		097	
018		038		058		078		098	
019		039		059		079		099	
020		040		060		080		100	

Figure 15: Legend for the BCC maps, interactive tool and charts

Table 4: Comparison between 1990 and 2050 conservation status
Blue indicates the amount of increase; red the amount of decrease. Derived from CAN8.5.



BCC	1990	2050
1	0.9105	0.7121
2	0.9022	0.7337
3	0.5688	0.6927
4	0.784	0.5831
5	0.8833	0.7069
6	0.8539	0.602
7	0.8377	0.5481
8	0.82	0.9011
9	0.8521	0.8293
10	0.7487	0.6656
11	0.8401	0.7484
12	0.9233	0.6814
13	0.8817	0.9982
14	0.7572	0.8712
15	0.8942	0.8636
16	0.618	0.5295
17	0.9185	0.8563
18	0.6025	0.4076
19	0.8623	0.7215
20	0.6534	0.5552
21	0.8031	0.584
22	0.7488	0.7855
23	0.6829	0.754
24	0.7627	0.9779
25	0.6695	0.6576
26	0.7996	0.8184
27	0.9006	0.7632
28	0.7802	0.8012
29	0.8305	0.9408
30	0.8604	0.7914
31	0.7817	0.7186
32	0.6811	0.3962
33	0.7613	0.6084
34	0.5809	0.3312
35	0.7855	0.7359
36	0.7348	1.0065
37	0.6773	0.6315
38	0.8009	0.6657
39	0.8947	0.7364
40	0.7423	0.8738
41	0.7386	0.6072
42	0.6819	0.7672
43	0.5304	0.5051
44	0.8906	0.9789
45	0.7868	0.8942
46	0.9011	1.0006
47	0.6925	0.759
48	0.8058	0.8111
49	0.7383	0.6192
50	0.8393	0.8903
51	0.6252	0.5728
52	0.8333	0.9217
53	0.882	1.0027
54	0.7774	0.7626
55	0.9278	0.8717
56	0.7982	0.9643
57	0.7097	0.5524
58	0.8296	0.7219
59	0.8369	0.8423
60	0.896	0.4779
61	0.6901	0.7024
62	0.8361	0.838
63	0.8762	0.7626
64	0.7969	0.6175
65	0.7512	0.7098
66	0.7555	0.7892
67	0.6972	0.8783
68	0.7418	0.7059
69	0.8627	0.8391
70	0.759	0.6484
71	0.7231	0.8826
72	0.9079	0.7625
73	0.5613	0.3187
74	0.8921	0.7384
75	0.7484	0.8706
76	0.8198	0.7503
77	0.8824	0.6431
78	0.7875	0.486
79	0.7904	0.7397
80	0.8059	0.8944
81	0.7887	0.575
82	0.8708	0.6764
83	0.7558	0.894
84	0.562	0.3703
85	0.8385	0.6748
86	0.8583	0.6723
87	0.7386	0.8465
88	0.7635	0.6857
89	0.867	1.0002
90	0.7305	1
91	0.8719	0.9778
92	0.8921	1
93	0.8671	0.475
94	0.9055	0.9978
95	0.8177	0.5194
96	0.8687	0.9021
97	0.8647	0.9627
98	0.8071	0.5736
99	0.7559	0.4458
100	0.8603	0.5277

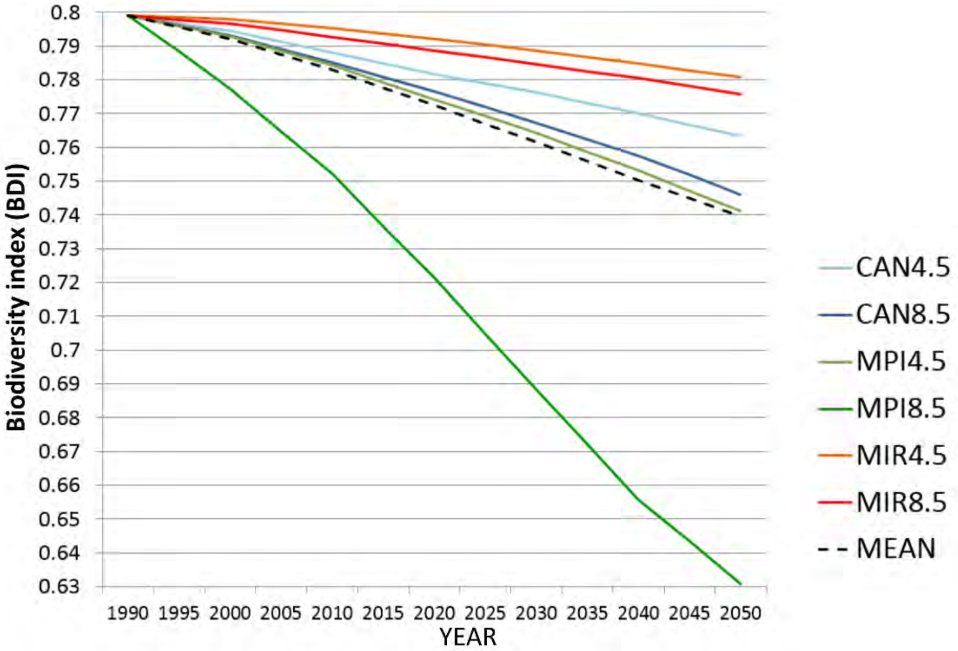


Figure 16: Projected BFT biodiversity index for the 3C region from 1990–2050, for each of six alternative climate futures, and the mean

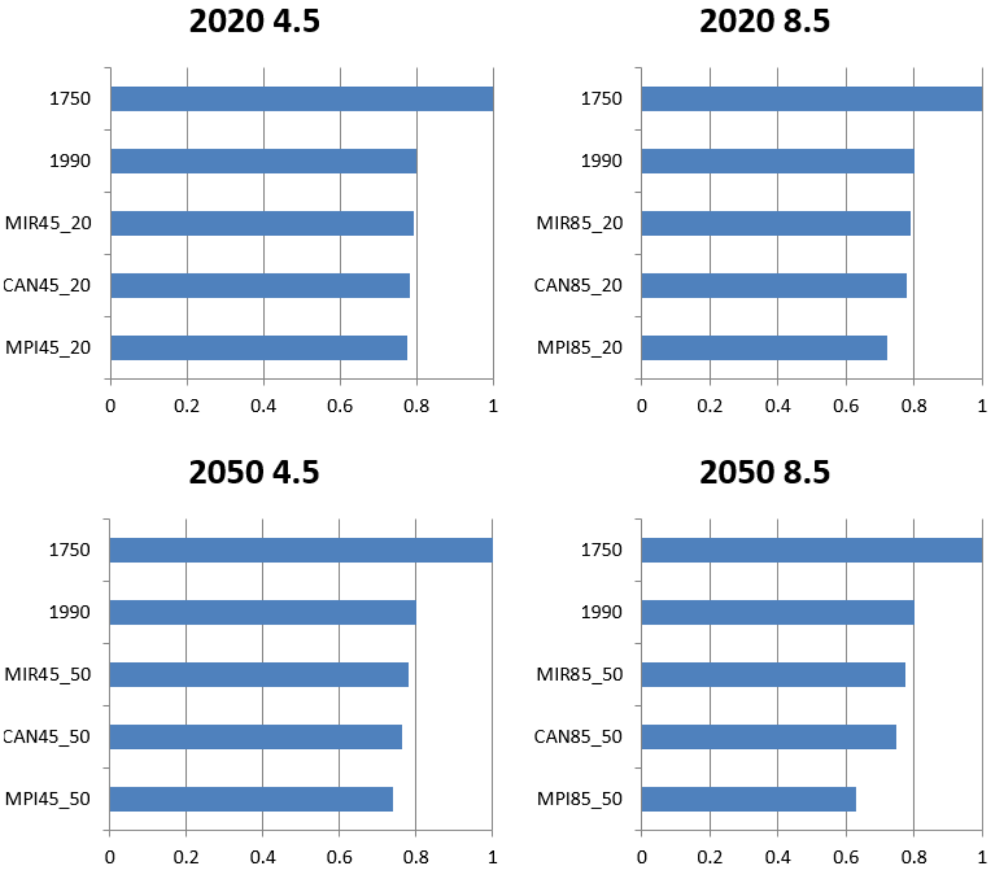


Figure 17: Projected BFT biodiversity index values

BDI values are shown for 1750 (equals 1); at 1990 (equals 0.80); and for each of six alternative climate futures at 2020 and 2050 (denoted with suffixes of '_20, and _50). RCP 4.5 models are shown on the left; RCP 8.5 on the right

Benefit mapping is intended as a management tool, either to direct conservation action to relevant places or as a basis for constructing viable scenarios. Conservation benefit maps can also be used in conjunction with other benefit layers within a multi-criteria analysis to maximise co-benefits across a range of domains such as carbon storage, salinity mitigation, agricultural productivity, e.g. see (Office of Environment and Heritage NSW in review); however, this process was not undertaken as part of the 3C project.

As well as the individual outputs, aggregated products were also produced through a simple scheme of averaging and summing, aimed at servicing the needs of NRM agencies [see section **2.4.6 Combined benefits mapping**]. There is no single correct way to combine the benefit layers for all purposes and planning contexts – for example, how much weight do you give the future in relation to the present? In the case of manage benefits (Figure 18) we essentially gave equal weight to the present; to 2020 forecasts and 2050 forecasts[8]. The rationale for this is that we need to facilitate a smooth transition from the present through the medium future (2020) and through to the longer future (2050). In a sense we are planning for ‘the long now’ (Carpenter 2002).

For revegetation benefits (Figure 19) we took a different approach, whereby only the combined benefits (across the six futures, equally weighted) for 2050 were considered. We reasoned that all revegetation efforts should aim towards meeting future climates (spatially and compositionally) due to the lag time involved in new plantings reaching maturity.

The high benefits associated with revegetation in the inland wheat belt (and adjoining future analogue areas) is due to severe historical depletion of vegetation types in this region. Coastal regions benefit from having both lower historical rates of clearing and, notwithstanding sea-level rise and increased incidence of extreme events, moderate bioclimatic range-shifts in comparison to the inland part of the region; however, at this scale the map does not discriminate between the relative benefits of revegetation within the eastern ranges and the East Coast. There are nonetheless positive benefits from revegetation east of the sheep–wheat belt that are worthy of consideration. Because of this, finer-scale maps have been produced for individual clusters and NRMs (on request) which show relative benefits at those scales in more detail.

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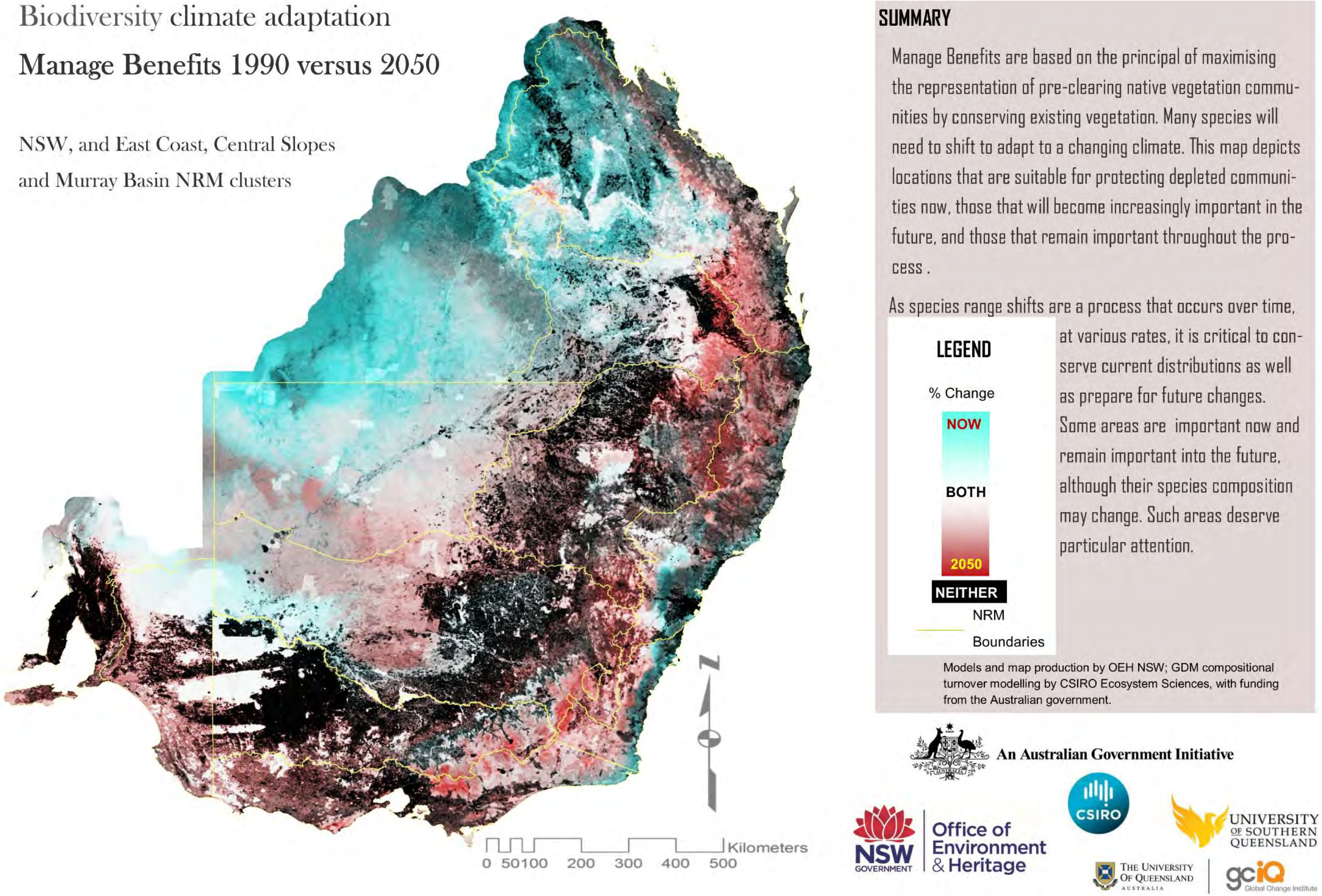
[8] 1990 was given a weight of 3; each of 6 2020 and 2050 surfaces a weight of one. 1990 was not given equal weight (i.e. 6) as the 1990 epoch is now half expired



Manage Benefits are based on the principal of maximising the representation of pre-clearing native vegetation communities by conserving existing vegetation. Many species will need to shift to adapt to a changing climate. This map depicts locations that are suitable for protecting depleted communities now, those that will become increasingly important in the future, and those that remain important throughout the process .

As species range shifts are a process that occurs over time, at various rates, it is critical to conserve current distributions as well as prepare for future changes. Some areas are important now and remain important into the future, although their species composition may change. Such areas deserve particular attention.

Models and map production by OEH NSW; GDM compositional turnover modelling by CSIRO Ecosystem Sciences, with funding from the Australian government.

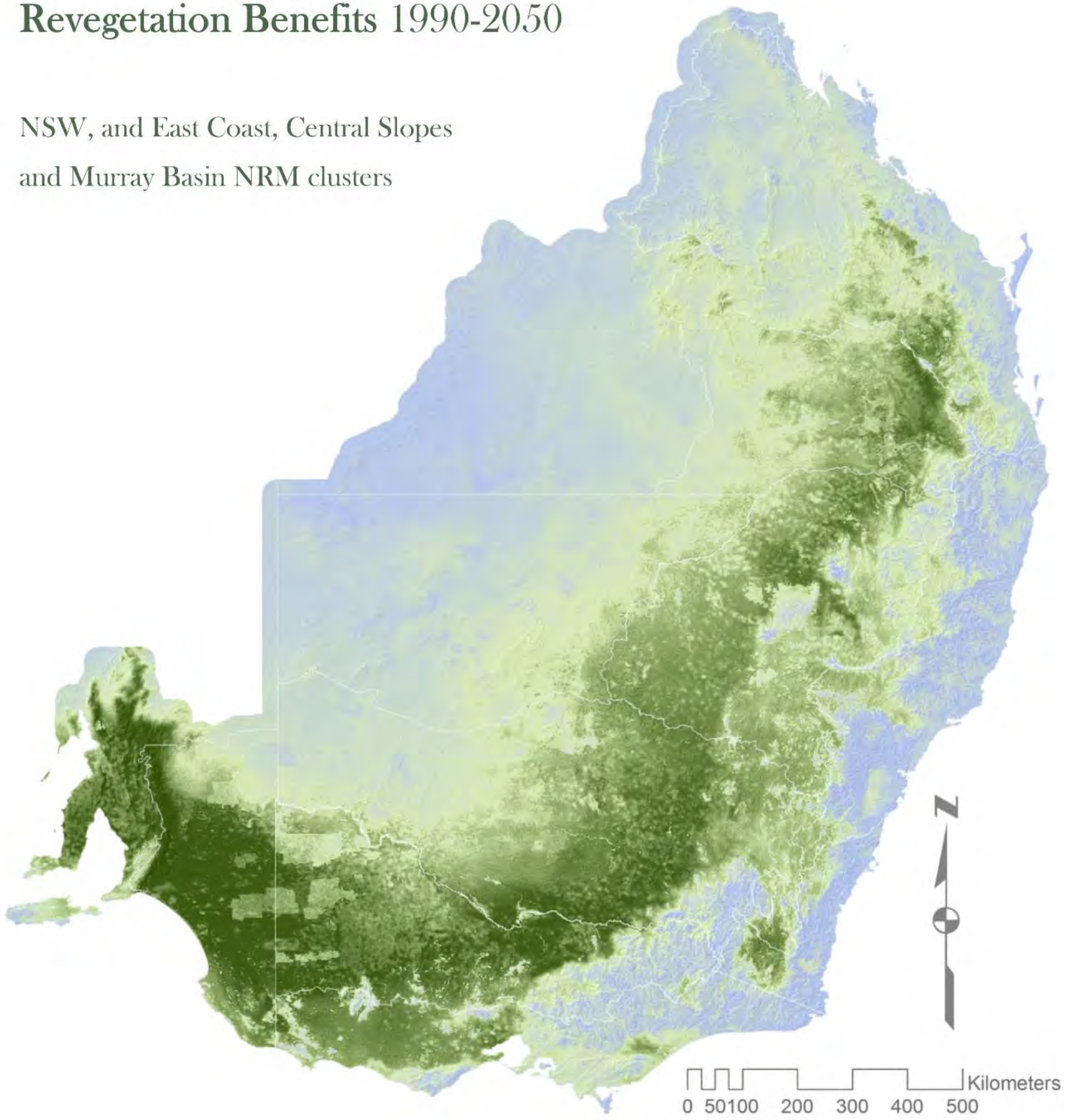
Figure 18: Manage benefits 1990 versus 2050

Blue indicates areas with high manage benefit in 1990 (averaged across all climate futures); red indicates high manage benefit in 2050; and white indicates high manage benefit across the timeframe

Biodiversity climate adaptation

Revegetation Benefits 1990-2050

NSW, and East Coast, Central Slopes
and Murray Basin NRM clusters



SUMMARY

Revegetation benefits are based on the principle of maximising representation of pre-clearing native vegetation communities through revegetation in areas that are expected to become suitable for target communities by 2050. Rates of loss used to weight the importance of communities are based on past clearing, degradation and fragmentation, as well as future contractions, expansions and shifts of bioclimatic envelopes due to climate change. Expected future distributions of bioclimatic class envelopes were derived by averaging the impacts of three climate projections (MPI, CAN and MIROC) each at RCP 4.5 and 8.5 .

LEGEND

Revegetation Benefits

HIGH

LOW

NRM Boundaries

Models and map production by OEH NSW; GDM compositional turnover modelling by CSIRO Ecosystem Sciences, with funding from the Australian government.

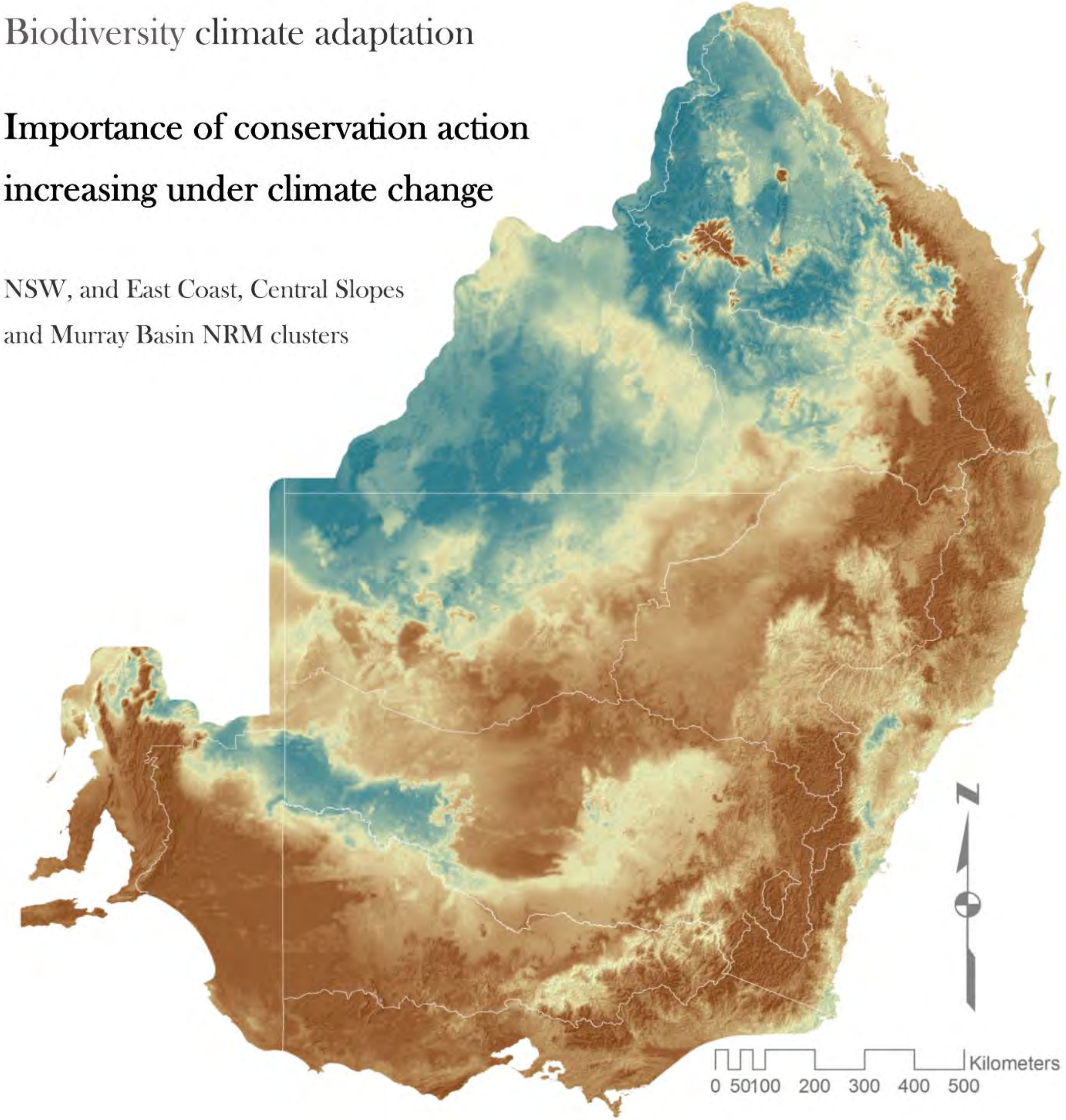
An Australian Government Initiative

Figure 19: Revegetation benefits

Biodiversity climate adaptation

Importance of conservation action increasing under climate change

NSW, and East Coast, Central Slopes
and Murray Basin NRM clusters



SUMMARY

Across the region, the benefits of undertaking conservation action increased significantly when the impacts of climate change were considered. This map shows the increase in importance for either managing existing vegetation or undertaking revegetation.

The analysis suggests that conservation action is more important than ever if we wish to avoid irreversible loss of biodiversity, and that certain areas are becoming disproportionately more important when climate change is considered.

LEGEND

Increase in importance over time

High

Low

NRM Boundaries

As would be expected, this analysis points to growing importance of some relatively cool, moist, elevated areas—where vegetation has been retained in good condition. However, these areas while growing in importance are not necessarily *the most* important place to invest in conservation at this time.

Models and map production by OEH NSW; GDM compositional turnover modelling by CSIRO Ecosystem Sciences, with funding from the Australian government.

Figure 20: Relative increases in BFT benefits
Average increases to manage and revegetation benefits across the six climate change futures

2.4.4 The 3CMP metapopulation model

The 3CMP metapopulation model is a novel approach, developed as part of the 3C project, to gain an alternative perspective on range-shifts that explicitly models the persistence of BCCs at each time-step through the combined effects of habitat condition and shifting BCC envelopes, local extinction processes and migration. 3CMP framework further considers competition for space between BCCs– outlined in Appendix 2.

3CMP is broadly based on the rapid evaluation of metapopulation persistence (REMP) methodology (Drielsma et al. 2009). Consistent with that approach, 3CMP occupancy is mapped across the region subject to the amount, quality and spatial pattern of habitat. It differs from REMP in some minor technical details:

- It does not employ separate resolutions for Neighbourhood Habitat Area and dispersal processes and does not calculate Metapopulation Capacity.
- It goes further by using the occupancy at each time-step as the pre-condition for deriving occupancy for the next time-step.
- At each successive time-step the habitat conditions are altered due to shifting envelopes.
- Occupancy for the new time-step is then calculated by modelling colonisation of potentially vacant areas (subject to the suitability of destination areas, the level of dispersal (propagule pressure) generated from the previous time-step, the level of connectivity across the intervening landscape), and local extinctions (a function of the amount of connected habitat to a site).

In the context of climate change modelling, the 3CMP model is an early attempt at this style of modelling and the results at this stage are preliminary. 3CMP has the limitations of considering each BCC as a separate entity, such that all habitat extinction rates and colonisation rates were chosen arbitrarily and were uniform across all BCCs, while habitat quality values varied across the BCCs. Nonetheless the model provides useful insights into possible processes and outcomes not afforded by other models. For example, Figure 6 highlights areas that are able to accept and transmit BCCs after considering shifting BCC envelopes, barriers to viability and movement. Many of these areas coincide with areas found to be important from the BFT assessment and other links modelling. Therefore we included these results within aggregated products, albeit with reduced weighting (see Appendix 1).

3CMP can be interpreted as comprising five steps that are iterated for each BCC at each time-step (see Appendix 2):

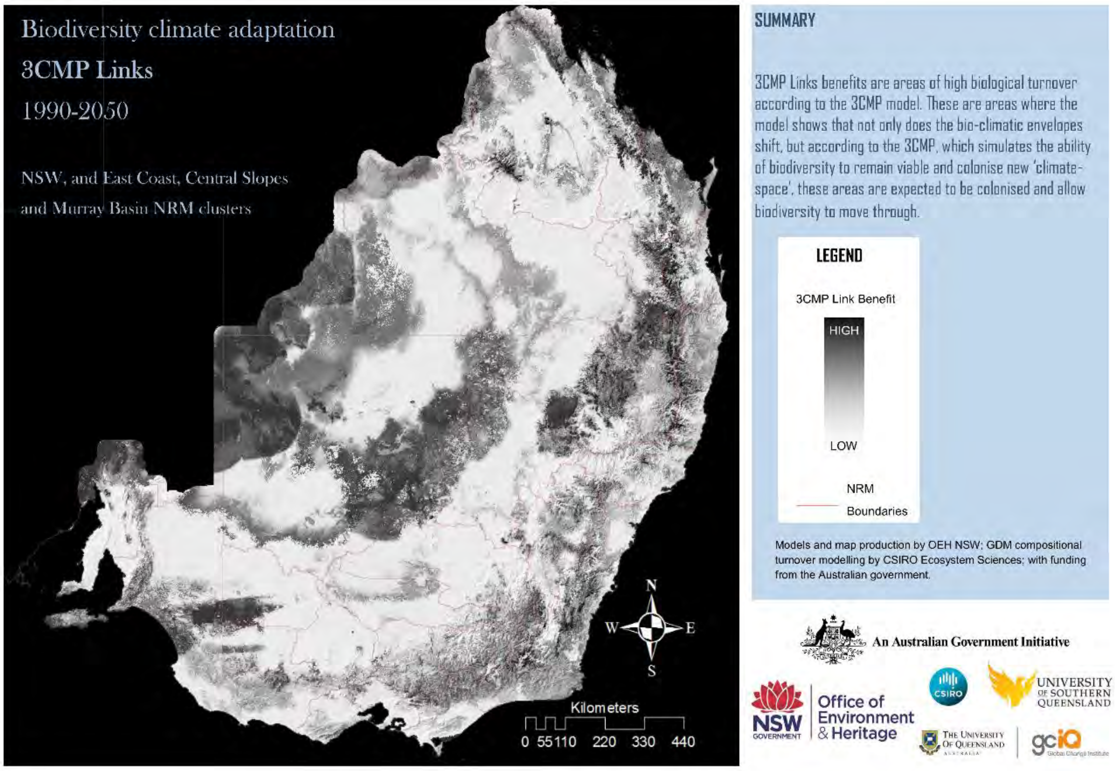
1. Calculate habitat suitability for each cell by multiplying vegetation condition with the bioclimatic envelope suitability for that class at that time (both range between zero and one).
2. Calculate cell permeability based on the mean of past and future habitat suitability.
3. Calculate colonisation potential (Hanski 1999) across space and time.
4. Calculate extinction rate as a function of connected habitat to the location (cell).
5. Calculate the occupancy of each cell by summing occupancy at the previous step, minus extinction, plus colonisation weighted by the amount of available colonisation space and apportioned according to the relative propagule pressure of the class.

The 3CMP model broadly reflects the general shift of envelopes to the south and to increasing altitude but with added movement constraints due to natural and anthropogenic barriers and constrictions.

There are a number of ways in which the 3CMP model can manifest hindrance to BCC shifts. These include any combination of the following:

- lack of suitable habitat to migrate to – for example at the top of mountains, cool climate species are stranded when temperatures increase
- lack of connectivity, barriers or fragmentation caused by clearing and degradation
- blocking by other BCCs – the model does not allow over-occupancy of space (occupancy probabilities cannot exceed one)
- non-viability – although connectivity may exist, if at any point through the process the amount of effective habitat is low, extinction rates increase and can seriously impact the ability of the BCC to generate propagules to colonise in the next time-period.

In the case of BCC21 (related to the New England Tablelands IBRA bioregion in NSW), the dynamics of the class are largely driven by a shrinking and fragmenting ecological envelope, suited to high elevations, where no higher elevations are available to ‘escape’ the prevailing rising temperatures. According to this model, BCC21 is already in serious decline by 2015 and will continue to contract to high-elevation areas north and south of Armidale, NSW. The BCC environment is expected to all but disappear as a distinct class by 2030 (see Figure 22). As there is no connectivity to suitable areas emerging at high elevations further south, the conservation of declining species or genotypes will depend on human agency to enable colonisation and long-term persistence of species.



3CMP Links benefits are areas of high biological turnover according to the 3CMP model. These are areas where the model shows that not only does the bio-climatic envelopes shift, but according to the 3CMP, which simulates the ability of biodiversity to remain viable and colonise new ‘climate-space’, these areas are expected to be colonised and allow biodiversity to move through.

Models and map production by OEH NSW; GDM compositional turnover modelling by CSIRO Ecosystem Sciences; with funding from the Australian government.

Figure 21: 3CMP Links, showing areas of expected colonisation and temporal compositional turnover

Dark areas show places that are predicted to successfully accept and/or transmit colonisers

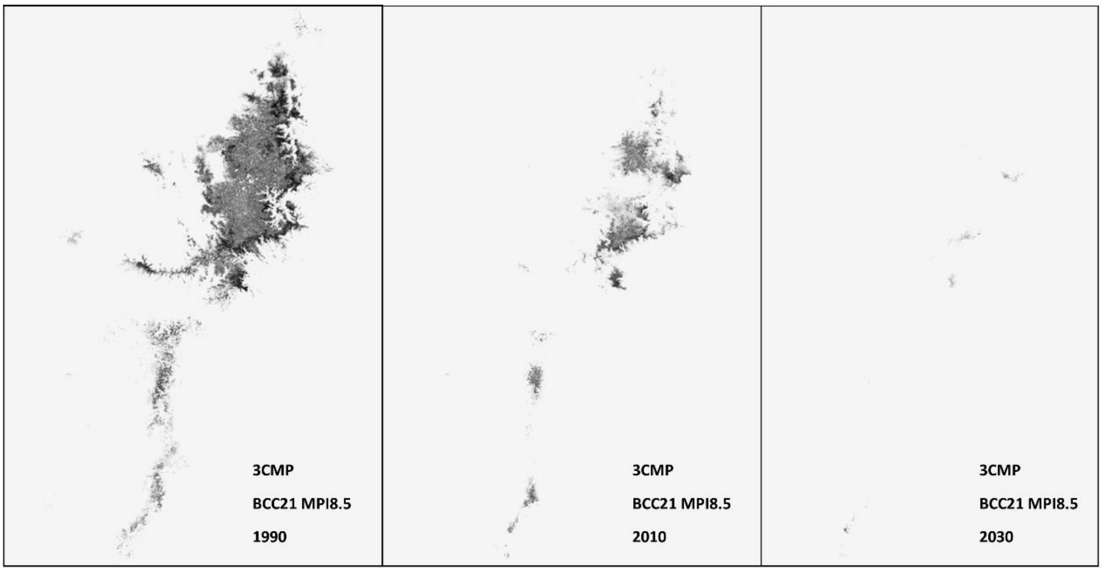
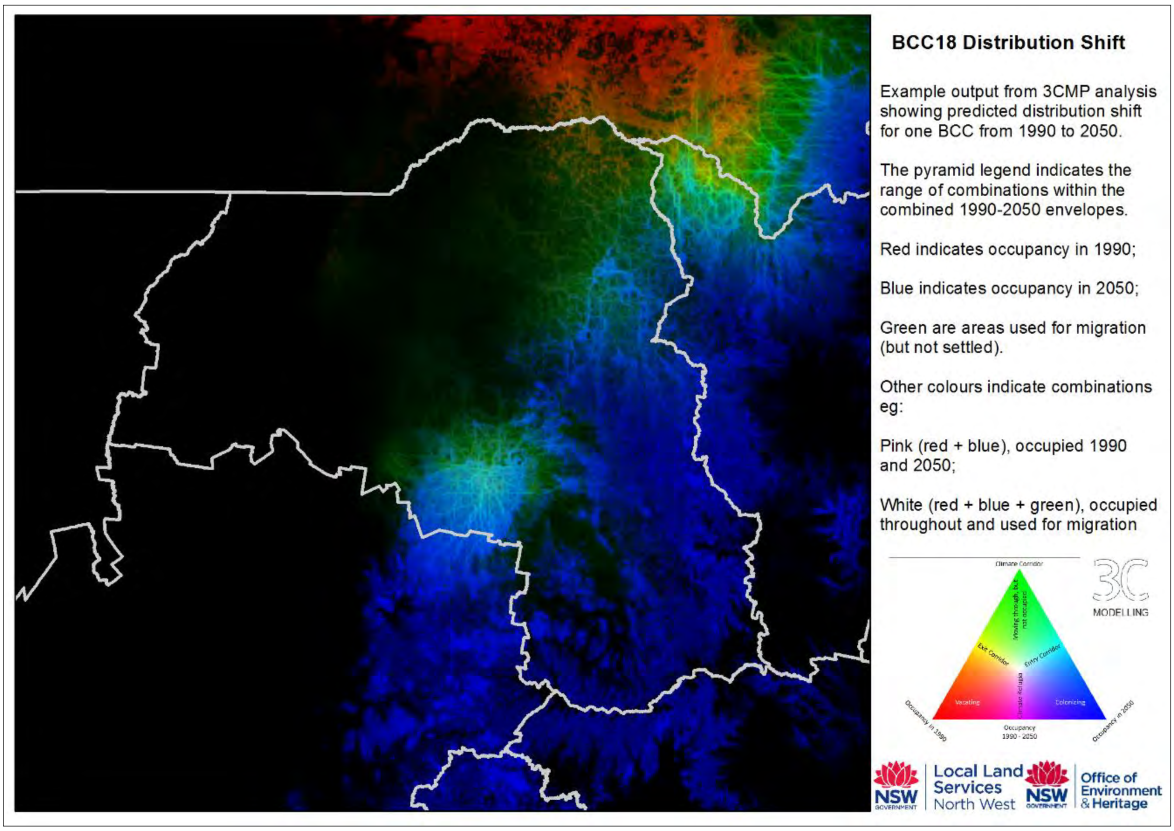


Figure 22: Results of the 3CMP model for BCC21 (New England Tablelands) for 1990, 2010 AND 2030 based on the MPI-8.5 future (most extreme case)



BCC18 Distribution Shift

Example output from 3CMP analysis showing predicted distribution shift for one BCC from 1990 to 2050.

The pyramid legend indicates the range of combinations within the combined 1990-2050 envelopes.

Red indicates occupancy in 1990;

Blue indicates occupancy in 2050;

Green are areas used for migration (but not settled).

Other colours indicate combinations eg:

Pink (red + blue), occupied 1990 and 2050;

White (red + blue + green), occupied throughout and used for migration

Figure 23: Example 3CMP output for North-West NSW showing predicted distribution shift for BCC18 from 1990 to 2050

Black areas are outside the envelope for BCC18 throughout the modelling period. The pyramid legend indicates the range of combinations within the combined 1990–2050 envelopes. Red indicates occupancy in 1990; blue occupied in 2050; green are areas used for migration (but not settled). Other colours indicate combinations, e.g. pink (red + blue), occupied 1990 and 2050; white occupied throughout and used for migration (red + blue + green).

Figure 23 provides an alternative perspective on bioclimatic range-shifts modelled by 3CMP, for BCC18 in this instance. The map highlights areas of local extinction, colonisation, movement corridors, and areas of relative stability, over the 1990–2050 period based on the MPI8.5 climate future. The map provides a comprehensive view of the dynamics of a single class through time considering not only its shifting envelope, but its capacity to persist while migrating through a matrix of variable permeability to movement. The map also suggests spatial priorities for conservation action such as protecting areas of refugia (‘habitats that components of biodiversity retreat to, persist in, and can potentially expand from under changing climatic conditions’ (Keppel et al. 2012, p.394)), preparing areas for colonisation and maintaining corridors.

These 3CMP map outputs are provided as examples only. They have not been prepared for all classes or for all climatic futures at this time.

Figure 24 shows the degree to which areas by 2050 achieve their potential to retain biodiversity in their original form of (1990 derived) BCCs. Many areas, being in good condition now, and shown to be important in this project (see Figure 27) are highlighted in this model to have none or limited occupancy, for any BCC, by 2050.

The 3CMP analytic process is highly computationally intensive in its present form, taking multiple days to complete a single climate future run. For this reason, at this stage, it has only been run for the MPI8.5. It is worth keeping in mind that MPI8.5 is the most extreme of the six climate futures used here (although based on a scenario that is currently being tracked globally) in terms of projected change in local biodiversity; however, if the MPI8.5 proves to be too extreme, it will merely be accelerating the envelope shift process, most likely forecasting changes that will occur, but ahead of time, especially given expected lags in biodiversity response (Norberg et al. 2012; Menéndez et al. 2006) not factored into the model.

2.4.5 3CLinks Benefits (climate corridors)

The 3CLINKS approach maps wildlife corridors at scales of the landscape and broader. This approach considers the ability of species to move across the landscape in response to shifting habitat suitability; both in response to seasonal variability and permanent climate-induced habitat shifts.

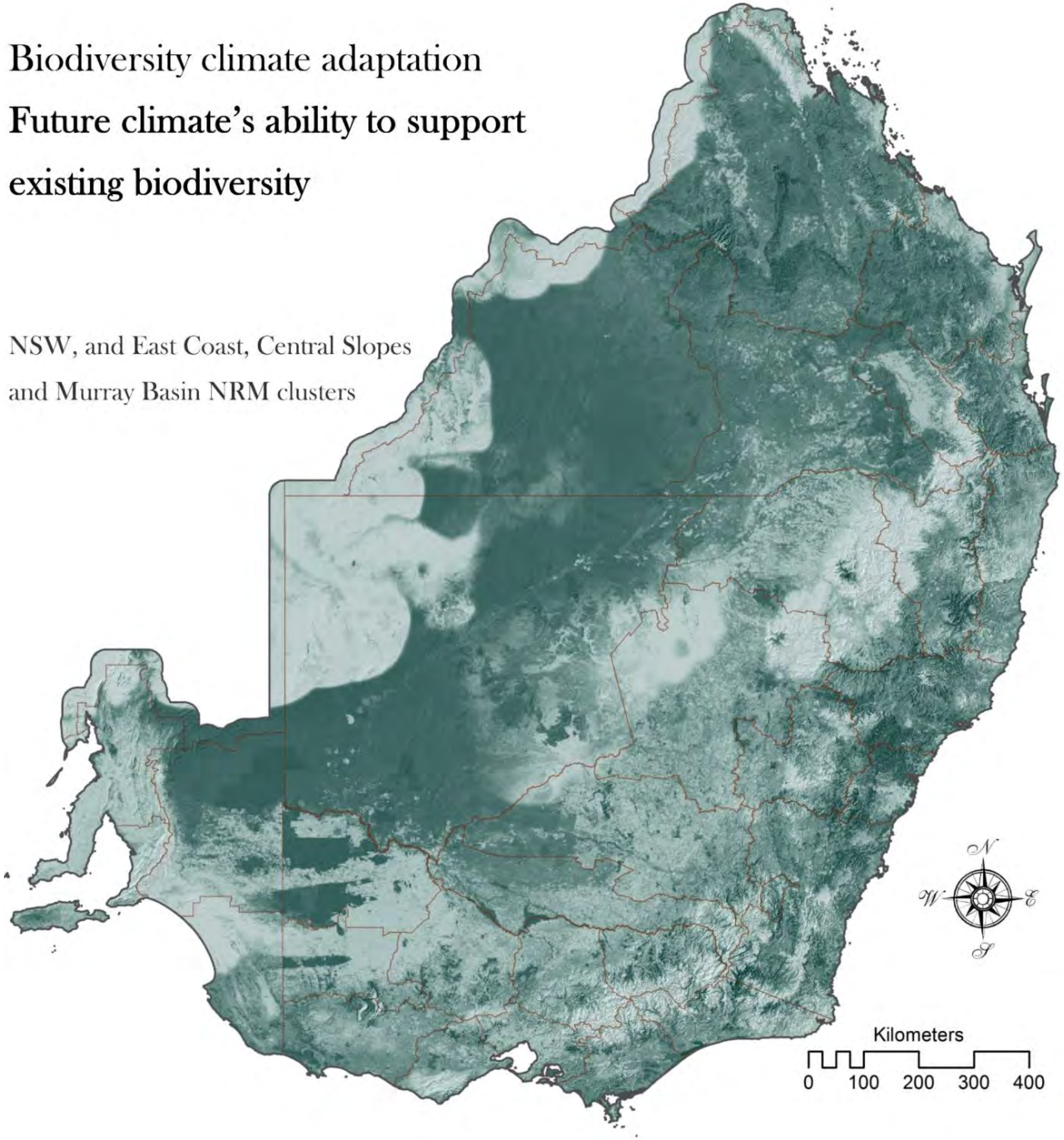
Maintaining and improving habitat connectivity by building integrated whole-of-landscape habitat networks is widely considered a practical biodiversity conservation measure in anticipation of climate change (Heller et al. 2009; Taylor et al. 2007). Habitat patches, while not always large enough or sufficiently intact to support populations, can play an essential role in connecting larger blocks of habitat (Mackey et al. 2010; Soule et al. 2004; Boitani et al. 2007; Smith 2007).

In developing the 3CLINKS benefits, two approaches were taken to modelling connectivity across the region. The first was a modification of previous landscape value (LV) mapping undertaken for the eastern and central divisions of NSW (Drielsma et al. 2013). This was extended across the 3C and generalised to consider connectivity based exclusively on predicted vegetation condition (as opposed to three broad vegetation structure classes as used for the NSW analysis). The range of spatial scales covered was extended to reflect the larger distances associated with the temporal feature of bioclimatic shifts.

Biodiversity climate adaptation

Future climate's ability to support existing biodiversity

NSW, and East Coast, Central Slopes and Murray Basin NRM clusters



SUMMARY

The predicted 'degree of fit' of current bio-climatic classes to a 2050 future climate based on the 3CMP model that considers bio-climatic suitability, landscape impacts on migration ability and ongoing viability.

Dark areas show where the capacity (vegetation condition) to support biodiversity is not realised in 2050 where 1990 derived bioclimatic classes are either unsuited, are unable to reach these suitable areas, or are insufficient in size to be viable, despite having good condition.

LEGEND

Decrease in fit

HIGH

LOW

——— NRM Boundaries

According to the 3CMP model, darker areas would either support novel classes or would degrade to a diminished condition.

Models and map production by OEH NSW; GDM compositional turnover modelling by CSIRO Ecosystem Sciences, with funding from the Australian government.

An Australian Government Initiative

University of Southern Queensland

NSW Government

Office of Environment & Heritage

CSIRO

The University of Queensland Australia

gciQ Global Change Institute

Figure 24: Degree of fit of 2050 conditions to 1990 BCC migrations based on the 3CMP model

The second approach considers bioclimatic shifts by extending the traditional Spatial Links Tool technique (Drielsma et al. 2007) to consider the ecological similarity between source and destination points of a least cost path, i.e. paths were found between source points in its present state, and destination points that are expected to be suitable to support similar species (to the source) in the future. Ecological similarity was calculated from the vascular plant GDM as the negative exponential sum of absolute differences across all transformed environmental variables between the source cell at 1990 and the destination cell at 2050. As an exemplar of change, this analysis used environmental variables for the MPI8.5 climate projection. The technique gives higher value to those paths that connect to sites that over time are expected to provide environmental conditions suitable for species likely to be present at the source.

Both analyses were performed across a range of spatial scales (Table 5) with the modified landscape value approach employing a multi-resolution multi-origin sampling technique (Drielsma et al. 2013). This technique involves multiple analyses at each resolution using sub-pixel offsets in grid origins when resampling to coarser resolutions. It captures detail that can be lost when resampling raster data to a coarser resolution. This enhancement has not yet been implemented for the second approach, in which environmental similarity of source and destination cells are considered.

Table 5: Summary of parameters used in the calculation of 3CLINKS benefits across a range of spatial scales

Ecological scale	Grid resolution(m)	No. grid offsets[9]	Paths per offset[2]	Total paths[10]	1/α (km)	Min. path distance (km)	Max. path distance (km)
Landscape	250x250	1	400,000	400,000	31.25	2.5	25
↑	500x500	25	8,000	200,000	62.5	5	50
	1,000x1,000	16	6,280	100,480	125	10	100
	2,000x2,000	25	2,000	50,000	250	20	200
↓	4,000x4,000	25	1,000	25,000	500	40	400
Interregional	8,000x8,000	25	500	12,500	1,000	80	800

For both approaches, connectivity was summed across scales (and resolutions for LV) and the resulting outputs then combined with equal weighting. As link benefits are intended to take into account each location's condition, the spatial configuration of its surrounding vegetation and larger-scale patterns of connectivity, vegetation condition data and an effective habitat area analysis (Drielsma et al. 2007) were also included in the LV product. The overall process of combining this information is presented in Figure 25 and Appendix 3. The 3CLINKS benefit analysis explicitly incorporates areas that are likely to facilitate species movement in response to changes in climatic variables, or areas that through investment aimed at consolidating existing vegetation are likely to support such movements (shown in Figure 25). Figure 25 highlights the scarcity of corridors across the wheat-sheep belt and therefore the importance of nodes such as the Pilliga forest in NSW and the corridors that flow from it to the east and west.

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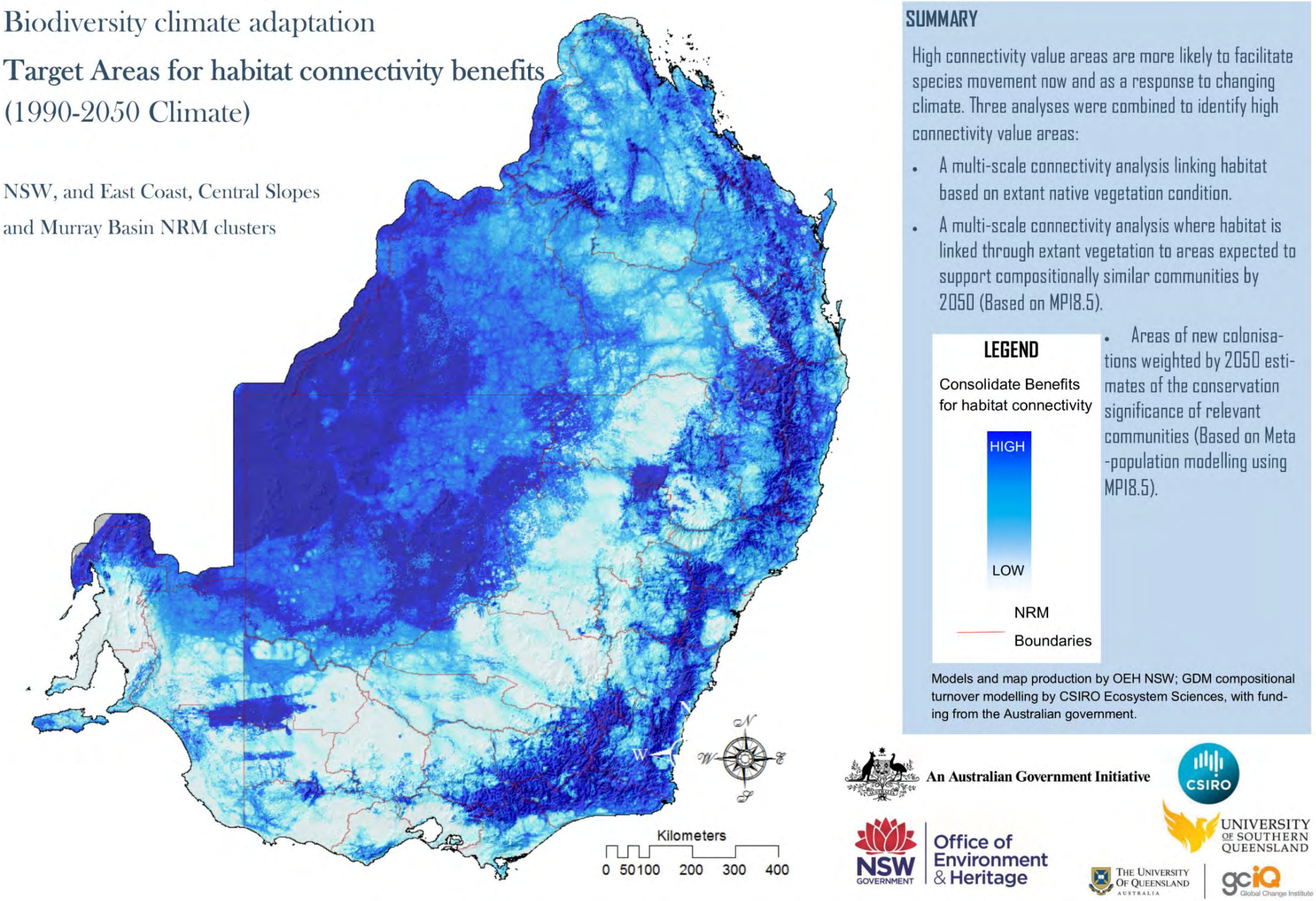
[9] Only applies to landscape value methodology

[10] Per analysis approach, x2 across both analyses



SUMMARY

High connectivity value areas are more likely to facilitate species movement now and as a response to changing climate. Three analyses were combined to identify high connectivity value areas:

- A multi-scale connectivity analysis linking habitat based on extant native vegetation condition.
- A multi-scale connectivity analysis where habitat is linked through extant vegetation to areas expected to support compositionally similar communities by 2050 (Based on MPI8.5).
- Areas of new colonisations weighted by 2050 estimates of the conservation significance of relevant communities (Based on Meta-population modelling using MPI8.5).

Models and map production by OEH NSW; GDM compositional turnover modelling by CSIRO Ecosystem Sciences, with funding from the Australian government.

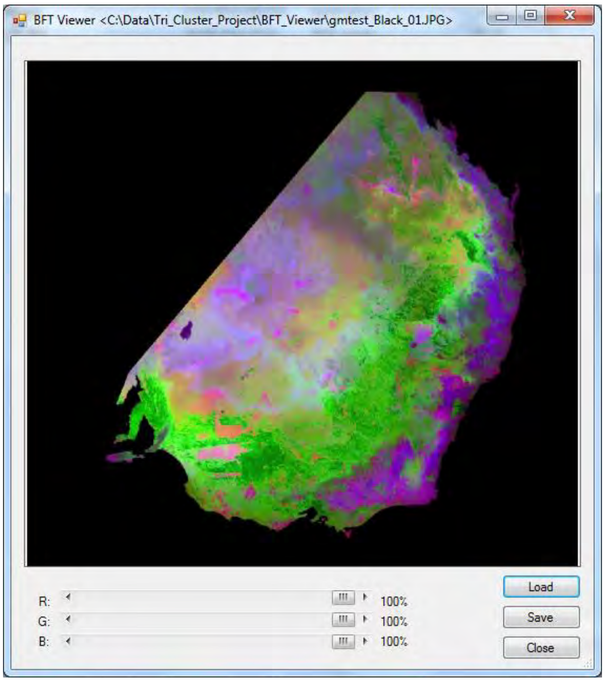
Figure 25: **3CLINKS benefits or climate corridors**

2.4.6 Combined benefits mapping

In order to assist end users to synthesise the findings of the 3C project, we partially undertook this task, based on simple rules; however, there are many potential ways to aggregate products and no single correct way to do it, so end users are encouraged to download the raw model outputs and undertake fit-for-purpose aggregations of their own, as required. The examples presented here can be used for planning purposes or may be a guide as to other possibilities. Some of the aggregated BFT benefit products are shown above. In addition to these we constructed an output that captures most of the 3C outputs in a single image, with each of the RGB bands representing manage, links (climate corridors) and revegetation benefits respectively (see Figure 27). While this product provides a perspective that would be difficult to achieve with separate views, it is necessary to revert to the primary products for clarity around individual components. To assist in interpreting the image, we provide a simple electronic map, a distributable application that allows each colour band (representing the three component benefit layers), to be viewed individually or with altered prominence (available from the authors MD or JL).

The BFT viewer (see Figure 26) enables the user to view jpeg files and adjust the relative intensity of the separate red, green and blue bands. This application was designed to use the composite RGB images created from the BFT priority grid results.

The BFT composite grids have separate analysis results encoded into each of the red, green and blue bands. Using the slider bars to adjust the relative intensities of each band allows the user to highlight interactions between the BFT results. These visual models can greatly assist the understanding of where multiple land-use strategies can achieve the most desired effect.


BFT Viewer <C:\Data\Tri_Cluster_Project\BFT_Viewer\gmtest_Black_01.JPG>

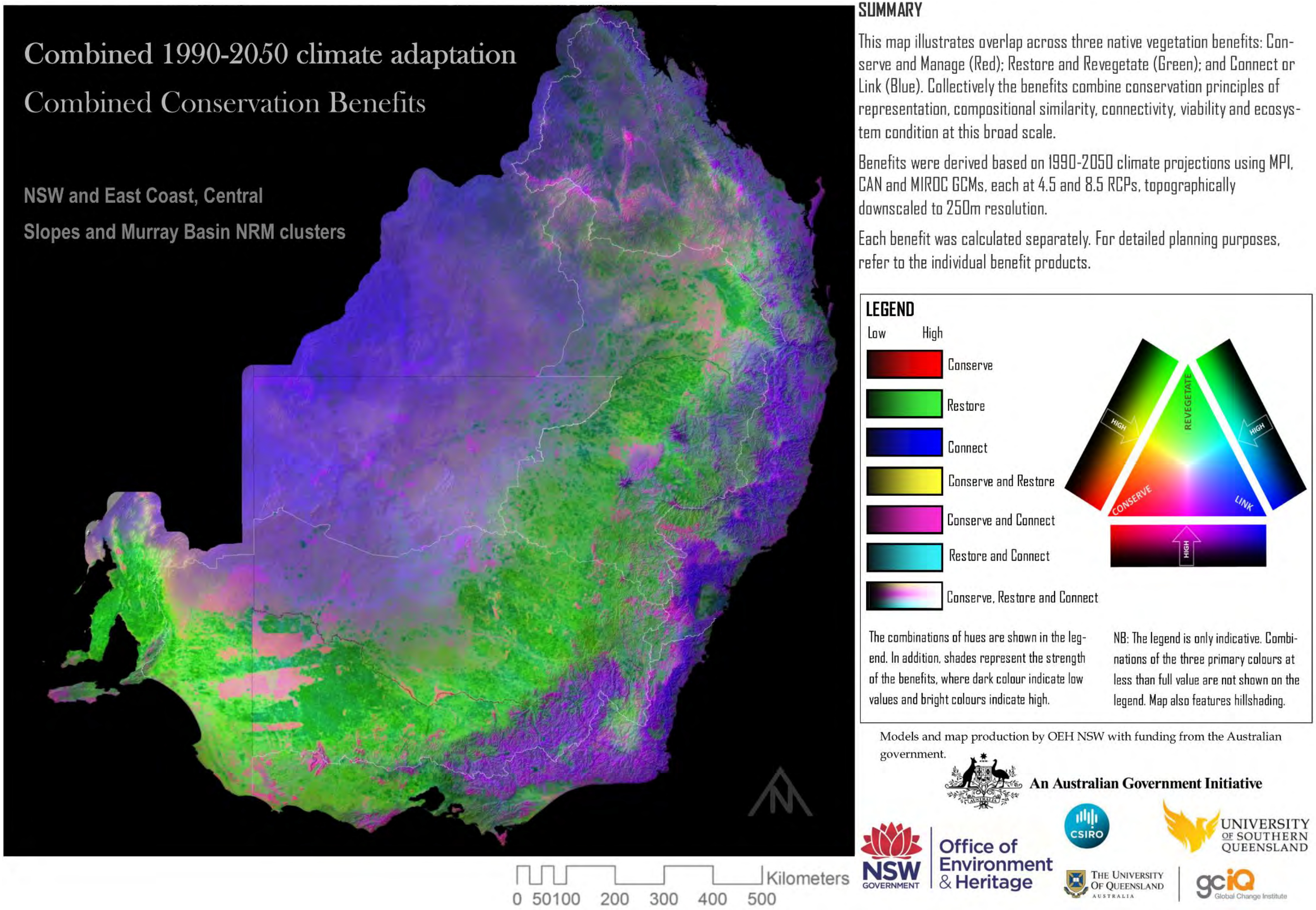
R: 100%

G: 100%

B: 100%

Figure 26: Screenshot of the BFT viewer

The tool, which will be distributed to end users, contains the same image of combined benefits (as in Figure 27). With this tool, users can adjust the individual colour bands, each of which represents a single benefit theme: red (R), manage benefits; blue (B), link benefits; green (G), revegetation benefits.



SUMMARY

This map illustrates overlap across three native vegetation benefits: Conserve and Manage (Red); Restore and Revegetate (Green); and Connect or Link (Blue). Collectively the benefits combine conservation principles of representation, compositional similarity, connectivity, viability and ecosystem condition at this broad scale.

Benefits were derived based on 1990-2050 climate projections using MPI, CAN and MIROC GCMs, each at 4.5 and 8.5 RCPs, topographically downscaled to 250m resolution.

Each benefit was calculated separately. For detailed planning purposes, refer to the individual benefit products.

The combinations of hues are shown in the legend. In addition, shades represent the strength of the benefits, where dark colour indicate low values and bright colours indicate high.

NB: The legend is only indicative. Combinations of the three primary colours at less than full value are not shown on the legend. Map also features hillshading.

Models and map production by OEH NSW with funding from the Australian government.

An Australian Government Initiative

Figure 27: **Combined NRM benefits map**

3 Discussion

Our 3C evaluations (see section entitled **2.4.2 BFT evaluation**) support expectations that the environmental conditions will change enough in the next few decades to exert significant pressure for change on biodiversity distributions. There is sufficient agreement across alternative futures and across assessment approaches to make general conclusions that can be incorporated into NRM planning.

3.1 Significance of climate impacts

Although not all BCCs, or species contained within them, will be equally impacted by climate change – some are expected to expand, and the distribution of impacts will be uneven – the 3C project's findings point to severe negative impacts on the overall persistence of biodiversity across the study region (see Figure 14). The alternative futures and analytical techniques used show variations in the severity of the impacts and the speed at which they manifest. Impacts arising from the RCP 8.5 projections (business as usual) represent an additional loss of biodiversity comparable to losses already experienced as a result of land clearing and agricultural land use from the time of European settlement and up to 1990.

In terms of the benefits of undertaking conservation action, there is sufficient agreement for a number of areas within the study area to stand out (in Figure 27). These are places where significance for conservation is reinforced rather than negated by considering a range of futures and methodologies.

Significantly there is some evidence to suggest (Figure 24) that some of the most important, currently high condition areas may become unsuitable or are unable to be colonised by any existing BCC, and therefore, without appropriate intervention, may transform into novel BCCs or degrade to poor condition versions of historical BCCs.

3.2 Key messages

Climate change impacts on biodiversity arise from geographic shifts, contractions, expansions and disappearance of BCC envelopes. Where new climate spaces open for displaced species, barriers to movement or lack of continuity of habitat limits the transition and their viability in new areas. Together these impacts will leave many species in habitat of reduced size and/or suitability where they risk extinction. *Collectively, losses to biodiversity arising from the impacts of climate change in the 3C region over the next 30–40 years could be comparable to losses due to land clearing and degradation from European settlement up to the present.*

The 3C BFT mapping of 'manage' and 'revegetation' benefits was undertaken for the 1990 as well as for the 2020 and 2050 futures. In each case the underlying conservation objectives were exactly the same, namely to maximise the persistence of the original biodiversity at the point of European settlement (although this cannot sensibly be the only objective in the future). *Benefits mapping across the 1990–2050 timeframe demonstrates a considerable geographic shift in benefit distributions as the conservation significance of individual BCCs changes and their modelled distributions shift.*

As demonstrated in the methods section, we need to manage areas of existing quality native habitat across this transition, including management to accommodate shifts and maintain high regional diversity. In the case of the white areas in Figure 18 (existing vegetation that has high manage benefits across the timeframe), climate-ready high benefit revegetation areas in Figure 19, or light areas in Figure 27: (where all benefits coincide), there are clear messages for NRM, supported across a range of models, timeframes and assessment methodologies. In other areas we need to think about how to manage areas to facilitate species' exits and entries. *For the sake of maximising the persistence of biodiversity through* *revegetation, the message would appear to be 'focus on the future', making use of future revegetation benefit areas and selecting species for revegetation that are likely to prosper under emerging climatic regimes; however, in many areas there may be other reasons to revegetate, i.e. for ecosystem services provided through natural ecological functions* (Lavorel et al. 2015)*.*

The 3C does not provide complete solutions for biodiversity conservation. *Much additional work is needed at the regional level and at finer scales largely relating to synthesising 3C with other domains (e.g. agricultural production, carbon sequestration, water quality and quantity, public amenity) and with finer-scale and more detailed biodiversity information (e.g. species-level conservation, fine-scale connectivity, fine-scale environmental variability).*

3.3 Further work

The climate change and modelling program will continue in 2015 through the NSW/ACT Regional Climate Modelling project (NARCLiM). There are opportunities to utilise NARCLiM projections to augment the current set of futures and to find whether NARCLiM, which more explicitly incorporates East Coast Lows, will add new information to the current 3C outputs. In addition, work being undertaken as part of the NARCLiM suite of projects (e.g. impacts on fire regimes, soil properties and erosion) should provide valuable biodiversity threat information that can be incorporated into the 3C framework.

There should also be opportunities to expand the set of currently completed model runs for the 3CMP and 3CLINKS as well as to further test and develop the novel approaches in those models. The 3CMP particularly represents opportunities for further development, including its use on other groups (e.g. mammals, reptiles and amphibians – GDM-modelled output data developed by CSIRO), narrower biodiversity entities including single species, or functional species groups, where more detailed knowledge of species habitat preferences and movement abilities could be incorporated. There is also a preliminary design in place for the 3CMP to work with continuous compositional turnover rather than classes (i.e. work directly with the raw rather than classified GDM outputs, as is the case in the AdaptNRM approaches), in collaboration with CSIRO (preliminary discussions were held in early 2014). The feasibility of that approach will be re-assessed and possibly progressed to development in the coming months.

The 3C team has begun engaging with individual NRMs seeking to incorporate 3C outputs with more detailed regional information and with other (non-biodiversity) attributes. For more on this, see Section 4.1.

4 Products

The entire suite of 3C products is listed in Appendix 4. The table in Appendix 4 includes a short description, the folder location within the standardised 3C product package, the filename(s), the file format or type, and notes. ‘URL’ indicates the location for download from TERRA NOVA. Access to products without a URL can be negotiated by contacting the NSW Office of Environment and Heritage (see contacts at the front of this document).

4.1 Use of products

As we have emphasised throughout this report, planning for climate change adaptation is challenged by high levels of complexity and uncertainty, common to planning and decision-making processes. We have attempted to embrace these matters with the approach taken, by incorporating a range of futures, a range of ecological modelling methodologies and by refraining from offering pre-packaged solutions; by enabling NRM planners, who are closer to real-world problems, to make the necessary contextualised decisions (Haag et al. 2001).

Products provided are not prescriptive. Rather, by providing big-picture contexts not otherwise easily accessed by local NRM agencies, enterprises and individuals, we intend these products to initiate place-specific interpretation. We invite users to explore the nature of possible climate scenarios in their regions using these products (and others) and to find creative and innovative ways to integrate 3C outputs with their own local data and knowledge, as part of an ongoing conversation and action around climate adaptation. We stress that climate adaptation is a class of problem that cannot be solved in the normal sense (as designing an engineering structure, such as a bridge, can be) and there is no single, correct solution. We therefore favour the flow of useful scenario-based information to decision-makers, to facilitate and support decision-making within this difficult context.

An obvious point of focus is the scale of the 3C analysis, the limitations of modelling and the coarseness of the biological units employed, and how this impacts on the project’s findings. We have followed a deliberate strategy for managing the complexity of our subject and used the cost-efficiency brought by collaboration with the NRM National project led by CSIRO. We recognise that there is high diversity within our coarse biological units (BCCs) and that the biodiversity could have been classified in many alternative ways. Other inputs, for example vegetation condition, will also exhibit errors when examined in high spatial detail. These ‘tools’ are not intended, nor are they fit, for undertaking assessment of individual species, or to prescribe ways to manage biodiversity at that level or at a fine spatial resolution (e.g. at the paddock scale); but they are appropriate for landscape-level assessment of trends where the aim is to highlight general locations where conservation actions are likely to have an overall positive effect on biodiversity as a whole, and to estimate the degree of those effects. It is expected that on closer examination, further refinement of the 3C findings will emerge, including:

- places that have fine-scale values that differ from coarse-scale values (e.g. local refugia, fine-scale corridors)
- place- and enterprise-specific conservation actions or integrated management that present opportunities at specific locations and times.

We recommend 3C products be used within a top-down-and-bottom-up approach to planning and decision-making that integrates the strengths from all sources of available knowledge and information.

The project has also opened the possibility for many potential secondary products, which we were unable to follow through in the course of this project. We trust that enough is provided at this stage to either enable progression to an enhanced form of decision-making and planning, or that the current set of outputs are sufficient to generate ideas and proposals for further analysis, either by or with the 3C modelling team, or elsewhere. For example, we were unable through time restrictions, to undertake a detailed comparison of the impacts on individual BCCs arising from the alternative futures, to apply the 3CMP and 3CLINKS models to futures other than MPI8.5, or to generate maps similar to Figure 23 for other BCCs using the 3CMP – or possibly combinations of BCCs. In terms of the 3C team undertaking further analysis, this will be largely governed by demand and resourcing, so please make your needs known if you have ideas or needs.

The primary products (the outputs from a single future and model) are scientifically based and supported by peer-reviewed publications (BFT, Spatial Links Tool), but this is not the case with the aggregated products. We invite people to make use of these, but stress that as products are combined into aggregated products, the more arbitrary the decisions embedded in the process become (e.g. weights). When making these decisions we followed a principle of simplicity wherever possible (e.g. equal weighting to each future, each technique), minimising any arbitrary decisions to support the *a priori* world views of the modellers. We did give added weight to well-supported, mature approaches over newer, less tested approaches.

Some users may wish to explore or use primary or intermediate products and create customised fit-for-purpose aggregations of their own. A common approach is to integrate finer-scale analysis for a smaller region to complement the big-picture products. Although we encourage innovative use of the 3C product, we cannot commit to re-running the 3C analysis with, for example, alternative parameterisations and input data, without co-contribution of resources.

From the regional perspective it is important to recognise that the 3C benefit values are relative indices. The range of values across the 3C may be much larger than the range within an individual NRM region. As the colours in the 3C maps are stretched across the entire 3C, the relative values within a single NRM may not be apparent at this scale and may wrongly suggest that values at the finer scale are insignificant or uniform. To overcome this issue the data needs to be viewed from the perspective of the NRM region, either through extracting the data for the smaller region or by resetting the colour legend to provide greater discrimination for that area.

The 3C modelling team has experience in developing cross-scale assessments. The team are available to discuss appropriate and alternative use of the products or possible further development, and have some negotiable capacity to collaborate on further analysis at the scale of an NRM area.

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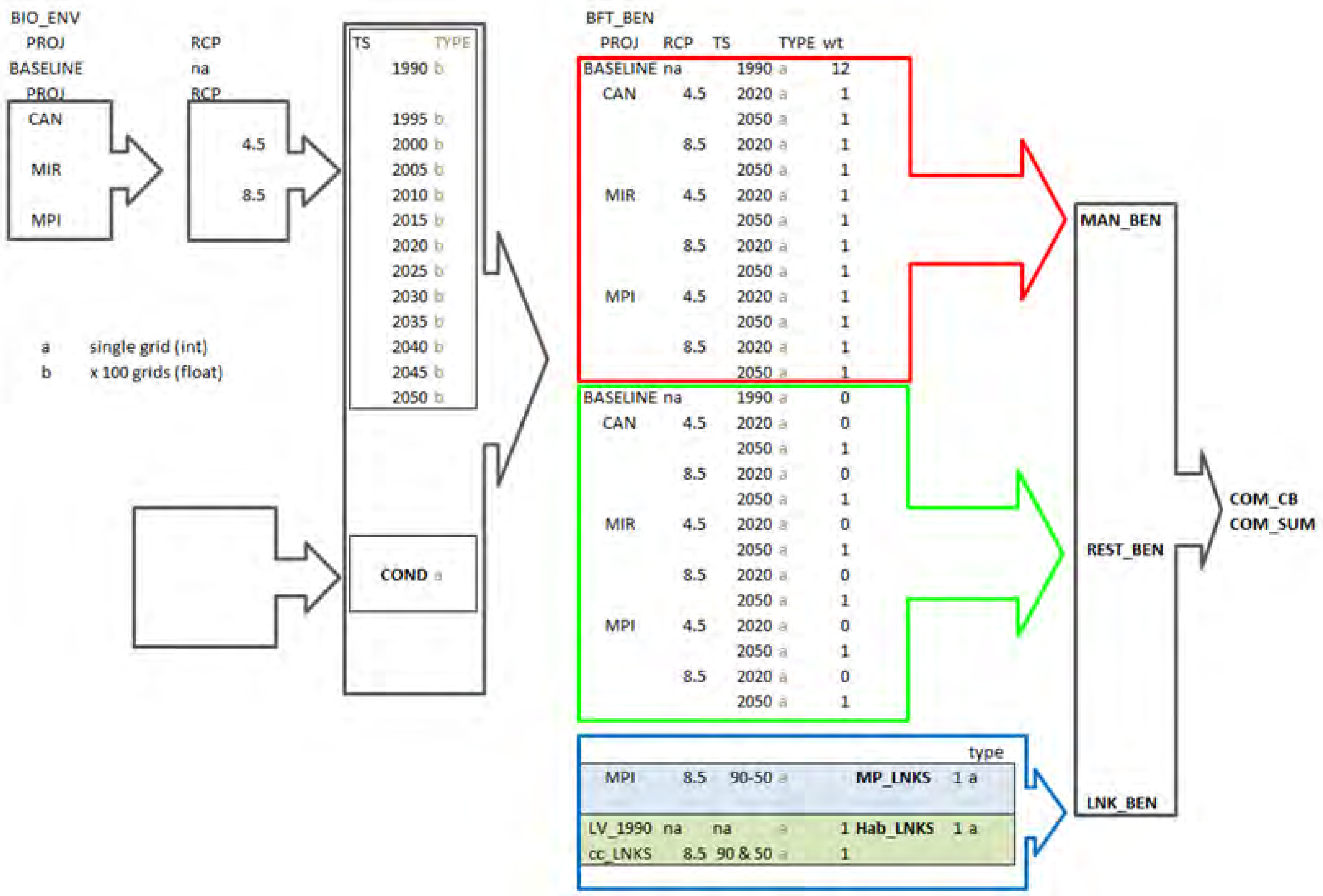
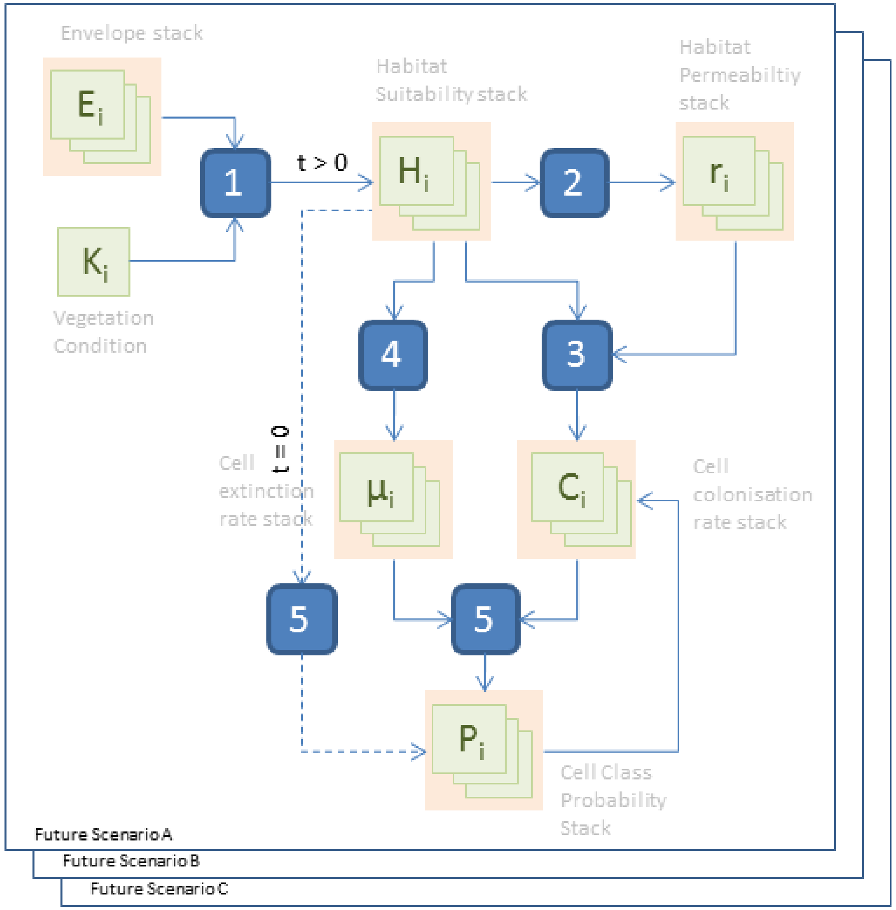
Appendix 1: Workflow for the creation of combined benefit products



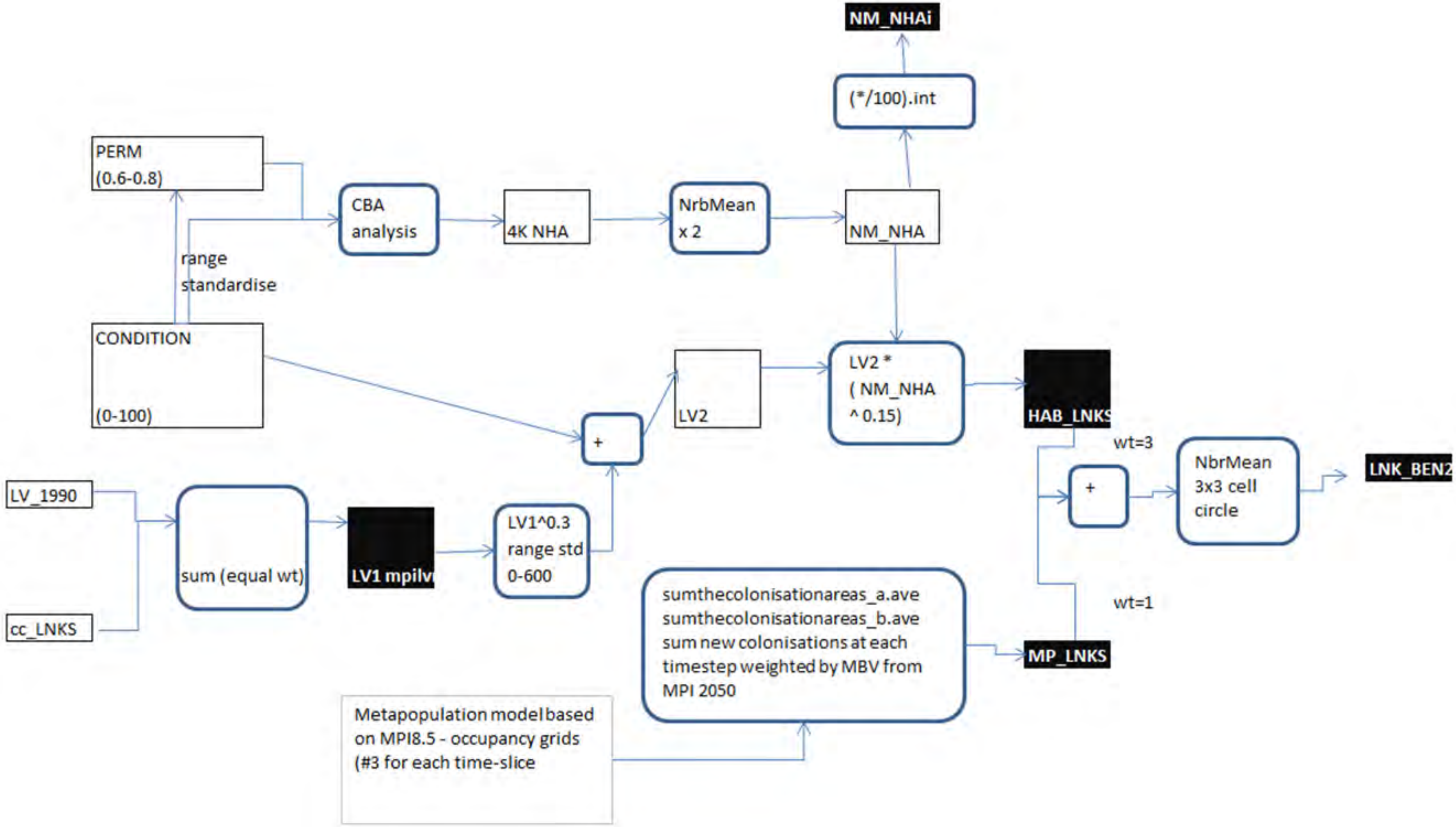
Appendix 2: The 3CMP methodology



Concept/step	**Symbol/equation**	**Notes**
1. Habitat (BCC) suitability for cell *i*	$\mathrm{H_i} = \mathrm{KE_i}$	Product of vegetation condition (K) and BCC envelope (H) for class *v*
2. Cell permeability	$r_{min} = e^{-\alpha_{max} z}$ $r_{max} = e^{-\alpha_{min} z}$	*z* – cell size (m); *v* – parameter; *d* – effective orthogonal cell distance Get the min. and max. permeabilities (r_{min} and r_{max}) from user-defined 1/α values (dispersal scale)
	$r = \left[\frac{(H_k + H'_k)(r_{max} - r_{min})}{2H_{max}}\right] + r_{min}$	Average the past and future habitat suitability for cells along the path. Range standardise between r_{min} and r_{max}
3. Cell colonisation potential	$\mathrm{w_{ij}} = \prod_{\mathrm{k=1}}^{\mathrm{m}} r_k$	Path permeability
	$S_i^t = \mathrm{cH_i} \sum_{\mathrm{j=1}}^{\mathrm{n}} [\mathrm{H_j}\ \ \mathrm{w_{ij}}\ \ \mathrm{P_j}]$	The capacity of neighbourhood cells (from previous time-step) to colonise the focal cell in time *t* + *Δt*. NB: Colonisation potential formulae (i.e. multiply by Hi) restricts colonisation to suitable habitat. NB: The Hj here reflects the fact that high occupancy does not always equate to high habitat value, i.e. a ‘sink’ rather that a ‘source’.
4. Cell extinction rate	$\mu_i \ = e/H''_i$	The rate of expiration of the bioclimatic class from the focal cell is inversely proportional to the connected habitat to cell *I* (H''_i) based on CBA analysis (Drielsma et al. 2007).

Concept/step	Symbol/equation	Notes
5. Cell class occupancy probability	$P_i^0 = \mathrm{H}_\mathrm{i}^0$ $B_i = 1 - \prod_{v=1}^{v}(1 - P_i)$ $P_i' = P_i + \frac{S_i B(K - \sum P_i)}{\sum S_i} - \mu_i' P_i$	Class probability at first time-step equals the envelope probability. B_i is the probability of the cell being colonised by any class *i* For subsequent time-steps colonisations (second argument) and local extinctions (third argument) are applied to the previous probability (first argument). The colonisation argument is constructed such that available colonisation space is governed by the condition of the cell, the combined colonisation probability across all BCC classes. Vacant space is allocated to competing bioclimatic class according to the relative strength of their colonisation pressure (colonisation rate).

Appendix 3: Workflow for the creation of link benefits



Appendix 4: 3C products list

ID	File	Type	Description	URL
	Derived products			
3c004	Combined19902050BenefitsRGB	tif; lyr; pdf	Combined 1990–2050 climate adaptation native vegetation benefits	www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/combined-1990-2050-climate-adaptation-native-vegetation-benefits
3c005	RetativeBenefitIncrease1990to2050	tif; lyr; pdf	Climate influence on benefits 1990–2050	www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/biodiversity-climate-adaptation-climate-influence-on-benefits-1990-2050
3c006	Links19902050Benefits	tif; lyr; pdf	3CLINKS benefits (climate corridors) 1990–2050	https://www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/3c-modelling-links-benefits-climate-corridors
	3CMP Links 1990-2050	GRID; zip	Colonisation by any class between 1990 and 2050 based on the MPI8.5 metapopulation model	https://www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/biodiversity-climate-adaptation-3cmp-links-1990-2050
3c007	Manage1990vs2050Benefits	tif; lyr; pdf	Manage benefits 1990 versus 2050	www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/biodiversity-climate-adaptation-manage-benefits-1990-2050
3c008	Manage19902050Benefits	tif; lyr; pdf	Manage benefits 1990–2050	www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/biodiversity-climate-adaptation-manage-benefits-1990-2050
3c009	Revegetate19902050Benefits	tif; lyr; pdf	Revegetate benefits 1990–2050	www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/biodiversity-climate-adaptation-revegetation-benefits-1990-2050

ID	File	Type	Description	URL
3c010	DegreeOfFit1990ClassesIn2050Climate	tif; lyr; pdf	3CMP predicted 'degree of fit' of 1990 bioclimatic classes to 2050 areas	www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/degree-of-fit-1990-classes-in-2050-climate
3c011	MetapopulationLinks19902050	tif; lyr; pdf	3CMP areas of high biological turnover	www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/biodiversity-climate-adaptation-3cmp-links-1990-2050
3c012	VegetationCondition2014	tif; lyr; pdf	Estimated vegetation condition 2014	www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/biodiversity-climate-adaptation-vegetation-condition-2014
	Raw benefits			
3c013	Manage Benefits	flt; hdr; zip & tif; zip	Conservation manage benefits derived for 1990, 2020 and 2050	www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/conservation-benefits-derived-for-1990-and-each-of-the-6-future-projections-at-2020-and-2050/1990benefits.zip/view
3c014	Revegetate Benefits	flt; hdr; zip & tif; zip	Conservation revegetate benefits derived for 1990	https://www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/biodiversity-climate-adaptation-revegetation-benefits-1990-2050
	GDM			
3c022	TSClassgrids*	GRID; zip	Incremental GDM Climate Change Projection Bioclimatic Envelope Classifications	www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/3c-modelling-incremental-gdm-climate-change-projection-bio-climatic-envelope-classifications

ID	**File**	**Type**	**Description**	**URL**
	Bioclimatic class			
	BCC profiles	PDFs	For each BCC a map where showing where it is the dominant class, and a species list	https://www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/3c-modelling-gdm-bioclimatic-class-profiles
	100 class nearest neighbour (dominant class) classifications	Gifs and GRIDs; zip	Dominate class grids for each of the six future climate scenarios between 1990-2050 in 5 year intervals	https://www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/3c-modelling-incremental-gdm-climate-change-projection-bio-climatic-envelope-classifications
	Report			
3c031	3c_Report	pdf	3C MODELLING Biodiversity Management Under Future Climate To 2050 Report - PDF file	www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/draft-report-3c-modelling-for-biodiversity-management-under-future-climate/3c-draft-201114.pdf/view
	Tools			
3c033	BFTViewer	exe; zip	Biodiversity Forecasting Viewer	Contact Jamie.love@environment.nsw.gov.au
3c034	GDMViewer	exe; zip	Generalised dissimilarity model Time Series Viewer	Contact Jamie.love@environment.nsw.gov.au
	GDM bioclimatic class profiles	100 x PDFs	Approximate distribution map and species list for each BCC	https://www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/3c-modelling-gdm-bioclimatic-class-profiles

ID	File	Type	Description	URL
	3C Cluster scale PDF maps			
	East Coast Cluster	PDFs	PDF maps, as seen in the 3C report, zoomed into the East Coast Cluster	https://www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/3c-modelling-east-coast-products
	Murray-Basin Cluster	PDFs	PDF maps, as seen in the 3C report, zoomed into the Murray-Basin Coast Cluster	https://www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/3c-modelling-murray-basin
	Central Slopes Cluster	PDFs	PDF maps, as seen in the 3C report, zoomed into the Central Slopes Cluster	https://www.terranova.org.au/repository/3c-modelling-east-coast-central-slopes-and-murray-basin-nrm-collection/3c-modelling-central-slopes-products