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Koalas in the Landscape

Landscape capacity to support koala populations through climate change – a technical report

Department of Climate Change, Energy, the Environment and Water
In partnership with
University of New England, Macquarie University

NSW GOVERNMENT

Acknowledgement of Country

Department of Climate Change, Energy, the Environment and Water acknowledges the Tradition Custodians of the lands whe we work and live.

We pay our respects to Elders past, present and emerging.

This resource may contain images or names of deceased persons in photographs or historical content.

Artist and designer Nikita Ridgeway from Aboriginal design agency Boss Lady Creative Designs created the People and Community symbol.

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Environment and Heritage
Department of Climate Change,
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Locked Bag 5022, Parramatta NSW 2124
Phone: +61 2 9995 5000 (switchboard)
Phone: 1300 361 967 (Environment and Heritage enquiries)
TTY users: phone 133 677, then ask for 1300 361 967
Speak and listen users: phone 1300 555 727, then ask for 1300 361 967
Email info@environment.nsw.gov.au
Website www.environment.nsw.gov.au

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The department acknowledges the contributions of Michael Drielsma[1,2], Jamie Love[1], Rajesh Thapa[2], Jillian Thonell[1], and Linda J Beaumont[3] in the preparation of this document.

[1] NSW Department of Climate Change, Energy, the Environment and Water
[2] University of New England
[3] Macquarie University

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Summary

The Koalas in the Landscape (version 1.0) project assessed the capacity of New South Wales (NSW) landscapes to support koala (*Phascolarctos cinereus*) populations now and up to 2070. The project identifies places that can support koala persistence in the face of the impacts of past reductions in habitat extent, quality and connectivity, combined with the projected impacts of climate change. Opportunities for management interventions and restoration activities that will help secure and expand koala populations are mapped.

In this project, koala landscape capacity is mapped for New South Wales. Landscape capacity is a measure of how usable habitat is for supporting populations based on the quantity and quality of habitat, and how easily species can move across the landscape to access sufficient resources to support populations. Summed landscape capacity across New South Wales is a useful metric for reporting on the current and projected status of habitat for koalas.

The Koalas in the Landscape project:

- reports on the current and forecasted status of koala landscape capacity in the absence of significant new management intervention
- identifies locations that are likely to support koala persistence in the face of past habitat reduction and future climate change
- guides management to the places most beneficial for habitat protection, enhancement and restoration interventions
- employs novel modelling techniques that build on koala habitat suitability mapping described in the *Koala habitat information base technical guide* (DPIE 2019), and adds koala to the 76 NSW landscape-managed threatened species assessed in terms of landscape capacity for the Persistence in the Landscape Project
- accounts for uncertainty surrounding future climates by employing an ensemble of downscaled NSW climate projections (NARCliM 1.0) but does not attempt to forecast changes in land use, or changes in native vegetation extent.

Glossary of terms and abbreviations

Climate change: change in the climate attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is, in addition to natural climate variability, observed over comparable time periods. The Intergovernmental Panel on Climate Change definition refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change can be due to natural internal processes or external forces, or due to persistent anthropogenic changes in the composition of the atmosphere or in land use.

Climate-ready koala tree species: koala feed tree species likely to be sustainable as the climate changes when planted in physically suitable places where they do not or have never occurred, but where they could be supported under future climate, regardless of the location's past vegetation composition.

Connectivity: the degree to which the landscape facilitates animal or plant movement or spread and ecological flows.

Coupled and uncoupled models: Coupled models are produced by constraining each epoch to places that can be successfully colonised from potentially occupied areas at the proceeding epoch. Uncoupled models are not informed by the previous epoch and therefore can include predictions into areas which contain suitable habitat for supporting koalas, but which are deemed unable to be passively colonised, and will therefore most likely remain unoccupied.

Disturbance regimes: Two disturbance regimes were modelled: 'reconstructed' refers to the pre-industrial (i.e. prior to 1750) state of habitat; 'modified' reflects changes since 1750 due to habitat clearing and modification, principally for agriculture, forestry and urban development.

Enhanced stream: landscape capacity modelling stream that assumes human intervention to ensure all capable habitats are colonised with koalas and koala feed trees.

ENM: environmental niche model.

Epoch: a period of time, rather than a point in time. NARCliM 1.0 climate projections represent a 20-year window for 2 future periods centred on 2030 (near future 2020 to2039) and 2070 (far future 2060 to 2079).

GCM: global climate model.

Habitat: an area or areas occupied, or periodically or occasionally occupied, by a species, population or ecological community, including any biotic or abiotic component.

Habitat construction stream: landscape capacity modelling stream that assumes human intervention to establish climate-ready koala tree species in physically suitable places in the future, regardless of the location's past vegetation composition.

Koala feed trees: Koalas feed primarily on the leaves of *Eucalyptus* trees. Of the over 100 tree species understood to be used by koalas in NSW, experts have identified 44 inland and 31 coastal tree species ranked as either high or significant.

Landscape capacity / koala landscape capacity model (KLCM): a measure of potential occupancy based on the pattern of suitable habitat, its quality and how easily koalas can move across the landscape to access that habitat. The rapid evaluation of metapopulation persistence (REMP) methodology is used to derive the koala landscape capacity model, the end point of the process of modelling koala habitat distribution for the Koalas in the Landscape project.

Landscape: a heterogeneous area of local ecosystems and land uses that is of sufficient size to achieve long-term outcomes in the maintenance and recovery of species or ecological communities, or in the protection and enhancement of ecological and evolutionary processes.

Modelling: computational simulation of a process, concept, or the operation of a system.

Models: an abstract, usually mathematical, representation of a system, which is studied to gain understanding of the real system.

Model portrayal: each model portrayal is a single run of the landscape capacity model based on a combination of species, epoch, climate model and whether data on historic clearing or disturbance to habitat is factored into the model or not.

NARCliM: NSW and Australia Regional Climate Modelling project. See AdaptNSW's *Climate projections* webpage.

NSW: New South Wales.

Passive stream: landscape capacity modelling stream that assumes persistent landscape capacity to support koala populations without active human intervention.

Persistence in the Landscape project: the landscape-managed threatened species modelling project under the Saving our Species (SoS) program.

Pre-industrial era: The pre-industrial era (circa 1750) is used as the reference state for the maximum ecosystem diversity, and the levels of diversity are predicted using a model of biodiversity pattern that has been derived using samples of species composition from the most intact examples of ecosystems. Pre-industrial refers to the time before Indigenous land use was displaced with European farming practices. This process began in NSW after colonisation by Europeans and continued into the modern era. Also referred to as 'original'.

RCM: regional climate model.

Refugia: grid cells classified as retaining suitable climate across consecutive time periods.

Representative concentration pathways (RCPs): RCPs are prescribed pathways for greenhouse gas and aerosol concentrations, together with land-use change, that are consistent with a set of broad climate outcomes used by the climate modelling community.

REMP: rapid evaluation of metapopulation persistence. A form of 'process modelling' based on current understandings of habitat space requirements and movement abilities parameterised for individual species, and habitat quality or condition (Drielsma and Ferrier 2009).

Woody vegetation: for vegetation monitoring using Landsat multi-spectral satellite sensors, vegetation formations (mainly woodlands and forests) that are over 2 m high and with more than 20% canopy cover; also known as 'detectable native forest'.

Key messages

- The Koalas in the Landscape project collated and produced koala habitat data spanning 2000 to 2070. The project modelled and spatially mapped koala landscape capacity across New South Wales and produced estimates for total landscape capacity through this timeframe. Spatial mapping was produced that integrates climate considerations into prioritising where best to conserve and restore koala habitat in the state.
- A marked loss of landscape capacity (down by 71%) occurred from the pre-industrial era (circa 1750) to 2000, mostly due to clearing of koala habitat. In the absence of significant added conservation efforts, from 2000 to 2070 a further 16% loss from pre-industrial times is expected, due solely to projected climate change impacts (no further clearing or habitat construction considered). Spatially, the greatest forecast losses in koala landscape capacity are in lower altitude areas on the western slopes and plains where landscape capacity was high in the past but where conditions are now becoming hotter and drier.
- Opportunities for building new koala habitat are mapped. These include planting climate-ready koala feed trees in currently cleared areas and areas where such trees can grow under new climatic conditions. The project's results should prove useful in guiding adaptation responses to conserving koalas in New South Wales.
- The Koalas in the Landscape (version 1.0) project represents a significant step in a process of innovative response to the significant challenges of adaptation planning for threatened species in response to a spectrum of pressures which include climate change. Work on version 2.0 is underway. It is making use of improved koala tree modelling and will complement landscape capacity mapping with koala climate migration path mapping.

1. Introduction

This report is structured such that the first 4 sections provide a relatively brief outline of the Koalas in the Landscape project, its general methods and results, and some discussion. The appendices contain additional background information on the project, and more intermediate results.

The project assessed the capacity of inland and coastal New South Wales (NSW) landscapes to support koala (*Phascolarctos cinereus*) populations in the face of past habitat reduction and future climate change. The project identifies opportunities for management intervention to improve koala population viability.

More specifically, the project aimed to:

1. quantify and map koala landscape capacity for NSW
2. evaluate likely changes to the capacity of landscapes to support koala populations arising from climate change.

The project identifies landscape locations that can support koala persistence in the face of the combined impacts of past reductions in habitat extent, quality and connectivity; and projected impacts of climate change. The project also identifies locations where opportunities exist for management interventions that will help secure populations through to 2070.

Koala populations depend on the availability of sufficient quantities of suitable habitat and connectivity between habitats across space and time. In this project, a measure of koala landscape capacity was calculated and used to help guide management. **Landscape capacity** is a measure, or metric, of potential occupancy that integrates the habitat present locally at each geographic location, with the ability of koalas to move to and from that location to access sufficient habitat to support a viable koala population. Landscape capacity was modelled for different timeframes: the pre-industrial epoch (circa 1750), the year 2000, and was projected into future climate up to 2070.

The Koalas in the Landscape project reports on the current status of landscape capacity, forecasts future koala landscape capacity, and guides management to the best places to focus efforts for habitat protection, enhancement and restoration. Outputs from this work include:

- mapping and summary statistics of landscape capacity across space and time
- mapping of potential climate refugia that require only protection
- mapping of places where timely management intervention may lead to expanded or additional populations.

The project outputs are best used in combination with finer-grained mapping and local knowledge, and broader criteria such as the exposure of koalas to threats from vehicles and predators, and the willingness of landholders to conserve habitat for koalas. The spatial data produced from this project is also well suited to being combined with other spatial data to identify where multiple benefits can be achieved, for example, conservation of multiple species and ecosystems, and carbon sequestration.

1.1 Project context

The project extends the Persistence in the Landscape project, a Saving our Species research project examining climate adaptation of 78 of the 110 landscape-managed threatened species in NSW (Drielsma et al. in press). The koala is one of the 110 landscape-managed threatened species but is being assessed separately in the Koalas in the Landscape project rather than the Persistence in the Landscape project. The koala project not only adds koala to the list of species for which this analysis is undertaken, but it demonstrates how a higher level of detail can be considered within the Persistence in the Landscape project framework.

The Saving our Species Persistence in the Landscape project was an extension of previous research on impacts and adaptation, where vascular plant communities were used as a surrogate for biodiversity (Drielsma et al. 2015a; Drielsma et al. 2015b). These analyses integrate the shifting distributions of environmental envelopes (OEH 2016) and the ability of populations to persist and adapt to these changes, by factoring in biotic movement abilities and functional connectivity. Within both of the current projects we are extending this research to individual species. The approach is being continuously improved to meet the challenges of biological conservation in a rapidly changing climate.

The Koalas in the Landscape project extends the work undertaken for the *Koala habitat information base technical guide* (DPIE 2019) which developed the model for deriving habitat suitability based on distributions of selected koala use tree species and climate. Using these a priori relationships, we projected habitat conditions into future climates by replacing contemporary climatic co-variates within models with projected future co-variables.

A koala rapid evaluation of metapopulation persistence (REMP) model was previously developed, among a suite of 38 species, for the Western Woodlands Way project (Taylor et al. 2012; Taylor and Drielsma 2012; Taylor et al. 2016). The parameterisation from the Western Woodlands Way project provided a starting point for the new koala landscape capacity model. This new model uses a major refinement of the REMP model, more specific co-variables for the environmental niche model, an extension of the study area, and projection into future climates.

The Koalas in the Landscape project seeks to account for uncertainty surrounding future climates by employing an ensemble of alternative climate projections, but it does not attempt to forecast changes in land use, or changes in native vegetation extent. The project therefore should be viewed as providing insight into the likely consequences to koalas and conservation needs for koala populations arising from current patterns of native vegetation and current projections of climate change. The project considers how projected trends in climatic conditions are expected to affect koala distributions up to 2070, but it does not account for stochastic events such as catastrophic bushfires or droughts which can lead to a sudden step-change to habitat conditions and koala distributions. The modelling considers the effects of climate change on the distribution of koala *Eucalyptus* feed trees, but does not specifically consider interactions between koalas and other species.

Future work could further refine the project outputs by incorporating new and improved data and knowledge. Mechanistic models of tree growth across NSW would improve the prediction of where and when new habitat could become useful to koalas. The framework can be used to test alternative land-use, management and restoration scenarios.

2. Methods

2.1 Study area

The Koalas in the Landscape project study area effectively includes all koala habitat in NSW. The project was first undertaken for inland NSW. It was later extended to include the NSW coastal regions in partnership with the University of Queensland.

Modelling methods were slightly different for each of these 2 regions. Inland NSW is the area from the eastern edge of the Great Dividing Range to the limit of historical koala range in western NSW (see Figure 1). It includes the western slopes and plains, the northern, central and southern tablelands, and Riverina areas, delineated through analysis of regional koala tree species preferences (DPIE 2019; Phillips 2000). The coastal region includes all remaining areas of NSW east of the inland area to the Tasman Sea. It includes the urban areas of Lismore, Grafton, Coffs Harbour, Newcastle, Sydney and Wollongong.

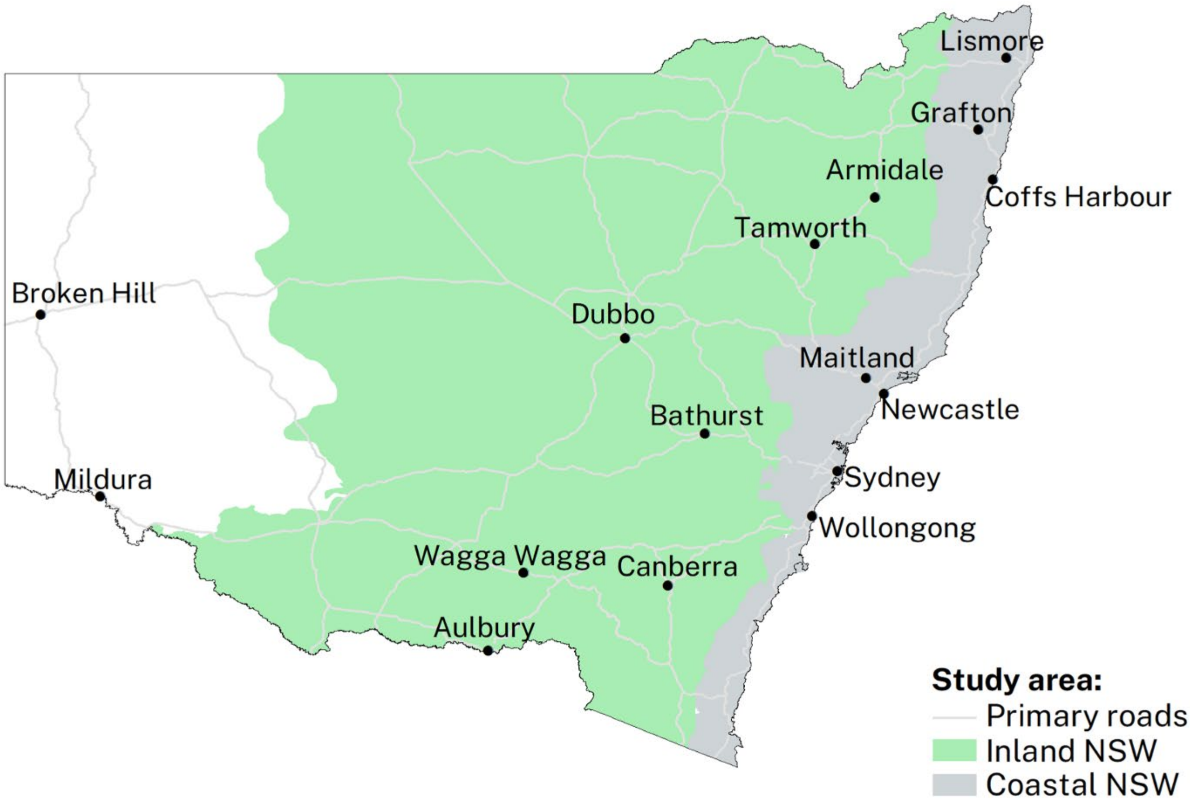


Figure 1 **Map of New South Wales showing the Koalas in the Landscape project study area**

2.2 General modelling approach

In general, the Koalas in the Landscape project methods mirror those of the Persistence in the Landscape project (Drielsma et al. in press) which examined multiple landscape-sensitive threatened species (see Figure 2 for the general approach; a more detailed workflow is provided in Appendix B, Figure 14).

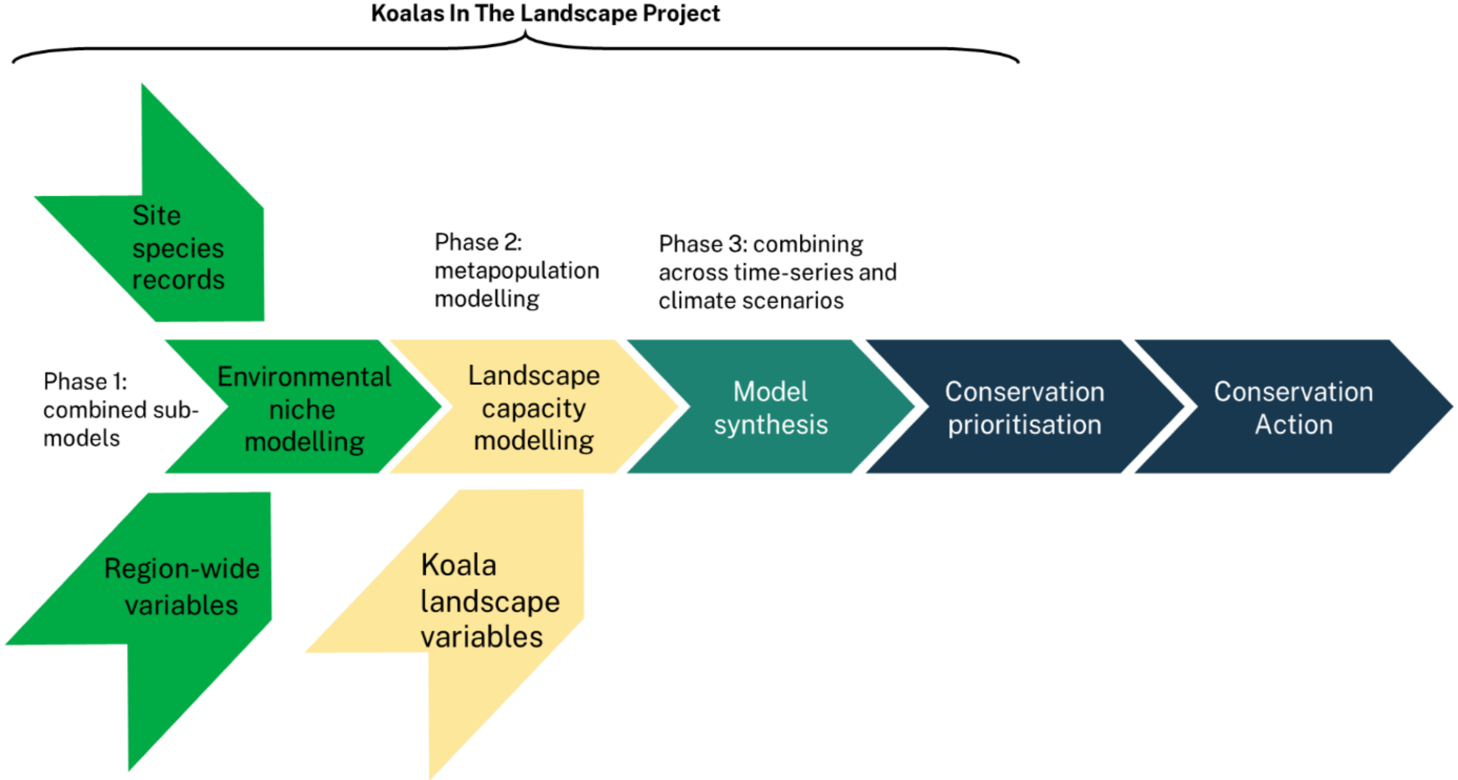


Figure 2 **General approach to landscape capacity modelling as adapted to the Koalas in the Landscape project**

The analysis comprises 3 main phases: environmental niche modelling, koala landscape capacity modelling and model synthesis. Phases 1 and 2 involve multiple calculations based on the ensemble of climate projections across a time-series.

The general method is to combine environmental niche modelling and metapopulation persistence modelling. Persistence in the Landscape project **environmental niche models** are produced from a single MaxEnt model (Phillips et al. 2006) – followed by the application of modifiers and masks – implemented in the *R* package maxnet (Phillips et al. 2017). Phase 1 of the Koalas in the Landscape project (see Section 2.4) individually modelled and then combined multiple sub-models of habitat suitability, comprising bioclimatic suitability, koala tree species distribution modelling, water availability, soil fertility and a map of woody vegetation.

As with 26 of the species modelled in the Persistence in the Landscape project, further processing (Phase 2, see Section 2.5) of the koala environmental niche model was undertaken using the REMP model (Drielsma and Love 2021; Drielsma and Ferrier 2009). The initial outputs were 90 × 90 m rasters (grids) of koala landscape capacity for the current and future epochs. **Landscape capacity** is a measure of potential occupancy based on the pattern of suitable habitat, its quality and how easily koalas can move across the landscape to access that habitat. It has a potential range of values between zero (no capacity) and one (maximum capacity). Koala landscape capacity was also summed across the study area, across past, present and future epochs, to report on and forecast NSW-wide status and trends.

A third phase of **model synthesis** (see Section 2.6) involved highlighting trends, identifying refugia and opportunities for conservation action.

Each phase and component of the project is described in the sections that follow, and more detailed, technical descriptions are provided in the appendices as follows:

- Appendix A: Projecting into future climates
- Appendix B: Phase 1 – Koala environmental niche model
- Appendix C: Phase 2 – Landscape capacity modelling (REMP)
- Appendix D: Phase 3 – Model synthesis
- Appendix E: Baseline koala environmental niche model review and validation
- Appendix F: Western Woodlands Way koala REMP model
- Appendix G: Data (describes the data package developed for publication with this report).

2.3 Model portrayals

The project developed a schema of model outputs to provide the necessary components for addressing the dual goals of evaluating koala landscape capacity through time and informing conservation actions. This involved multiple versions, or ‘portrayals’, of the model, encompassing: 12 projected climate scenarios; 2 disturbance regimes; and passive and enhanced streams of tree species occupancy (see Figure 3).

Climate scenarios comprised of:

- 4 NARCliM 1.0 (NSW and Australian Regional Climate Modelling, version 1.0) global climate models (GCMs) – CSIRO-Mk3.0, ECHAM5, MIROC3.2 and CCCMA3.1

- 3 NARCliM 1.0 regional climate models (RCMs) – R1, R2 or R3
- an 8-step decadal time-series, between 2000 and 2070.

All projections used the 2010 IPCC's SRES A2 emissions scenario (which is equivalent to the high representative concentration pathway of RCP8.5), which was clearly the pathway being most closely tracked at the time when the project was being designed. Representative concentration pathways are emissions scenarios that represent different levels of mitigation.

Two **disturbance regimes** – reconstructed and modified – were modelled. The reconstructed scenario models koala habitat in pre-industrial times (i.e. prior to 1750, see Glossary), without anthropogenic clearing or modification due to drivers such as agriculture, forestry and urbanisation. The modified scenario reflects changes since circa 1750, that is, modelled habitat in cleared areas are removed and degraded habitat is scored lower. The 2000 reconstructed scenario is used here in terms of climate to represent pre-industrial (pre-clearing) conditions on the assumption that the climate in 2000 is similar to that in 1750.

Modelling scenarios were configured into passive and enhanced **modelling streams**.

The **passive stream** identifies areas where koala populations can persist despite climate change, with no need for active intervention other than protection from clearing and other threatening processes. The passive stream considers present tree species persistence and passive migration of koala populations to new locations through time in response to future climate change. The passive stream helps to highlight where koala population viability can be maintained while range shifts occur through existing habitat connections.

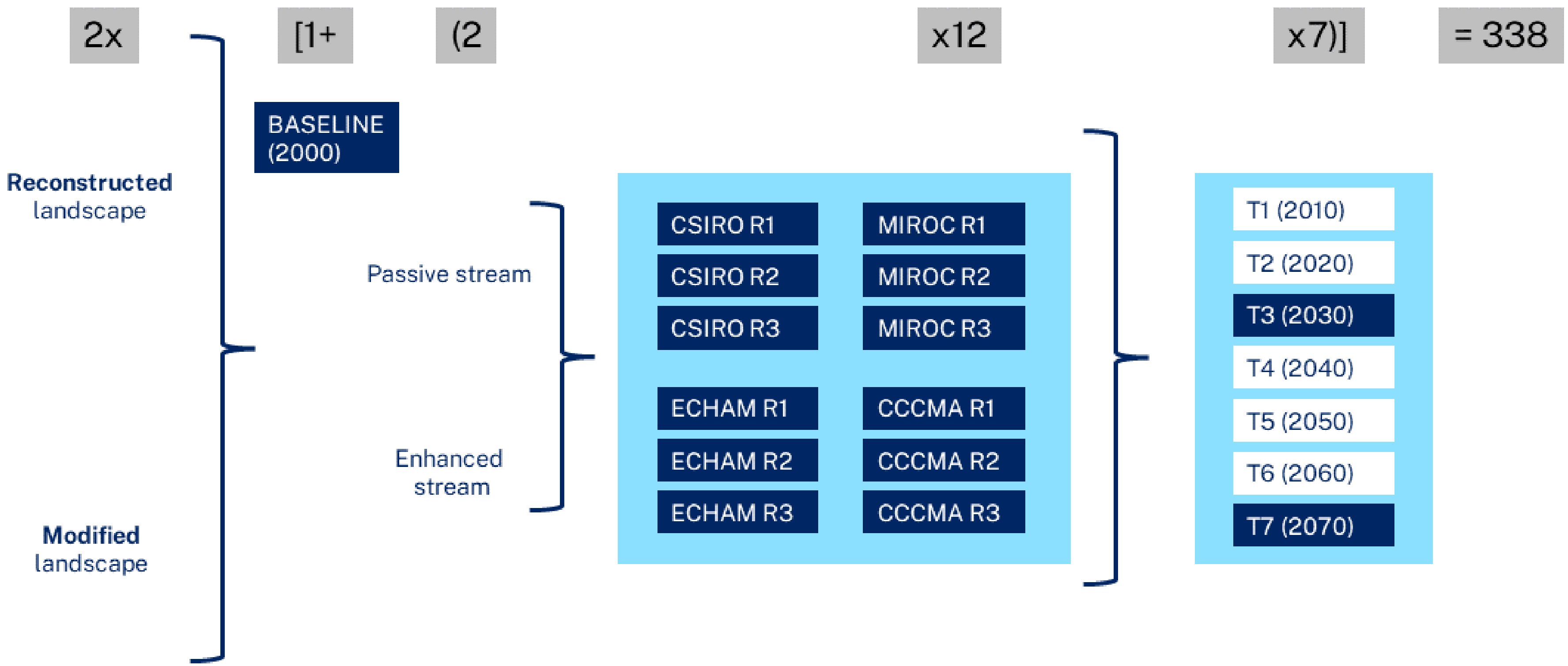


Figure 3 **Koalas in the Landscape model structure**

The entire process generates 338 model portrayals based on a reconstructed and modified landscape, and a passive and enhanced version of each of 4 global climate models (CSIRO, ECHAM, MIROC and CCCMA), 3 regional climate models (R1, R2 and R3), 7 projected epochs (T1 to T7, with T3 and T7 epochs modelled and other interpolated), and a 2000 (baseline) model.

With the passive modelling stream, only koala feed trees species distributions in 2000 are assumed able to contribute to future koala landscape capacity, as new tree species cannot be expected to passively establish and mature rapidly enough as areas become newly suitable for their growth. Conversely, as suitability for koala trees diminishes in certain locations, a reduction of koala habitat suitability is reflected in the model.

Combined spatial and temporal connectivity was considered in the passive stream by coupling the REMP modelling (see Section 2.5) across the 8 time-series. Successive coupled models after the baseline model are constrained by how unoccupied suitable habitats can be passively colonised by koalas from occupied areas in the previous time-step.

The **enhanced stream** highlights areas where management intervention can lead to substantial enhancement to landscape capacity in 2070, by introducing koala feed trees and/or by enhancing the capacity for koala populations to reach emerging habitats. In some cases this could involve introducing koala feed tree species to places where they do not or have never occurred, but where they could be supported under future climate (referred to as 'climate-ready koala tree species').

With the enhanced stream the REMP time-series modelling is uncoupled. Uncoupled models are not informed by the previous time-step. Uncoupled models are useful in identifying areas that have potential to support koalas, including emerging habitats where connectivity to a source population is limiting and where active management, including building habitat connectivity or assisted migration, can facilitate expanded populations of koalas.

See Appendix A for further details.

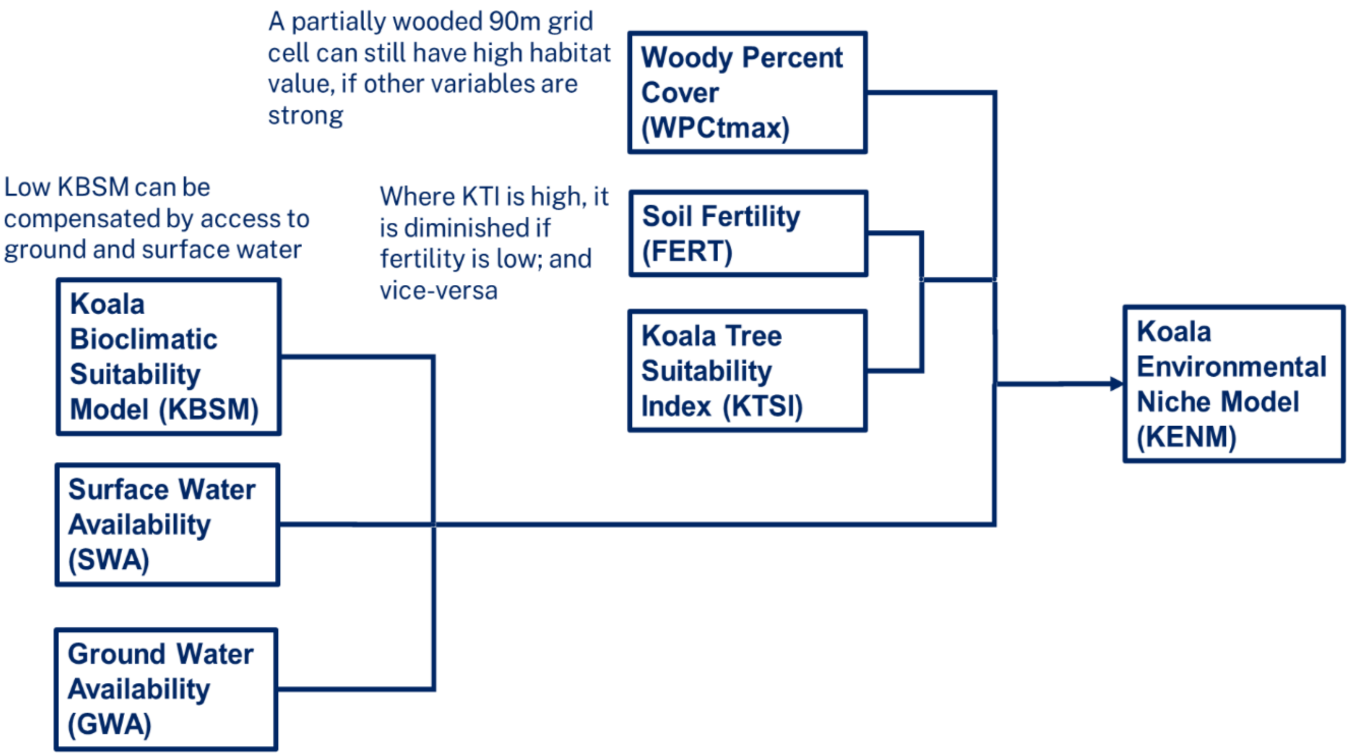
2.4 Phase 1 – koala environmental niche model

Initially, a baseline koala environmental niche model relevant to pre–climate change conditions was developed, centred on the year 2000. The koala environmental niche model (see Appendix B) synthesised sub-models of:

- koala bioclimatic suitability model
- koala tree species suitability index (DPIE 2019; Phillips 2000)
- ground water and surface water availability
- soil fertility.

Habitat suitability was also masked to the woody class of a woody/non-woody layer (see Figure 4). The koala environmental niche model formula (Figure 4) was refined following review by koala experts (see Appendix E). The coastal region did not include water availability or soil fertility, which were considered significant drivers only in the inland region. The koala bioclimatic and tree species suitability models were then projected into the 12 future climate scenarios using NSW climate modelling (NARCliM 1.0) (Evans et al. 2014) (see Appendix A), to epochs centred on 2030 and 2070. A decadal time-series from 2000 to 2070 was derived through interpolation between 2000 and 2030, and 2030 and 2070.

(a) Inland model



(b) Coastal model

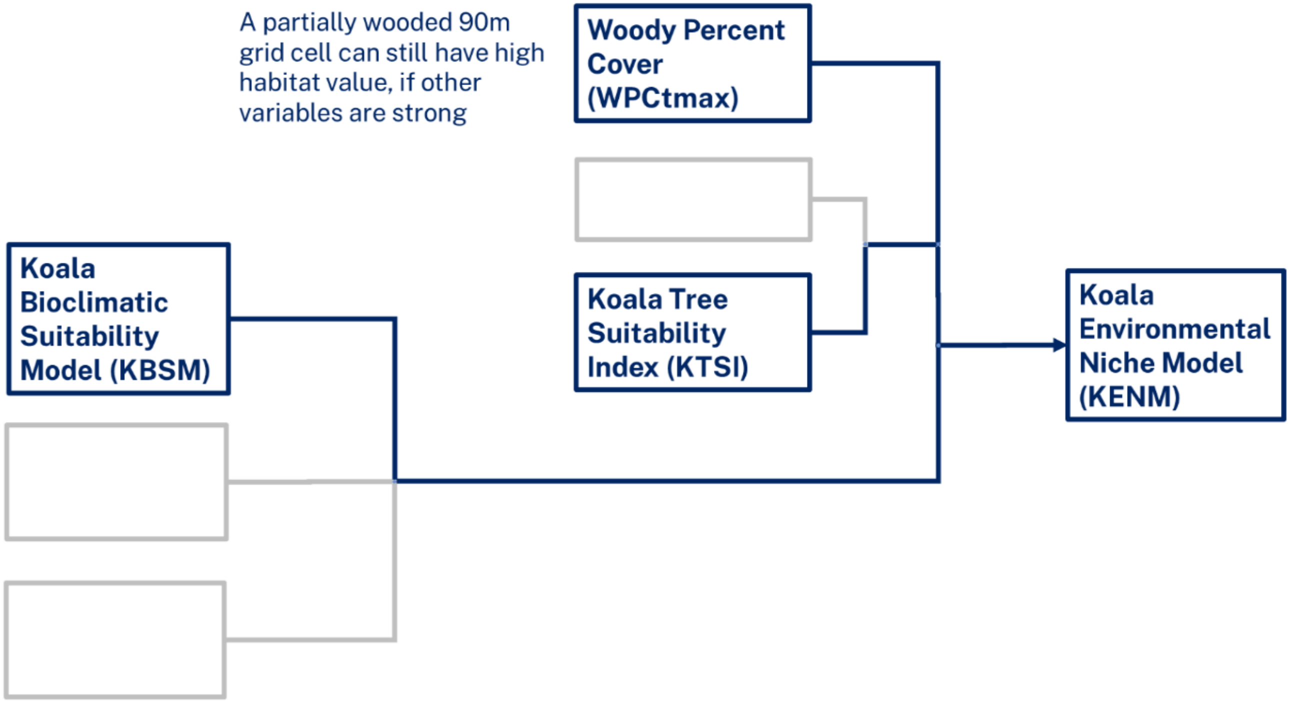


Figure 4 **General workflow for producing a single portrayal of the koala environmental niche model (KENM): (a) inland region model; and (b) coastal region model**

The workflow is repeated for each portrayal by replacing baseline climatic variables with projected variables for the koala bioclimatic suitability model and koala tree suitability index models.

The formulae used to combine the sub-models is shown in Appendix B.

2.5 Phase 2 – landscape capacity modelling

Phase 2 of the project assessed koala landscape capacity at each time-step of each scenario (see Appendix C). This was undertaken by applying metapopulation dynamic modelling to the koala environmental niche models using the rapid evaluation of metapopulation persistence (REMP) model (Drielsma and Love 2021; Drielsma and Ferrier 2009). The REMP model considers the amount and spatial arrangement of habitat in relation to koala population habitat requirements, and individual movement abilities.

Koala landscape characteristics were needed as input to the REMP model, comprising minimum viable area to support a population, and movement abilities through woody and non-woody vegetation. A koala REMP model was previously developed for the Western Woodlands Way project (Taylor et al. 2016; see Appendix F). The parameterisation from that project provided a starting point for the new koala landscape capacity model. Those parameters were further revised by expert elicitation and are presented in Table 1. Koala landscape characteristics were aimed at representing female koalas as the distribution of less-mobile females is considered a limiting factor to koala population persistence. For detail of Phase 2 methods see Appendix C.

Table 1 Koala landscape characteristics used in the rapid evaluation of metapopulation persistence (REMP) model (inland and coast)

Landscape parameter	Value
Minimum viable habitat area	5,000 hectares
Minimum home range movement ability	1 metre
Maximum home range movement ability	1,000 metres
Minimum dispersal movement ability	1 metre
Maximum dispersal movement ability	50,000 metres

2.6 Phase 3 – model synthesis

The following sections describe the mapping products produced through the Koalas in the Landscape project model synthesis. For detail of Phase 3 methods see Appendix D.

2.6.1 Landscape capacity consensus map

A map of model consensus for the passive 2070 stream was generated to show areas of relatively high landscape capacity, while accounting for differences across the GCMs. Model consensus was calculated as the number of GCMs that lead to landscape capacity in 2070 above a given threshold.

For input, the analysis used the 4 passive 2070 landscape capacity grids (see Section 2.2), one for each GCM (averaged across the 3 RCMs). Model consensus was calculated by setting a landscape capacity threshold of 0.25 for the 4 inputs. Iterating through these, at each step the output grid cell for any given location was incremented by one if the input grid value fell above the 0.25 threshold for that location. As this process was completed across 4 inputs, if all 4 inputs fell above the threshold for a grid cell, the result was 4.

2.6.2 Koala conservation options map

The implications of the Koalas in the Landscape project for management were summarised in a single koala conservation options map. The conservation options map synthesises opportunities for management to secure or minimise loss of landscape capacity, and to enhance koala populations into the future, using the Phase 2 outputs.

The koala conservation options map (see Section 3 Results, Figure 10) is a composite image where each of 3 component surfaces relevant to climate-ready koala management is assigned to 3 colour bands in the output image. These are described below, and in Appendix D.

MS01 – Koala landscape capacity

Koala landscape capacity highlights areas capable of supporting koala populations in 2070 based on the passive model.

MS05 – Latent capacity

Latent capacity is the potential to support koala populations in 2070 based on the enhanced model. Latent capacity is calculated as the difference in landscape capacity between the 2070 passive (MS01) and enhanced streams.

MS06 – Habitat construction benefits

Habitat construction benefits is the potential to construct new koala habitat with climate-ready koala feed trees, which connect to other areas with viable koala landscape capacity in 2070 (MS01).

Once the 3 components were combined into the composite map, 4 key management options became apparent on the map. These are named and coloured as follows:

- conserve and enhance – chartreuse (yellow-green)
- connect and enhance – cyan (bright blue)
- construct – magenta
- enhance – blue (see Appendix D for more detail).

A continuous range of colours are possible due to how the components overlap. For example, green is mostly a combination indicating relatively high landscape capacity circa 2070, but which could also be further enhanced with the planting of koala tree species. Each of the 3 main individual components and a range of other lower-level components can also be used for various purposes, for example, to combine with other spatial layers, such as carbon sequestration potential, for prioritisation.

The key management options and the underlying methods are described below, and are further described in Section 3.3 and Appendix D.

Conserve and enhance (chartreuse)

'Conserve and enhance' areas are characterised by high koala landscape capacity (MS01) in 2070. In practice there are little or no conserve-only areas in the study area (i.e. yellow on the map) because the most suitable areas can generally still benefit from some enhancement. For example, if eucalypts currently occupying an area are becoming less suitable with climate change, koalas would benefit from introducing other eucalypt species (dependent on local dietary preferences, see Appendix B). Thus, there are substantial areas coloured chartreuse on the conservation options map which are therefore termed 'conserve' and 'enhance'.

Connect and enhance (cyan)

'Connect and enhance' includes areas where additional landscape capacity can be achieved by 2070 through active management by overcoming impediments to koalas accessing these areas. Management could include enhancement with climate-ready koala feed tree species, improving connectivity and/or assisted relocation of individuals. 'Connect and enhance' comprises areas that typically have low landscape capacity but have moderate levels of latent capacity (MS05) and construction benefits (MS06).

Construct (magenta)

'Construct' includes areas where koala occupancy is possible by 2070, if those areas were fully restored with koala feed and habitat trees. 'Habitat construction' involves the establishment of climate-ready koala tree species, belonging to the *Eucalyptus* genus, in places that are expected to remain or become suitable for these plant species by 2070, but in which trees are predominantly not present now. Construct areas are expected to be otherwise suitable for koala survival in 2070, including being sufficiently connected to viable populations in 2070 (i.e. connected to MS01 areas).

Habitat construction P_i is based on the following assumptions:

- Each location is fully restored to a climate-ready state, that is, koala tree species suitable to that site in 2070 are established (based on the 2070 enhanced stream model).
- Currently cleared areas as well as currently vegetated areas are considered. In the latter case new tree species are prospectively introduced, as required.
- Connectivity of each location is considered in relation to the passively viable habitat network in 2070. Connecting to the passively viable network enables the location to be occupied in 2070 once climate-ready (enhanced-stream) habitat construction occurs.

Enhance (blue)

'Enhance' includes areas where there is low koala landscape capacity by 2070 (MS01), but latent capacity (MS05) is high and the area is well-enough connected to viable areas

(MS01) to allow colonisation. Suitable climate-ready koala feed trees need to be introduced.

Unsuitable (white)

Unsuitable areas have zero to very low existing or potential landscape capacity across all components, that is, they have low MS01, low MS05 and low MS06.

3. Results

Results from Phase 3 of the project include evaluation of past and current status, projected trends, and spatial products. These were derived by combining Phase 2 scenario outputs in different ways.

3.1 Evaluation of status and trends in koala landscape capacity

The general evaluation results (averaged across climate projections) for landscape capacity across time are provided in Table 2 and Figure 5. These results were obtained by summing P_i across the study area at each epoch (averaged across the climate projections). Figure 5 shows how much koala landscape capacity can be conserved by protecting existing areas of suitable native vegetation across the study area, and what gain (or averted loss) in koala landscape capacity can be achieved through enhancing existing native vegetation or replanting cleared areas with koala feed trees. Figure 6 is a map of hindcasted and forecasted koala landscape capacity from 1750 to 2070. Figure 7, the degree of expected change map, shows expected change in koala landscape capacity between 2000 and 2070.

Results show a marked loss of habitat from the pre-industrial era (circa 1750) to 2000, due mostly to clearing of suitable native vegetation. From 2000 forward, forecasted change is due solely to projected climate change impacts on koala landscape capacity (no further clearing or habitat construction is considered). Spatially, the greatest forecast losses in koala landscape capacity are in areas where there was high capacity in the past but where conditions are expected to become increasingly hotter and drier, often at lower altitudes on the western slopes and plains. Koala landscape capacity is forecast to increase slightly in some parts of the Cobar Peneplains Bioregion in the north-west of the study area. This is due to the influence of the 'wetter' climate projections (MIROC3.2 and CCCMA3.1). The majority of the western part of the study area, within the historic range of the koala and where little or no koala landscape capacity currently exists, is forecast to experience no change and to remain unable to support koala populations into the future.

Table 2 **Summed koala landscape capacity (millions of hectares) through time, including passive, enhanced, and habitat construction modelling stream components**

	Pre-industrial 10^6 ha (% of pre-industrial)	2000 10^6 ha (% of pre-industrial)	2030 10^6 ha (% of pre-industrial)	2070 10^6 ha (% of pre-industrial)
Passive	31.44 (100)	9.04 (29)	5.67 (18)	4.12 (13)
Enhanced	–	–	10.72 (39)	9.02 (33)
Habitat construction	–	–	–	17.06 (58)

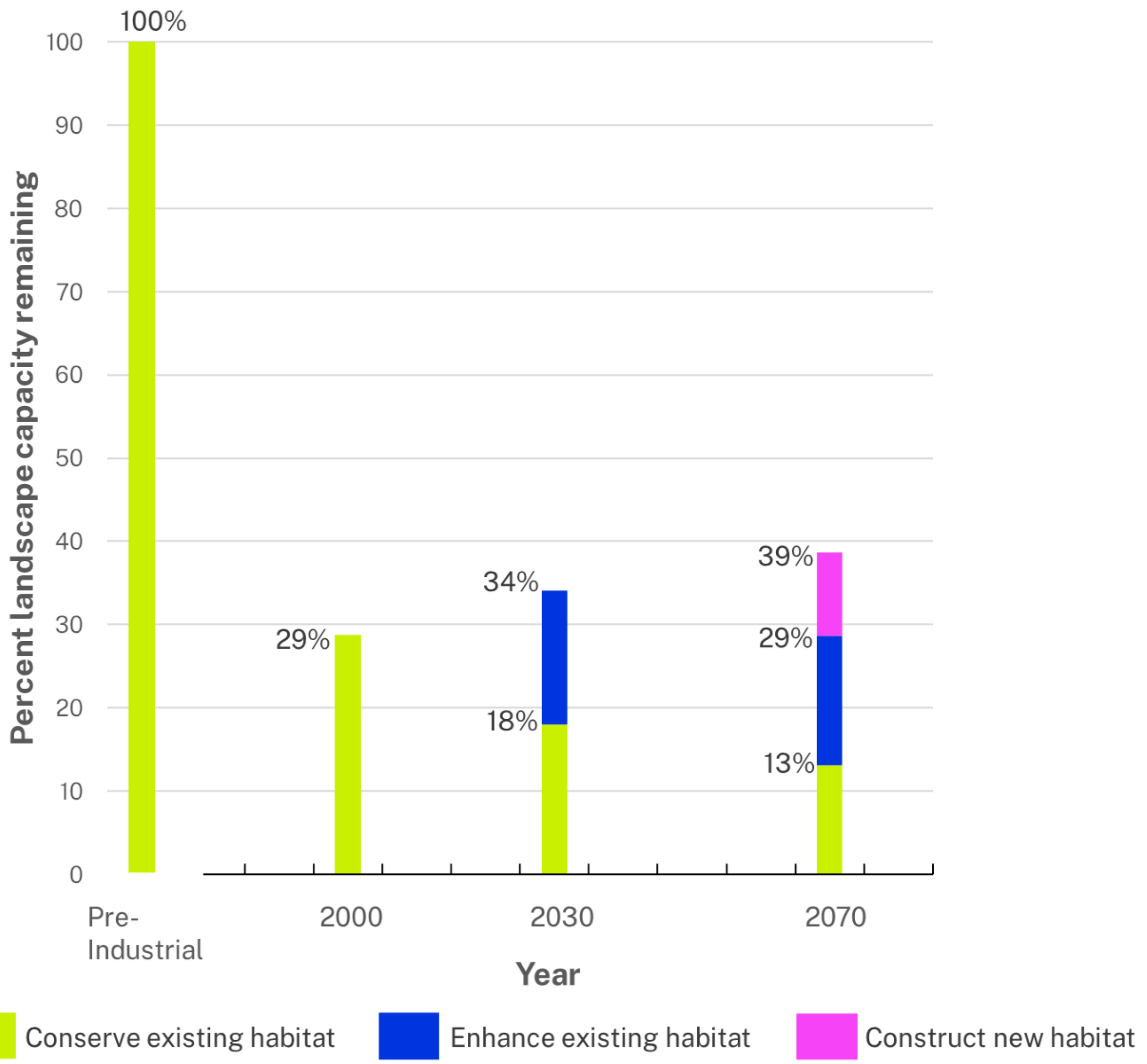


Figure 5 **Summed koala landscape capacity through time**

The chart shows the full potential for koala habitat: through enhancing habitat by 2030 and 2070; and through the construction of new habitat by 2070.

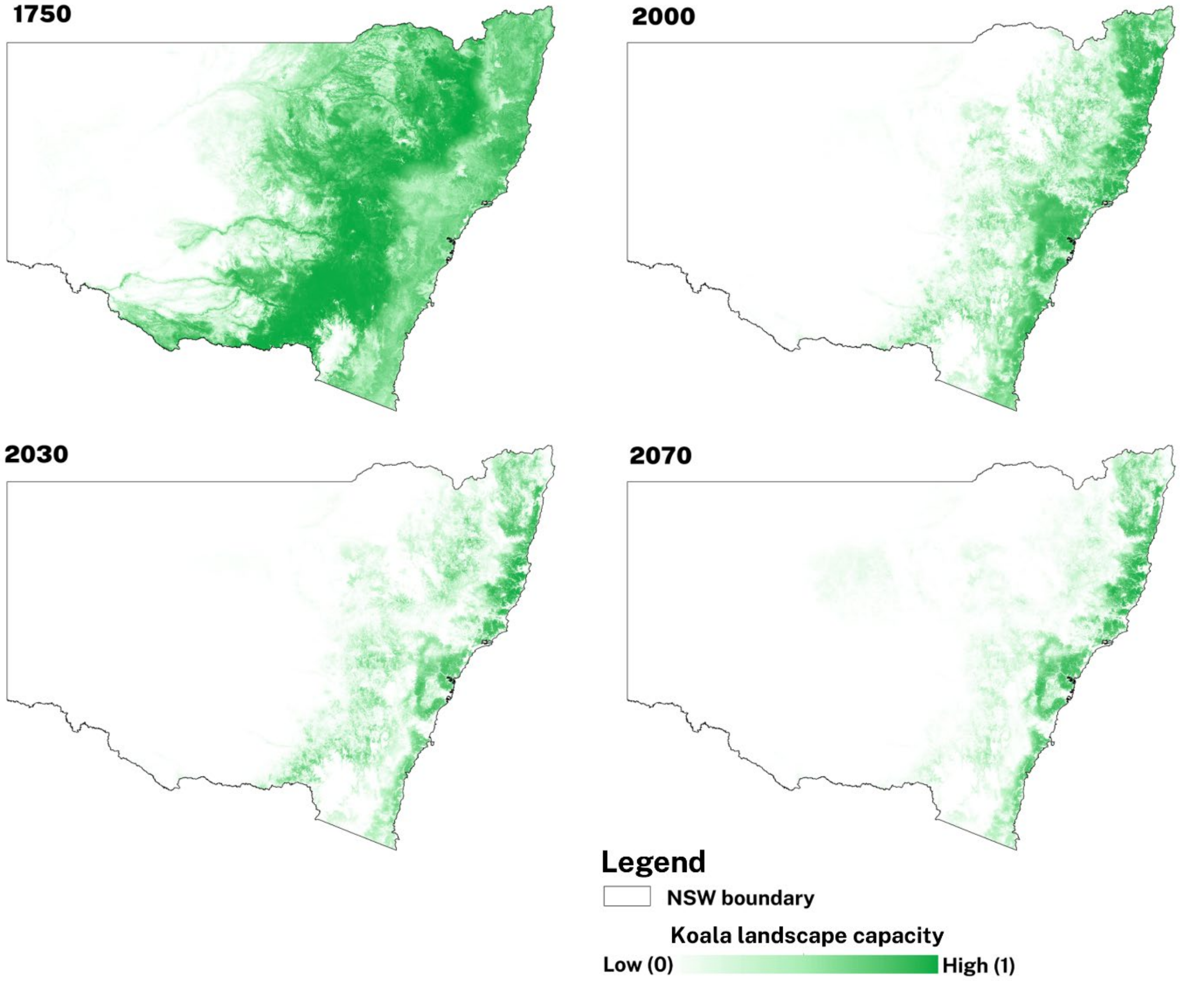


Figure 6 Maps of koala landscape capacity through time based on the passive modelling stream. Pre-industrial (top-left), 2000 (top-right), 2030 (bottom-left), and 2070 (bottom-right)

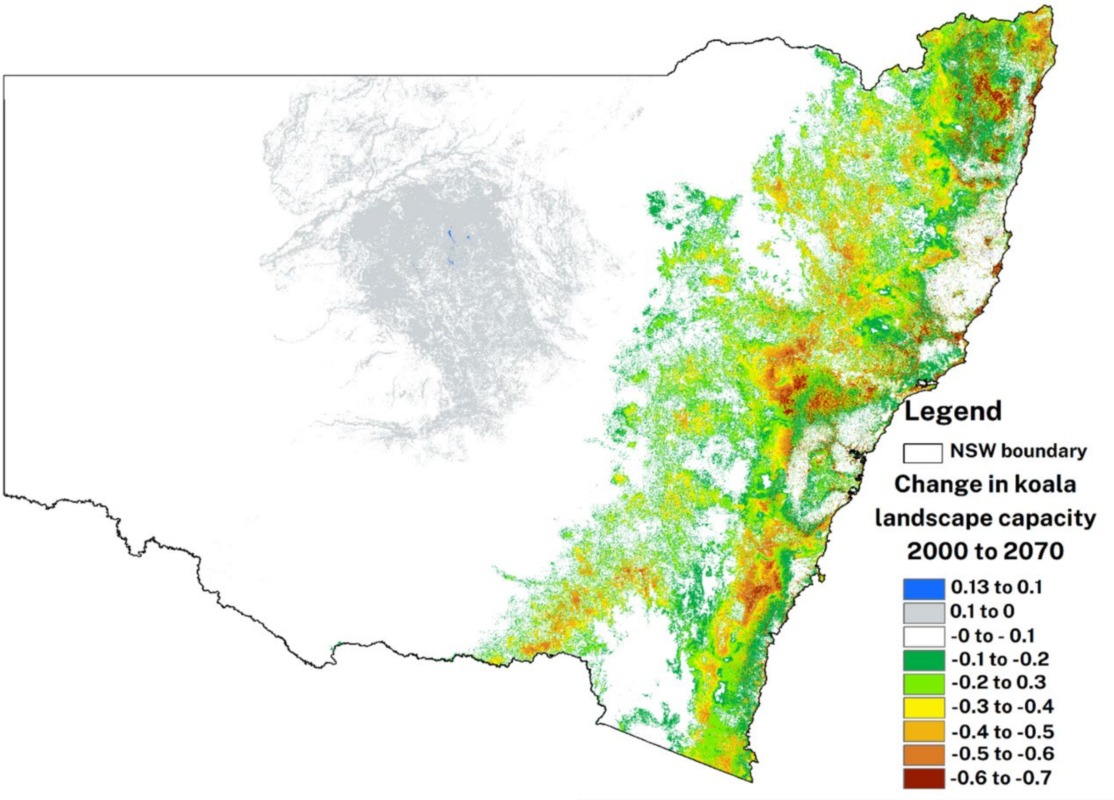


Figure 7 **Projected change in koala landscape capacity 2000 to 2070. Increase (blue and grey), stability (white) and reduction (green to red). Data is averaged across projections, based on the passive stream. Range of possible values is between −1.0 and +1.0.**

3.2 Model consensus map

The koala landscape capacity consensus map is presented in Figure 8. Areas with high values in this map indicate places with relatively high forecasted koala landscape capacity in 2070 regardless of the climate scenario used, and can therefore be considered to be comparatively low-risk in terms of investing in conservation. In order to discriminate across the study area, the threshold was set quite low at 0.25 (full range of model outputs is zero to one). When thresholds above 0.25 were tested, they yielded little consensus because locations with values above 0.25 become increasingly scarce by 2070. This reflects the fact that passive landscape capacity is generally in decline across the study area, and therefore yields relatively few locations where koala landscape capacity is high across the GCMs by 2070. This output does not consider additional places that could become suitable for koalas by 2070 through management intervention. The reversed scores (that is 4 – grid value) also equates to the number of models that agree that future landscape capacity will be below the threshold.

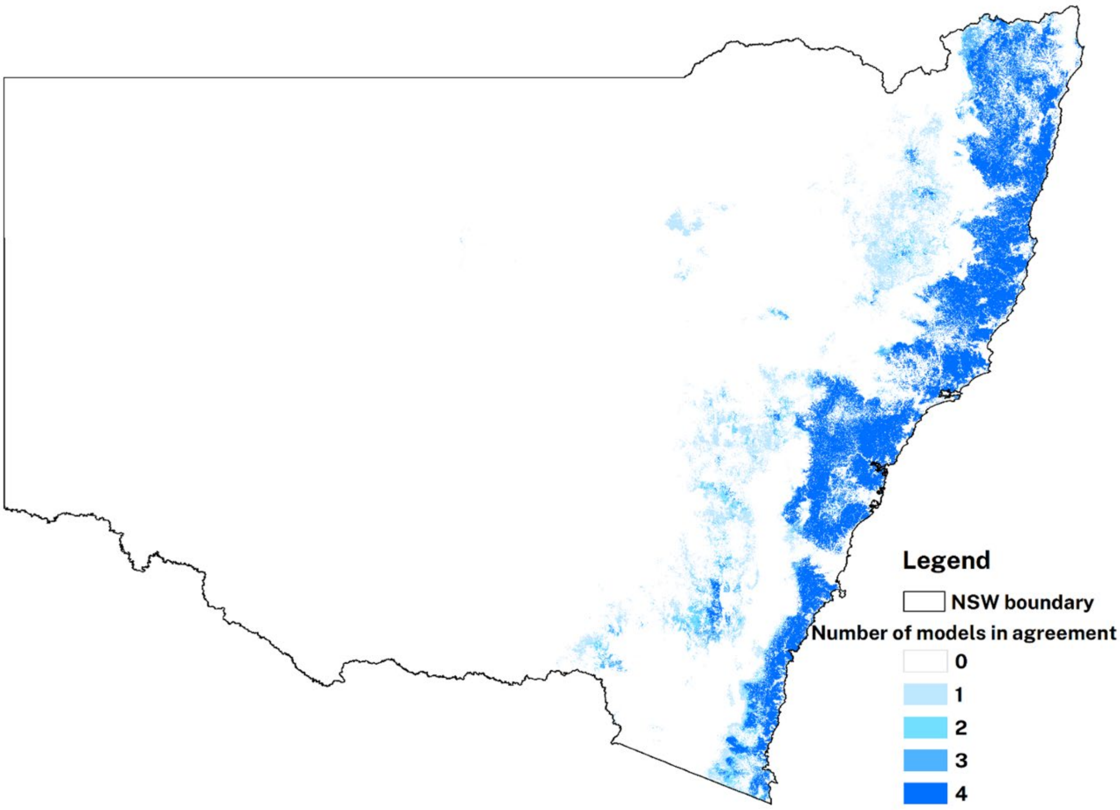


Figure 8 **2070 consensus map for passive distribution in 2070. Colours represent the number of global climate model scenarios that lead to landscape capacity above the 0.25 threshold**

3.3 Koala conservation options map

The koala conservation options map identifies place-specific landscape management actions that are most relevant to promoting koala landscape capacity. Four key management zones emerged from this analysis (comprising major areas on the map). These include both one-to-one matches with the component bands of the map (Appendix D, MS07), as well as combinations of the component bands. The 4 key management options apparent on the map are:

- **Conserve and enhance** (chartreuse) – are areas with relatively high landscape capacity in 2070. To be useful for koala populations they mostly require protection from threats, but koala landscape capacity in these areas can also benefit from further enhancement with climate-ready koala feed trees.
- **Connect and enhance** (cyan) – are suitable areas that are not well connected to projected koala populations. To be useful for koala populations they would require reconnecting, or the translocation of populations of koalas into them; and they require the establishment of climate-ready koala feed trees.

- **Construct** (magenta) – are areas suitable and connected to projected koala populations but are projected to be largely devoid of koala trees.
- **Enhance** (blue) – are suitable areas that are connected to projected koala populations but require enhancement with climate-ready koala feed trees.

Unsuitable areas are areas identified as having no potential to provide koala landscape capacity by 2070 (white areas on the map).

The 4 key management options are conceptually illustrated in Figure 9, with increased intervention required from left to right. The koala conservation options map is shown in Figure 10.

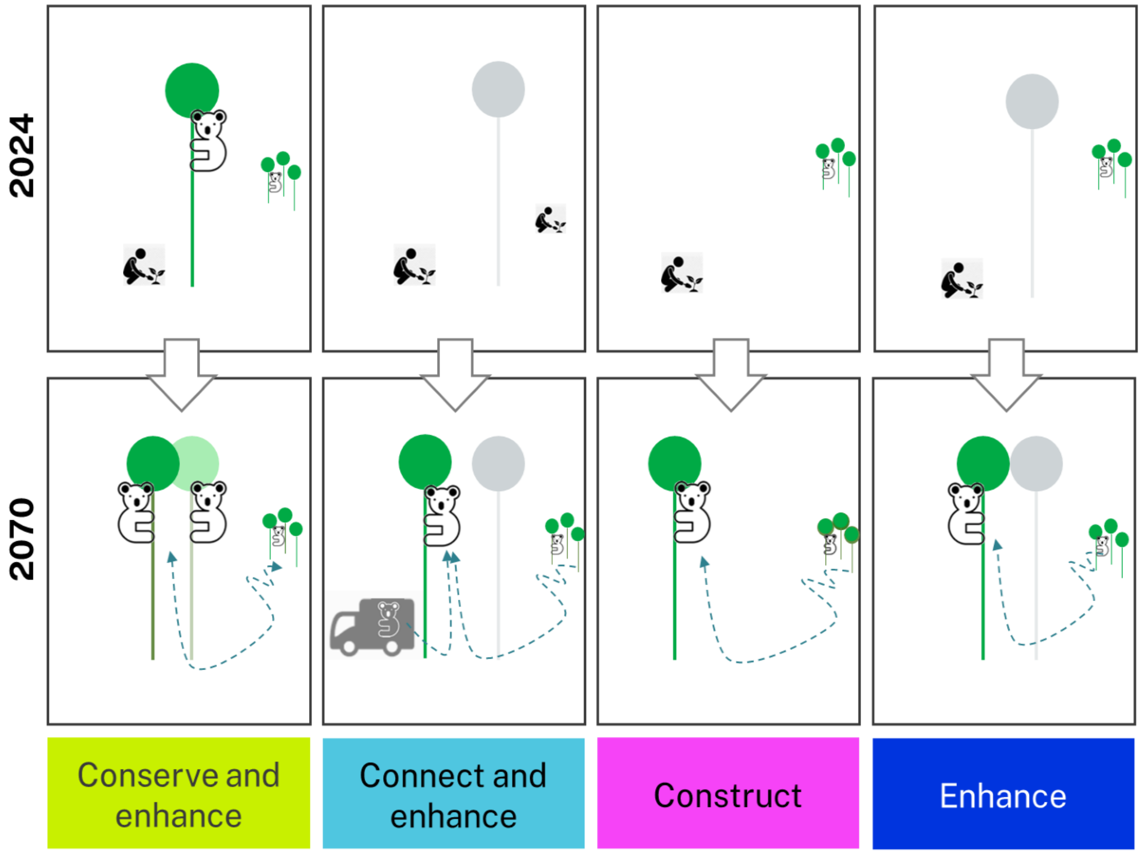


Figure 9 **Key management options in the conservation options map**

Map colours are as indicated in the label boxes at the base of the figure. In the boxes, the larger foreground picture on the left represents the site of interest; the smaller background picture on the right represents functionally connected neighbourhood. Dark green tree symbols represent the most suitable at the epoch specified at the left of each row, light green trees are less suitable and grey trees are unsuitable. Dashed lines indicate modes of migration and assisted migration (via the van). Changes in the site of interest and neighbourhood through time are indicated between the box in the top row (now, 2023) and the box below it (2070). Trees can become less suitable, planted trees can mature into suitable trees, and new connections in the neighbourhood can be established.

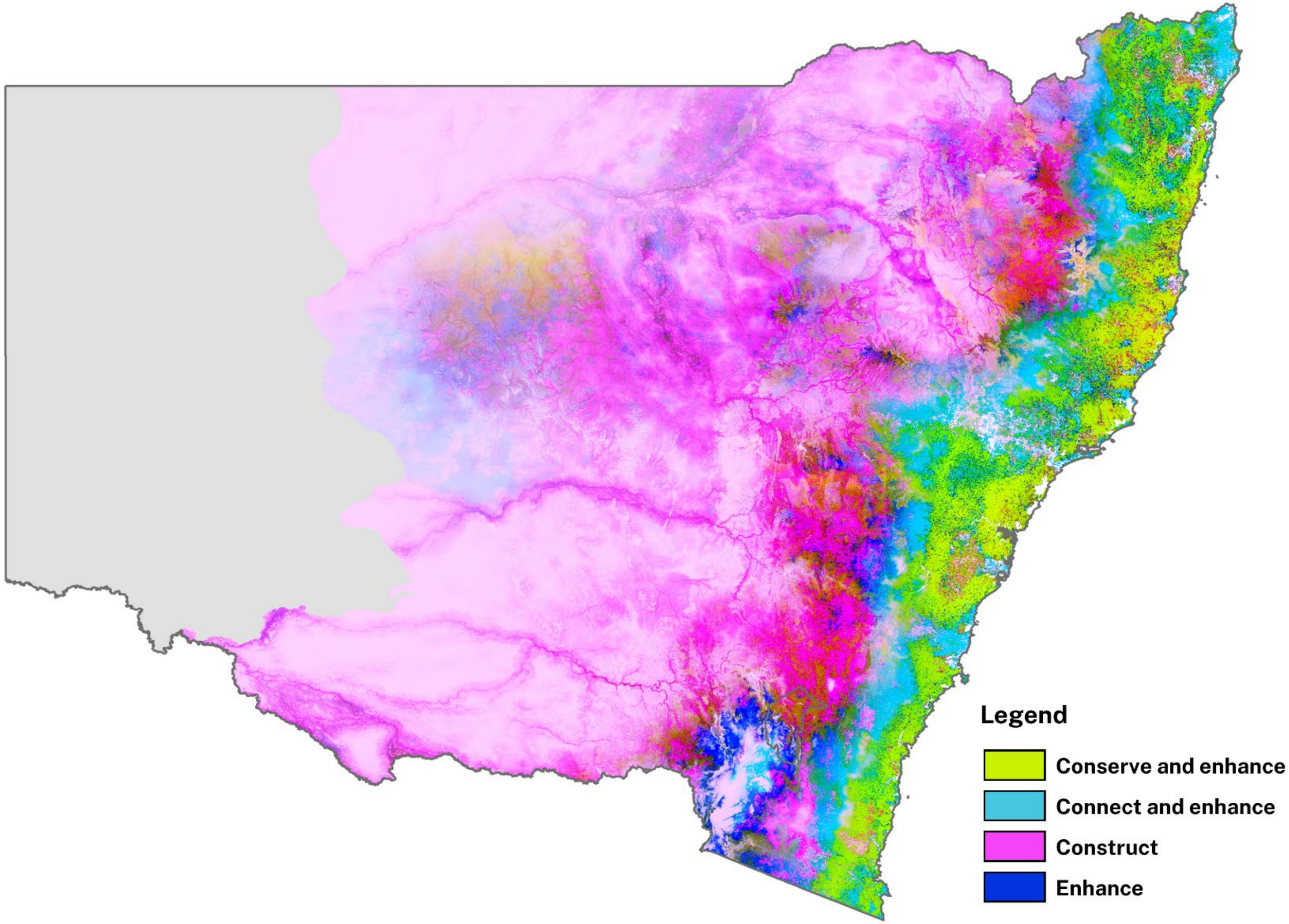


Figure 10 **Conservation options map for koalas in New South Wales**

4. Discussion

The results show a marked loss of koala landscape capacity from the pre-industrial era due to clearing, particularly across inland NSW. From 2000 forward, additional projected loss is due solely to climate change (no further clearing or habitat construction is considered). The project identifies the potential, overall and spatially, for improving the future prospects for koala populations.

4.1 Model accuracy and usability

Any model of koala occupancy projected into future climates carries a high degree of uncertainty, so we seek to be transparent about the limitations of the model and therefore what the findings of this study can confidently be used for. This document presents the factors included into the Koalas in the Landscape model. Other potentially significant factors are not, and often cannot be, included into the workings of the model.

The findings are suitable for informing landscape habitat protection, enhancement and restoration (or ‘habitat construction’ – defined by this project as the establishment of climate-ready koala tree species in physically suitable places in the future regardless of past species distributions/vegetation composition). However, the findings are best used, especially for the purpose of planning species recovery, in conjunction with finer-grained information on threats, local habitat conditions, and opportunities for action.

The modelling undertaken within this project is sophisticated in comparison to many alternatives, however, it remains simplistic in contrast to the real-world complexities of species-habitat-climate interactions. Although significant effort was applied to validate and refine the model, it remains imperfect and must be used carefully and wherever possible in combination with other sources of knowledge. It is also limited in terms of being a deterministic approach to population dynamics which does not account for stochastic events that are known to have historically shaped the distributions of species and ecosystems and will continue to do so. Each model from this project is fit for the intended purpose of providing a koala-centric lens for viewing NSW landscapes. The project does not aspire to provide definitive predictions of koala distributions, especially into the future.

Specific limitations of this project include:

- **Water availability** (used in the inland model only) was kept constant at the 2000 baseline level. It was not possible within the limitations of this study to project changes in water accessibility into future climate scenarios. Within the study area, climate models disagree on the direction precipitation is trending.
- **Resolution** – The species distribution models and all further analyses were limited to a maximum spatial resolution of 90 × 90 m grid cells. Although this can be considered ‘high resolution’ in terms of a NSW-scale analysis, it is too coarse to fully account for fine-grained habitat interactions which respond to habitat features, such as individual trees, small creeks and other water bodies.

- **Environmental niche models** – These models were developed using a limited, common set of environmental predictor surfaces. We cannot be sure that we have used all the appropriate drivers to accurately predict suitable koala habitat.
- **Rapid evaluation of metapopulation persistence model** – The REMP model is an idealised perspective on population dynamics that does not consider all the complicated aspects of day-to-day movements and dispersal. The analytical basis of the REMP model has been progressively improved through the course of recent Saving our Species projects. At this time the REMP model has been comprehensively reviewed, including the explicit use of species home ranges for the first time (Drielsma and Love 2021). REMP does not consider other drivers, including interspecific competition, predation, disease, direct human interference (e.g. road kills), or stochastic events such as fire and storms.
- **Climate projections** – Climate projections will improve or be replaced over time as monitoring refines parameters. The modelling framework developed in this project can be re-used with new climate projections. New NARCliM projections are currently being developed.
- **Aggregated products** – Aggregating the models used in this project in various ways could produce many potential products. The Phase 3 products are examples aimed at guiding current management options. Future decisions may require alternative aggregations or additional products to provide guidance.
- **Data inputs** – Although validated and compiled from a variety of recognised sources, the data is spatially and temporally biased. This is true for the response data used to build the model.

The Koalas in the Landscape project modelling can be improved in the following ways:

1. Validate with field data, or determine if additional field data is required to improve the models.
2. Develop more sophisticated methods, for example, develop better modelling variables that more specifically address koala habitat preferences.
3. Improve the tree modelling, for example by accounting for lag effects and regeneration. Compare the performance of mechanistic flora modelling to correlative models.
4. Re-run Koalas in the Landscape models using new climate projections when they become available.
5. Re-run environmental niche models using latest, best-practice approaches and data.

Appendix A: Projecting into future climates

The project developed a schema of model outputs, that could provide flexibility to derive a range of primary (landscape capacity) and secondary products (benefits surfaces), for use in informing conservation actions (see Figure 3 in Section 2.3). We refer to each instance within this schema as a 'model portrayal'. Each portrayal is a single run of the landscape capacity model based on a combination of the following:

- 4 global climate models (GCMs) – CSIRO-Mk3.0, ECHAM5, MIROC3.2 and CCCMA3.1 (see 'NARCliM climate projections' section below)
- 3 regional climate models (RCMs) – R1, R2 or R3
- 7 decadal epochs (from 2010 to 2070) with a baseline of 2000
- 2 disturbance regimes (reconstructed and modified)
- 2 time-series coupling options (coupling on or off).

Seven decadal epochs, or time-steps, were interpolated between the 2000 baseline and the 2030 and 2070 projections provided from the NARCliM 1.0 (NSW and Australia Regional Climate Modelling, version 1.0) project (Evans and Ji 2012a; Evans et al. 2014). Modelling was undertaken for 2 disturbance regimes: 'reconstructed', where all original habitat is assumed intact and at optimal ecological condition; and 'modified', where the contemporary current pattern of vegetation clearing and modification tempers the habitat value at each location along a range from pristine (unmodified) to cleared (habitat total removed) (Gibbons and Freudenberger 2006; Love et al. 2020; Tehrany et al. 2017; Zerger et al. 2006).

Coupled models are produced by constraining each epoch to places that can be successfully colonised from potentially occupied areas at the proceeding epoch. This leads to a more realistic distribution of landscape capacity, highlighting areas which have sufficient habitat connectivity from one epoch to the next. Uncoupled models are not informed by the previous epoch and therefore can include predictions into areas which contain suitable habitat for supporting koalas, but which are deemed unable to be passively colonised, and will therefore most likely remain unoccupied.

The 2 main model streams (passive and enhanced) are described in Figure 3.

For the Phase 3 analysis, the large number of projections/time-steps/streams were managed by successively averaging to a smaller number of management-focused outputs, by combining P_i outputs using the schema in Figure 11. The 3 RCM outputs were averaged for each GCM (9 models – 4 outputs per future epoch plus baseline); and globally (5 models – 2 per epoch plus baseline).

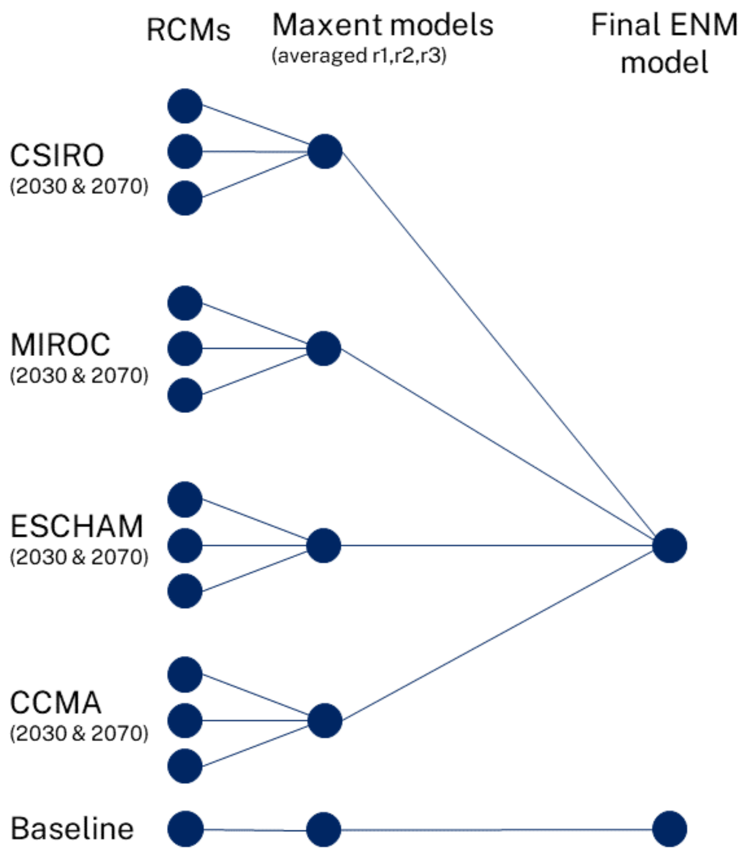


Figure 11 **Schema for averaging P_i outputs for the synthesis phase**

The rapid evaluation of metapopulation persistence (REMP) model is run using the koala environmental niche model (KENM) for the 12 climate projections, then averaged into landscape capacity outputs for the baseline and for the 2030 and 2070 epochs. Other decades are interpolated between these.

Models were run across 2 main streams – 'passive' and 'enhanced'. These were combined to derive a third stream, termed 'habitat construction'. These streams are described below and Figure 12 illustrates these concepts in relation to 5 hypothetical patches of habitat:

- **Transition a ⇨ a**: The habitat remains suitable from 2000 to 2070. Stream is passive; action is conserve.
- **Transition a ⇨ b**: New habitat can appear by 2070 within the currently suitable area that extant populations can reach. Stream is passive; action is conserve.
- **Transition a ⇨ c**: As for transition a ⇨ b, but extant populations cannot reach patch c unaided. Stream is enhanced; action is to build connectivity or assisted migration.
- **Transition a ⇨ d**: Koalas can reach new habitat. Although the area is suitable for koala trees to grow, none are there in 2000. Stream is enhanced; action is to modify vegetation composition by 2070.

- **Transition a ⇨ e (or a ⇨ b ⇨ e)**: Koalas can reach suitable area from current population, but the area is currently not woody vegetation. Stream is habitat construction; action is establishing suitable trees by 2070.

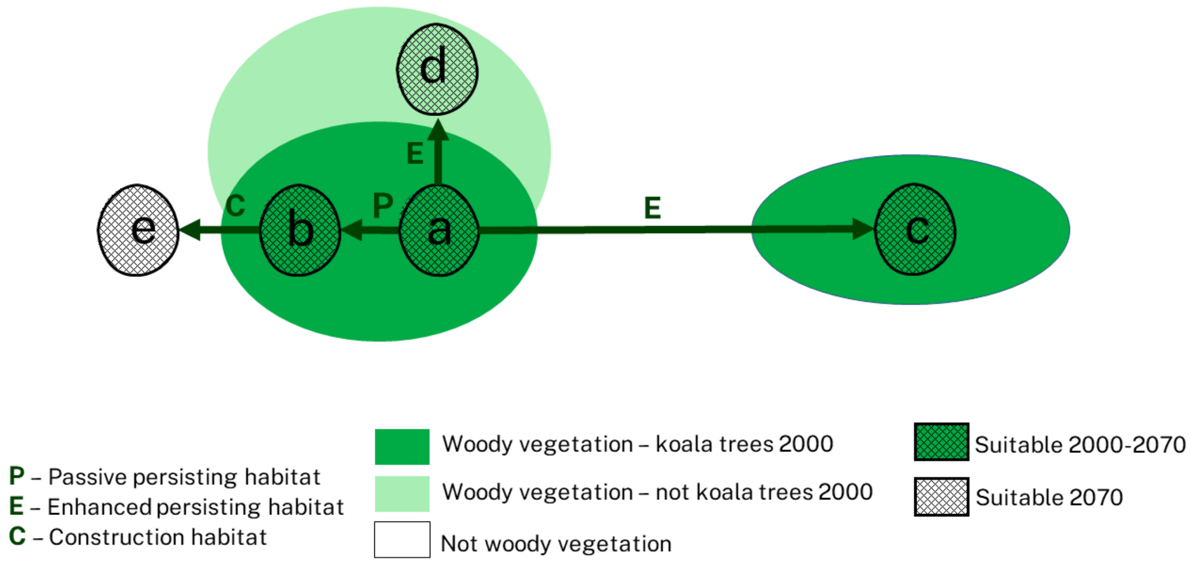


Figure 12 **Conceptual diagram of the 3 streams: passive, enhanced and habitat construction**

Figure 12 is a simplification. Nuanced versions of these transitions occur on-ground. For example, habitat construction can further enhance patch 'b' by providing more climate-ready tree species than those forecast to persist.

Model streams

Passive stream

This stream identifies areas where koala populations can persist through climate change with no active intervention other than conserving the native vegetation already present.

The 'passive' stream is built using the following 2 criteria.

- Using the modified koala tree suitability index (KTSI, Appendix B) only koala resource trees present at the baseline epoch can contribute to landscape capacity in the future, but modelling allows these trees to decline if climate change makes locations unsuited for the tree species in the future. Tree resources established into emerging ecological niches are not included.
- Using the 'coupled' REMP model, only areas that koalas (through their own movement abilities) can reach and establish viable populations are included.

Enhanced stream

This stream identifies areas where koala populations can persist subject to climate change, but only if enough climate-ready koala tree species are added to the existing vegetation. It also shows where assisted migration of koalas would be needed to allow koalas to populate emerging habitats.

The 'enhanced' stream is built using the following 2 criteria:

- Using potential KTSI where koala resource trees which **could** grow in an area at a given epoch contribute to the modelling. This includes trees established through planting into emerging ecological niches. Only uncleared areas of native vegetation at the baseline epoch are included (i.e. fully cleared areas require additional effort to transition to koala habitat).
- Based on the 'uncoupled' REMP model (see Figure 3 in Section 2.3). Landscape capacity of emerging habitats does not rely on functional connectivity from areas of landscape capacity in the previous epoch. Therefore, these are areas that could support koala populations, but it would require enhanced connectivity and/or assisted migration.

Habitat construction stream

The 'habitat construction' stream provides guidance on where intervention can lead to viable populations by establishing koala tree species to build connectivity that leads to passively stable koala populations in the future. All parts of the study area, including those currently cleared of native vegetation, are assessed in terms of their suitability for habitat construction.

The habitat construction stream uses a 2070 uncleared, enhanced scenario, to find places suitable for habitat construction. These areas are evaluated in terms of meeting future environmental conditions and being functionally connected to places capable of supporting viable populations in 2070 (see Appendix D).

NARCliM 1.0 climate projections

NARCliM downscaled 4 GCMs (Evans and Ji 2012a) based on a single socio-economic scenario, SRES A2 (equivalent to representative concentration pathway 8.5), using 3 RCMs (Evans and Ji 2012b). RCMs were based on the Weather Research and Forecast (Skamarock 2008) model with 3 different physics schemes applied (R1, R2 and R3). The 4 GCMs – MIROC3.2, ECHAM5, CCCMA3.1 and CSIRO-Mk3.0 – were chosen for the NARCliM project to capture the full range of uncertainty within the Coupled Model Intercomparison Project's Phase 3 GCMs, while also providing the most independent set of climate scenarios that spanned the largest range of plausible future climates. The 3 RCMs were used to dynamically downscale each of the 4 GCMs separately, resulting in 12 equally plausible future climate scenarios.

The 4 GCMs each represented a different climate trajectory of either warmer or hotter and wetter or drier future conditions (Figure 13). The increase in temperature from the 2000 centred baseline to the 2070 centred projections ranges approximately from 1.9°C under CSIRO-MK3.0 to 2.8°C under ECHAM5. The change in precipitation ranges approximately from a 12% decrease under CSIRO-MK3.0 to a 14% increase under MIROC. This range of projected climate futures allowed the NARCliM scenarios to span all likely future conditions rather than attempting to predict a single most likely climate outcome, which at the time was expected to fall somewhere within these trajectories.

A full set of ANUCLIM and MTHCLIM climate variables (Hutchinson and Xu 2015) were developed at a 0.0025 (~250 m) resolution for the 2000 centred baseline and each future climate scenario centred on 2030 and 2070. The 2000 centred baseline variables were derived from observed Bureau of Meteorology monthly mean climate data from 1990 to 2009. Projected variables were based on each of the NARCliM climate scenarios for 2020 to 2039 for the 2030 centred 'near future' and 2060 to 2079 for the 2070 centred 'far future'.

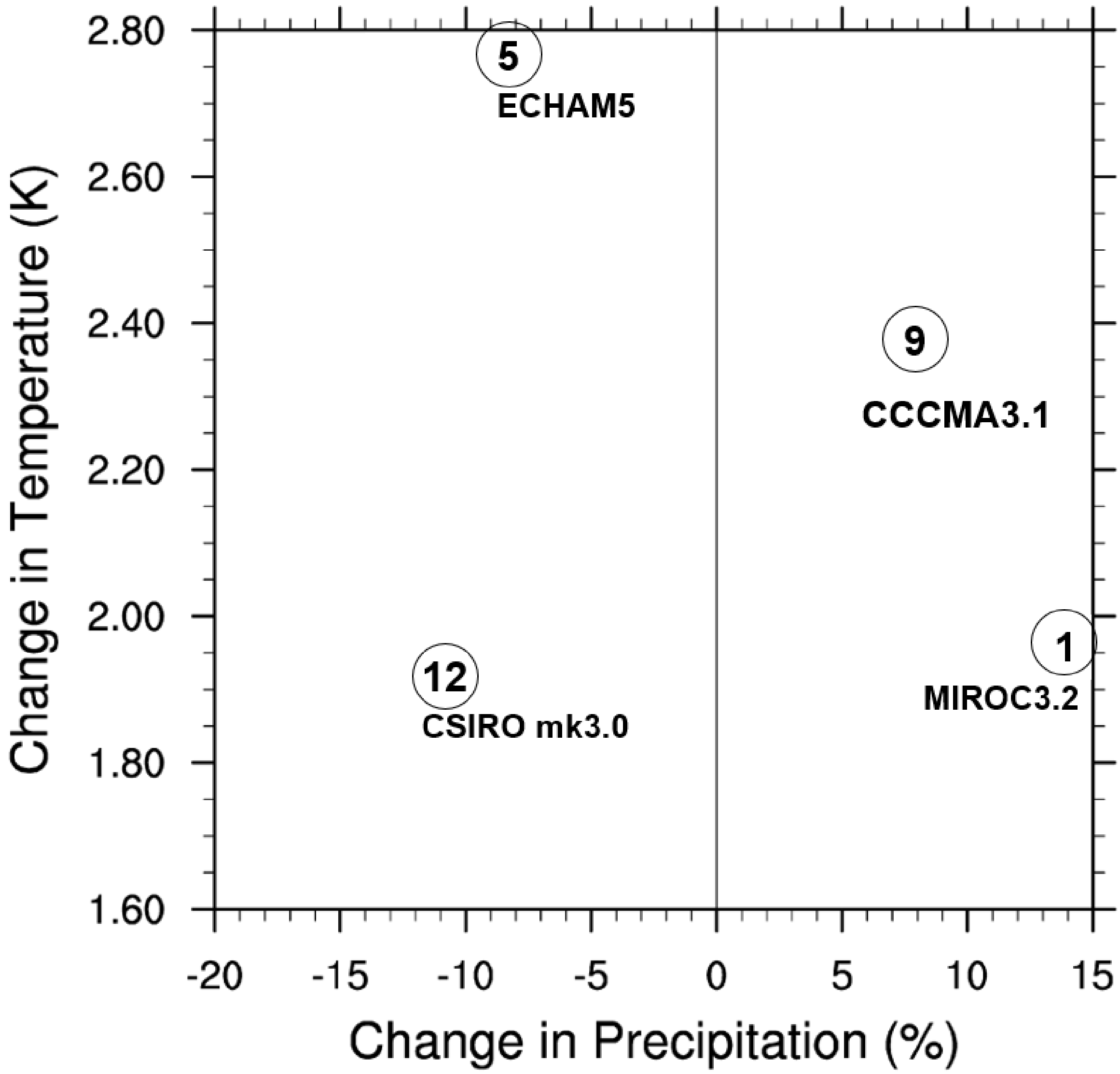


Figure 13 **The climate trajectories of the 4 global climate models (GCMs) downscaled under NARCliM showing their model independence rankings (numerical values) and the far future (2070 centred) projected climate change space they cover relative to the 2000 centred baseline (adapted from: Evans and Ji 2012a)**

By 2070, the MIROC scenarios project a warmer, wetter future climate while ECHAM5 projects a hotter, drier future. CCCMA projects a hotter, wetter future and CSIRO-MK3.0 a warmer, drier future climate.

The AdaptNSW website (see link in 'More information' section) provides further information about the NARCliM climate scenarios and how the models were selected and downscaled.

Appendix B: Phase 1 – Koala environmental niche model

Environmental niche models

Environmental niche models (ENMs) estimate habitat suitability for a species across a region, based on the assumption that the environmental tolerances and preferences of the species are described by the location of current populations (Franklin 2010). ENMs are useful tools for exploring the distribution of **suitable habitat**. They do not predict the actual distribution of a species but identify the location of suitable habitat (with respect to the environmental variables used).

Once established using a real-world scenario, ENMs can be applied to alternative scenarios to assess the suitability of a region under altered environmental conditions. ENMs are an important input to dynamic models of populations such as rapid evaluation of metapopulation persistence (REMP) models, which extend an ENM to indicate areas where **populations** can persist.

There are numerous reasons why a region may be predicted to have high suitability in an ENM for a species but there is no documented population. For example, it may be because:

- dispersal limitations prevent the species from occupying the location
- additional variables influencing the distribution of the species, such as those related to competition or resources, may be absent from the model
- populations may have been extirpated before records were obtained
- sampling in that location could be inadequate
- model resolution or fitting may be sub-optimal.

ENMs fall into 2 broad categories: those that use both presence (P) and absence (A) of the target species (PA models) and those that require presences only (PO models). Repeated comparisons of algorithms have failed to identify a single 'best' approach, although generally PA models have higher predictive performance (Elith et al. 2006). We used both a PA model and a PO model. Using both types of ENM allowed us to refine the baseline ENM, maximising its quality by using robust model performance criteria.

We used boosted regression trees (BRT, also referred to as gradient boosting machine, GBM) to produce a PA model to model the distribution of koala food trees. It incorporates regression trees and 'boosting', combining numerous simple models to improve predictive power (Elith et al. 2008). To produce the PO ENM we used MaxEnt software, known for high performance (Elith et al. 2006). It contrasts presences with a random sample of locations from within the study area (Syfert et al. 2013). We projected the baseline ENM into future climates and used these as inputs to the REMP modelling which models landscape capacity (Appendix C).

ENMs are largely a product of the field data – they report on the relationship between biophysical variables and historic observations. A REMP model is a downstream product of this that seeks to model the time-lagged outcome of population dynamics. REMP modelling attempts to factor in the long-term outlook to help guide management decisions. A species may be recorded in an area, but that area is not necessarily capable of supporting a population in the longer term. In some cases, extinction debt is yet to be paid (Jackson and Sax 2009).

Koala environmental niche model

The koala environmental niche model (KENM) combines a suite of sub-models that included statistical and expert-based models, using Equation 2 for the inland region of the study area and Equation 3 for the coastal region. The coastal model components were combined using a simple geometric mean. The main components of the KENM model are listed in Table 3. Figure 14 illustrates how the components were combined for the inland model (see Figure 4 in Section 2.4 for the coastal model). Each of the sub-models are described in sections below. The KENMs for inland and coastal regions were kept separate. The inland and coastal landscape capacity models were joined at the end of phase 2 (see Section 2.5).

Equation 1 Formula for calculating koala environmental niche model for the inland region

$$KENM = WPCtMax$$
$$\times$$
$$\{KTSI + [FERT \times (1.0 - KTSI) \times (1.0 - (1.0 - KTSI)^2)]\}$$
$$\times$$
$$\left[KBSM + \left(GWA \times SWA \times (1.0 - KBSM)\right)\right]$$

Equation 2 Formula for calculating koala environmental niche model for the coastal region

$$KENM = (WPCtMax \text{ x } KTSI \text{ x } KBSM)^{1/3}$$

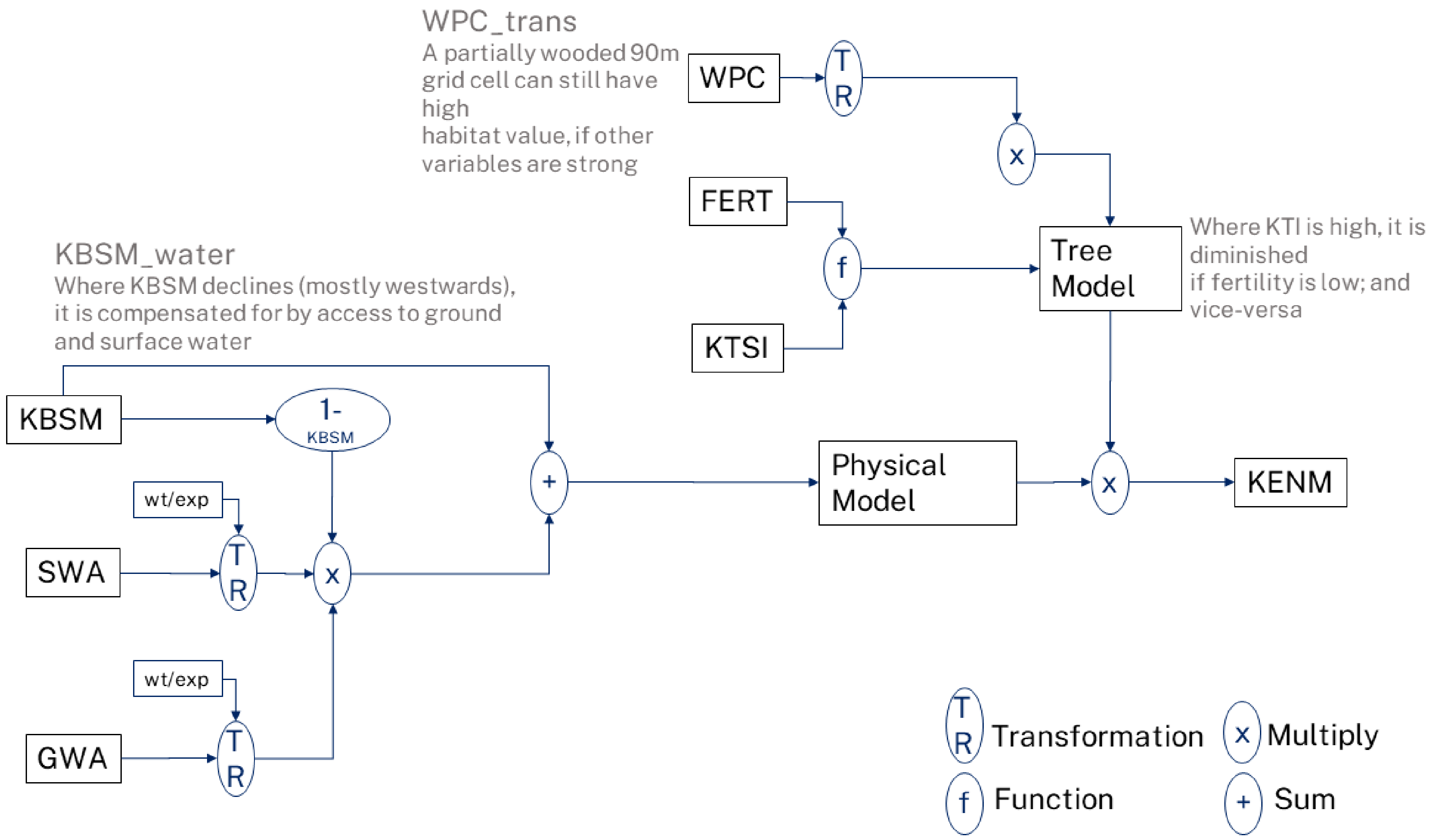


Figure notes: See Table 3 for description of abbreviations.

Figure 14 Detailed workflow for producing a single portrayal of the koala environmental niche model for the inland region

The workflow is repeated for each portrayal by replacing baseline climatic variables with projected variables for the koala bioclimatic suitability model and koala tree species index models

Table 3 Components of the koala environmental niche model (data sources are provided in Appendix G)

Abbreviation	Model/Sub-model	Description	Climate response	Model
KENM	Koala environmental niche model	A MaxEnt environmental niche model (ENM) that represents the distribution of suitable habitat; used as input to the REMP model	Projected to 2030 and 2070	Inland & coastal
KBSM	Koala bioclimatic suitability model	A boosted regression tree ENM of the distribution of suitable locations considering koala physiological tolerances to climate	Projected to 2030 and 2070	Inland & coastal
KTSI	Koala tree species index	An expert-based index of tree suitability – distribution of suitable tree species. Two versions derived: passive (stable) and enhanced (potential)	Projected to 2030 and 2070 (see section on 'passive' and 'enhanced' streams)	Inland & coastal
SWA	Surface water availability	An expert-based index of surface water availability	Kept constant	Inland
GWA	Ground water availability	An expert-based green accumulation index as a surrogate for ground water availability.	Kept constant	Inland
FERT	Soil fertility	A 4-class classification of parent material: • mafic (high fertility) • intermediate (mod-high fertility) • siliceous lower (mod-low fertility) • siliceous upper (very low fertility soils). These classes were applied to the KENM as weights of 1.0, 0.8, −0.2, and −0.4, respectively.	Kept constant	Inland

Abbreviation	Model/Sub-model	Description	Climate response	Model
WPCtMax	Woody percent cover	The percent of woody vegetation per pixel is calculated as the percentage of 5 m source pixels within each 90 m destination pixel that is mapped as having woody extent	Kept constant	Inland & coastal

Sub-models used to create the koala environmental niche model

Koala bioclimatic suitability model

The koala bioclimatic suitability model (KBSM), is an ENM developed using MaxEnt, with procedures similar to the previous koala environmental niche model developed for the Koala Habitat Information Base, which is available on the SEED data portal. The KBSM for the Koalas in the Landscape project was fitted using koala occurrences from the Atlas of Living Australia within the area of interest, as well as occurrences along the east coast from areas above 500 m elevation (see section below). The model predictor surfaces (covariates) are:

- maximum temperature
- annual precipitation
- soil pH
- soil organic carbon
- available water capacity.

The KBSM was developed for the baseline year, 2000, using recent and historical records, then projected to 2030 and 2070 by replacing baseline climatic predictors with projected climatic predictors. The model predicts bioclimatic suitability of habitat within the study area, based on the above 5 covariates. The suitability is expressed along a scale from zero to one (low to high suitability). It is shown in Figure 15.

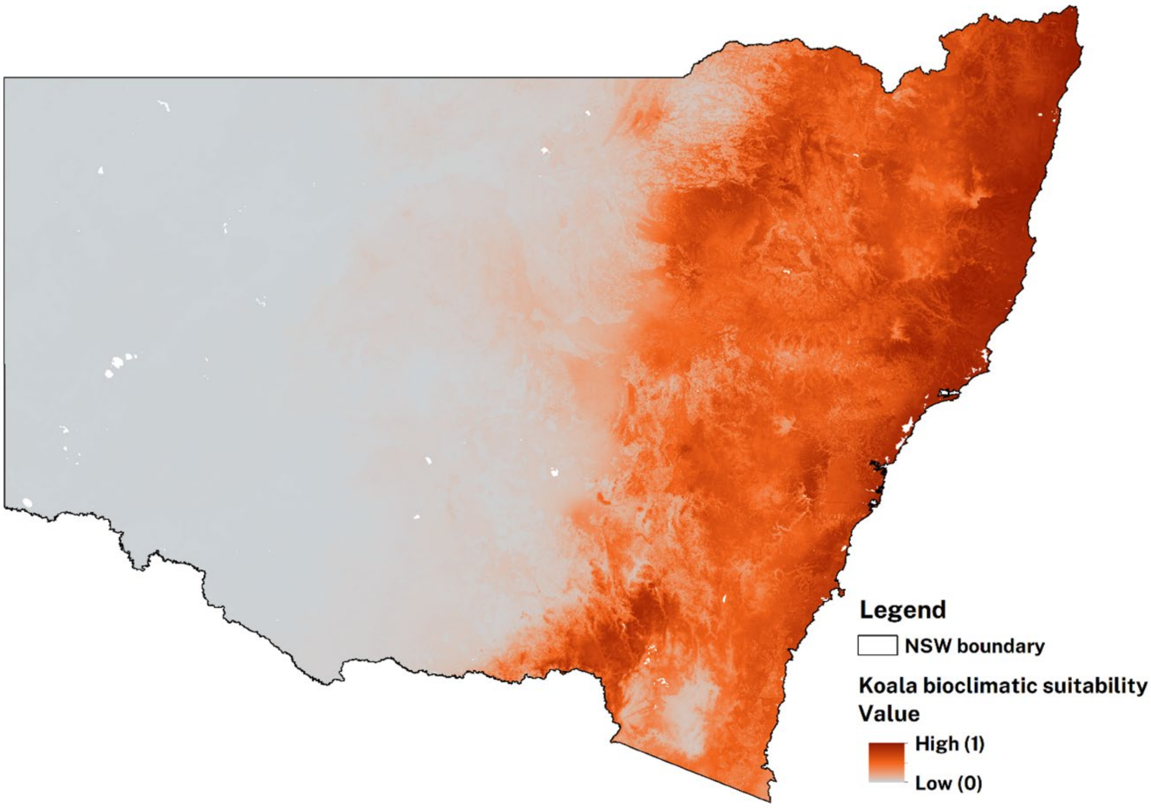


Figure 15 **Koala bioclimatic suitability model (2000 baseline model)**

Koala bioclimatic suitability model occurrence data

Due to physiological differences between inland and coastal koalas, we restricted occurrences to those within the study area (with a 5 km buffer) and those at elevations above 500 m (outside the study area but environmentally similar and well-connected to the highly cleared New England Tablelands). The occurrence data was cleaned and verified, as part of the development of the Koala Habitat Information Base. Occurrences were thinned to different spatial extents for the Koala Habitat Information Base, with SF6 (i.e. to 0.064 degrees) resulting in the most accurate habitat suitability models. For consistency, we retained occurrences filtered to SF6.

Background points

MaxEnt requires information on the available environment across the study area, which are referred to as 'background points'. Background points were extracted from forested areas in the same IBRA (Interim Biogeographic Regionalisation of Australia) subregions as koala records. The environmental data behind these points came from the *National forest and sparse woody vegetation data (version 3.0) 2018* (DEE 2019). This is at a 25 m resolution, with cells given values for forest, sparse woody, and non-woody land cover. Temporal distribution is for 23 years from 1988 to 2018. Koala records were shifted to nearest tree (at 5 m resolution). Forest data (DEE 2019) was converted to 90 m resolution using the nearest neighbour algorithm.

Grid cells classified as forest and within an IBRA subregion containing '*n*' koala records were used to define the pool of background records. These were then randomly selected to fit models.

An alternate approach would be to use records from other arboreal mammals, to attempt to match the spatial biases between the koala records and background records.

Koala tree suitability index

Koala occurrence is driven by the presence of koala's preferred feed tree species. Over 100 tree species have been identified across NSW as showing evidence of koala use (OEH 2018). Tree use is regionally based, with different trees showing evidence of use in different parts of the state. Certain tree species are preferred and are used more consistently and at a higher rate than others. Koala tree use is ranked as high, significant, irregular or low across NSW (OEH 2018).

Existing thematic vegetation maps in NSW are either incomplete, are only available at low resolution (spatial and/or thematic), or are available for only a single epoch. For this project we used targeted tree species modelling which provided high spatial definition, consistent, and statewide depiction of the distribution of trees koalas depend on, projected to 2070.

In total, 44 inland tree species ranked as either high or significant use in inland NSW were selected for modelling the inland region of the study area and 31 species for the coast, and their distribution was projected into future climatic scenarios (see Table 1, Section 2.5). These tree species were modelled separately and then combined, taking cognisance of regional preferences, into a single layer, the koala tree suitability index (KTSI). It is a grid surface describing the current probability of finding a koala preferred tree species at a particular location (DPIE 2019).

The baseline 2000 KTSI is shown in Figure 16.

The KTSI model combines the predicted distributions of a total 58 tree species which were generated using BRT, a correlative species distribution model. The BRT models were fitted with presence-absence tree plot data downloaded from BioNet and 18 covariates were used to predict the distribution of the preferred *Eucalyptus* trees in Table 4 and Table 5. We used 6 climatic, 6 landscape and 6 soil covariates (Table 6).

Table 4 Koala tree species selected for modelling of future climatic scenario distributions for the inland region of the study area (after DPIE 2019)

Scientific name	Common name
Eucalyptus acaciiformis	Wattle-leaved peppermint
Eucalyptus albens	White box
Eucalyptus biturbinata	Grey gum
Eucalyptus blakelyi	Blakely's red gum
Eucalyptus bosistoana	Coast grey box

Scientific name	Common name
Eucalyptus bridgesiana	Apple box
Eucalyptus brunnea	Mountain blue gum
Eucalyptus camaldulensis	River red gum
Eucalyptus canaliculata	Large-fruited grey gum
Eucalyptus chloroclada	Dirty gum
Eucalyptus conica	Fuzzy box
Eucalyptus coolabah	Coolibah
Eucalyptus crebra	Narrow-leaved ironbark
Eucalyptus cypellocarpa	Monkey gum
Eucalyptus dalrympleana	Mountain gum
Eucalyptus dealbata	Tumbledown red gum
Eucalyptus dwyeri	Dwyer’s red gum
Eucalyptus elata	River peppermint
Eucalyptus globoidea	White stringybark
Eucalyptus goniocalyx	Bundy
Eucalyptus laevopinea	Silver-top stringybark
Eucalyptus largiflorens	Black box
Eucalyptus maidenii	Maiden’s blue gum
Eucalyptus mannifera	Brittle gum
Eucalyptus melanophloia	Silver-leaved ironbark
Eucalyptus melliodora	Yellow box
Eucalyptus microcarpa	Western grey box
Eucalyptus microcorys	Tallowwood
Eucalyptus moluccana	Grey box
Eucalyptus nicholii	Narrow-leaved black peppermint
Eucalyptus nobilis	Forest ribbon gum
Eucalyptus nortonii	Large-flowered bundy
Eucalyptus pauciflora	White sally, snow gum
Eucalyptus pilligaensis	Narrow-leaved grey box
Eucalyptus polyanthemos	Red box
Eucalyptus populnea	Bimble box/poplar box
Eucalyptus prava	Orange gum

Scientific name	Common name
Eucalyptus punctata	Grey gum
Eucalyptus quadrangulata	White-topped box
Eucalyptus radiata	Narrow-leaved peppermint
Eucalyptus rossii	Inland scribbly gum
Eucalyptus sclerophylla	Hard-leaved scribbly gum
Eucalyptus tereticornis	Forest red gum
Eucalyptus viminalis	Ribbon gum

Table 5 **Koala tree species selected for modelling of future climatic scenario distributions for the coastal region of the study area**

Scientific name	Common name
Corymbia gummifera	Red bloodwood
Eucalyptus albens	White box
Eucalyptus bancroftii	Orange Gum
Eucalyptus biturbinata	Grey gum
Eucalyptus blakelyi	Blakely's red gum
Eucalyptus bosistoana	Coast grey box
Eucalyptus camaldulensis	River red gum
Eucalyptus canaliculata	Large-fruited grey gum
Eucalyptus cypellocarpa	Monkey gum
Eucalyptus deanei	Mountain blue gum
Eucalyptus eugenioides	Thin-leaved Stringybark
Eucalyptus globoidea	White stringybark
Eucalyptus grandis	Flooded gum, rose gum
Eucalyptus longifolia	Woollybutt
Eucalyptus maidenii	Maiden's blue gum
Eucalyptus melliodora	Yellow box
Eucalyptus microcorys	Tallowwood
Eucalyptus moluccana	Grey box
Eucalyptus nobilis	Forest ribbon gum
Eucalyptus paniculata	Grey Ironbark
Eucalyptus parramattensis	Parramatta Red Gum, Drooping Red Gum
Eucalyptus propinqua	Small-fruited grey gum

Scientific name	Common name
Eucalyptus punctata	Grey gum
Eucalyptus quadrangulata	White-topped box
Eucalyptus resinifera	Red Mahogany
Eucalyptus rubusta	Swamp Mahogany
Eucalyptus saligna	Sydney blue gum
Eucalyptus tereticornis	Forest red gum
Eucalyptus viminalis	Ribbon gum
Eucalyptus tricarpa	Mugga Ironbark
Melaleuca quinquenervia	Broad-leaved paperbark

Table 6 List of covariates used in the koala tree suitability index (KTSI) model

Group	Predictor description	Units	Original resolution	Reference/Source
Climate	Radiation of seasonality: coefficient of variation (bio23)	C of V	250 m	Baseline and Future: Evans et al. 2014
Climate	Annual mean temperature (bio1)	°C	250 m	Baseline and Future: Evans et al. 2014
Climate	Isothermality 2/7 (bio3)	unitless	250 m	Baseline and Future: Evans et al. 2014
Climate	Min temperature of coldest period (bio6)	°C	250 m	Baseline and Future: Evans et al. 2014
Climate	Precipitation of driest period (bio14)	mm	250 m	Baseline and Future: Evans et al. 2014
Climate	Precipitation of wettest period (bio13)	mm	250 m	Baseline and Future: Evans et al. 2014
Landscape	Euclidean distance to 2nd order streams and above	m	30 m	NSW Office of Water. Derived by DCCEEW
Landscape	Euclidean distance to 6th order streams and above	m	30 m	NSW Office of Water. Derived by DCCEEW

Group	Predictor description	Units	Original resolution	Reference/Source
Landscape	Exposure to the NW (high = exposed (drier forests); low = sheltered (moister forests)).	index	1 sec (~30 m)	Ashcroft and Gollan (2012)
Landscape	Cold air drainage	index	1 sec (~30 m)	Ashcroft and Gollan (2012)
Landscape	Topographic position index using neighbourhood of 250 m radius	index	1 sec (~30 m)	Derived by DCCEEW from smoothed 1 sec Shuttle Radar Topography Mission (SRTM)
Landscape	Topographic position index using neighbourhood of 2,000 m radius	index	1 sec (~30 m)	Derived by DCCEEW from smoothed 1 sec SRTM
Soil	Available water capacity proportionally combined depths from 0 to 100 cm	%	100 m	Baseline: Soil and Landscape Grid of Australia. Future: J. Gray (pers. com. 2020)
Soil	Clay content proportionally combined depths from 0 to 100 cm	%	3 sec (~90 m)	Soil and Landscape Grid of Australia. Proportion derived by DCCEEW
Soil	Silt content proportionally combined depths from 0 to 100 cm	%	3 sec (~90 m)	Soil and Landscape Grid of Australia. Proportion derived by DCCEEW
Soil	Sand content proportionally combined depths from 0 to 100 cm	%	3 sec (~90 m)	Soil and Landscape Grid of Australia. Proportion derived by DCCEEW
Soil	pH from 0 to 100 cm depths (pHCa), proportionally combined from depths 0 to 100 cm.	pHCa	100 m	Baseline: Gray et al. (2015). Future: Gray and Bishop (2019)
Soil	Soil organic carbon from 0 to 100 cm depths (t/ha), proportionally combined from depths 0 to 100 cm	t/ha	100 m	Baseline: Gray et al. (2015). Future: Gray and Bishop (2019)

Habitat phasing

An assumption is made that future distributions of habitat tree species will be constrained by current distributions, that is, new species of trees will not 'automatically' appear in a location when it becomes suitable; but existing tree species can decline as climate becomes less suitable (see Section 2).

The effects of climate change on habitats and species are expected to range between direct effects and time-delayed effects. Direct effects include mortality due to heat stress and lack of water; and time-delayed effects include loss of reproductive vigour, loss of genetic diversity and habitat loss. The compensatory effect to habitat loss offered by shifts in habitat distribution and emerging new habitat is likely to be reduced in the case of koalas. Koalas depend on mature trees, which will be prone to more frequent extreme climatic events throughout their growth. Amplifying potential habitat loss, existing resource trees can be lost swiftly and irreversibly. Within this context our forecasting timeframe is relatively short (10 and 50 years); barely enough time to allow for new habitat to emerge, even in ideal conditions. Additionally, we must be cognisant of the phasing effects of climate change. Emerging habitats lag behind their suitable climate envelope. New habitats begin to establish within their preferred biophysical envelop, but as they mature, the niche has moved. Thus, there are 2 approaches we can consider:

1. KTSI-passive: Consider only the loss of habitat and assess the ability of existing habitat to survive and continue to provide sufficient resources to sustain viable koala populations.
2. KTSI-enhanced: Consider emerging habitat within dynamic scenarios, where resources take time to develop subject to tree growth rates, projected biophysical conditions and threats from extreme events. Within this approach habitat may fail to reach full habitat potential due to phasing habitat envelopes. During the transition to new species (or species provenances) habitat may require active planting, where natural colonisation cannot be relied upon.

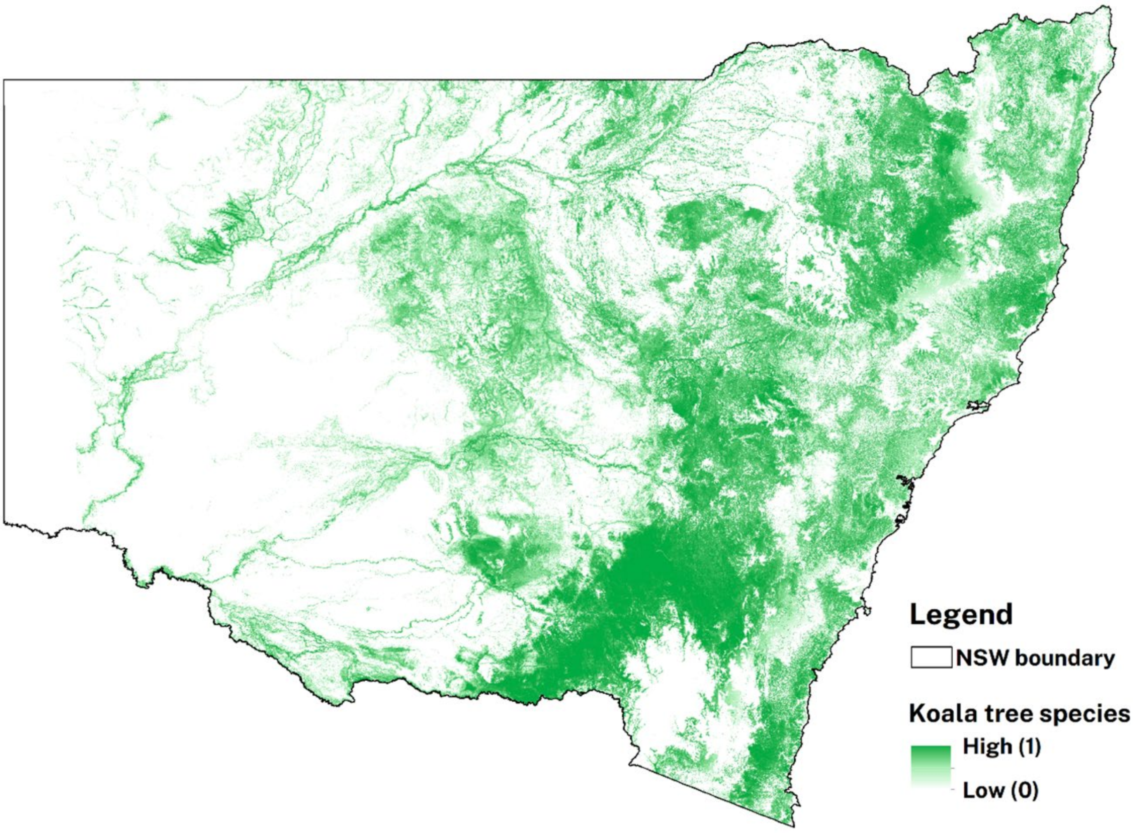


Figure 16 Koala tree species index map (2000 baseline model)

Access to water (inland only)

Access to water (ATW) is known to be a critical driver of koala distribution, especially in association with hotter conditions and heatwaves. Anecdotally, lack of access to water has driven the crash in koala populations in the Pilliga in recent years (Dan Lunney pers. comm.). With the expectation of further and more severe future climatic fluctuations, koala populations are expected to be further impacted in the drier parts of the inland study area. Future conservation planning efforts will need to consider the benefits of remedial actions such as providing artificial sources of drinking water to supplement naturally available water sources. The ability of koalas to utilise environmental water makes habitat construction a possible conservation strategy in naturally wetter areas.

For this project, custom access to water layers (one for surface and one for ground water) were developed and integrated into the KENM. These are described in the following sub-sections.

ATW was kept constant at the 2000 baseline level. Future climate models disagree on the direction precipitation is trending within the study area. It was outside of the scope of this study to predict future changes in water accessibility.

Surface water availability

Surface water availability (SWA) was based on the distance to perennial waterbodies, and weighted by distance to water, with a stream order modifier.

Perennial water sources were derived from 2 sources: monthly Sentinel surface water and Landsat surface water.

Sentinel water detection was performed in Google Earth Engine by applying a water detection index and threshold (Ricardo et al. pers. comm.) to monthly median pixel reflectance values. Monthly binary water masks were summed for all 48 months from 1 January 2016 to 1 January 2020. Pixels were assigned a value of one (water) where water was detected for more than 24 months (>50% detection rate).

The Landsat count of water prevalence (dd7) detected surface water using the *Statewide landcover and tree study* water index (dd6) with topographically corrected reflectance over 24 years of data from 1988 to 2012. For a single date this is a binary mask. Band 1 is the count of water prevalence; Band 2 is the count of non-null input pixels. Pixels were assigned a value of one (water) where water was detected for more than 50% of non-null input pixels.

The maximum of the 2 binary water masks was taken so that a value of one was assigned where either product detected water and no data was applied elsewhere. The Euclidian distance to the nearest water pixel was calculated up to a maximum 50 km distance then a logistic transformation was applied to derive distance to water bodies (DWB) (see Figure 17 and Equation 4). The transformation's midpoint of 0.95 is equivalent to 2,500 m and d_{max} (0.5) represents the maximum 50 km distance. The surface water availability map is shown in Figure 18.

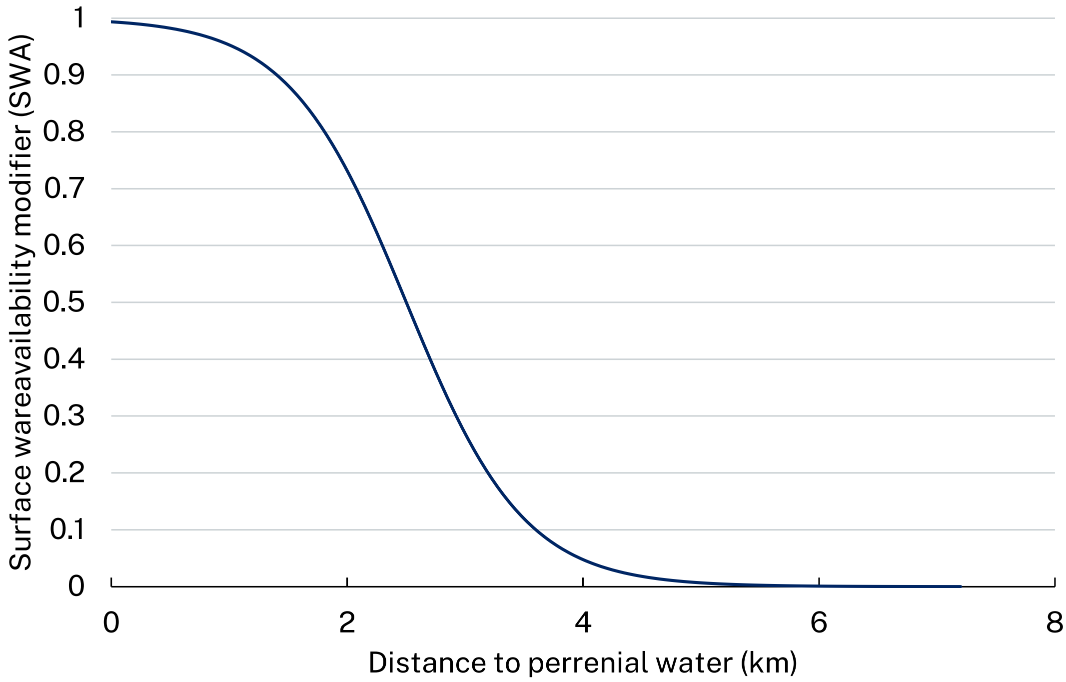


Figure 17 **Surface water availability modifier as a function of distance to perennial water**

Equation 3 $SWA = \frac{1}{1+e^{-100(x-0.95)}}, \quad x = 1 - \left(\frac{d}{d_{max}}\right)$

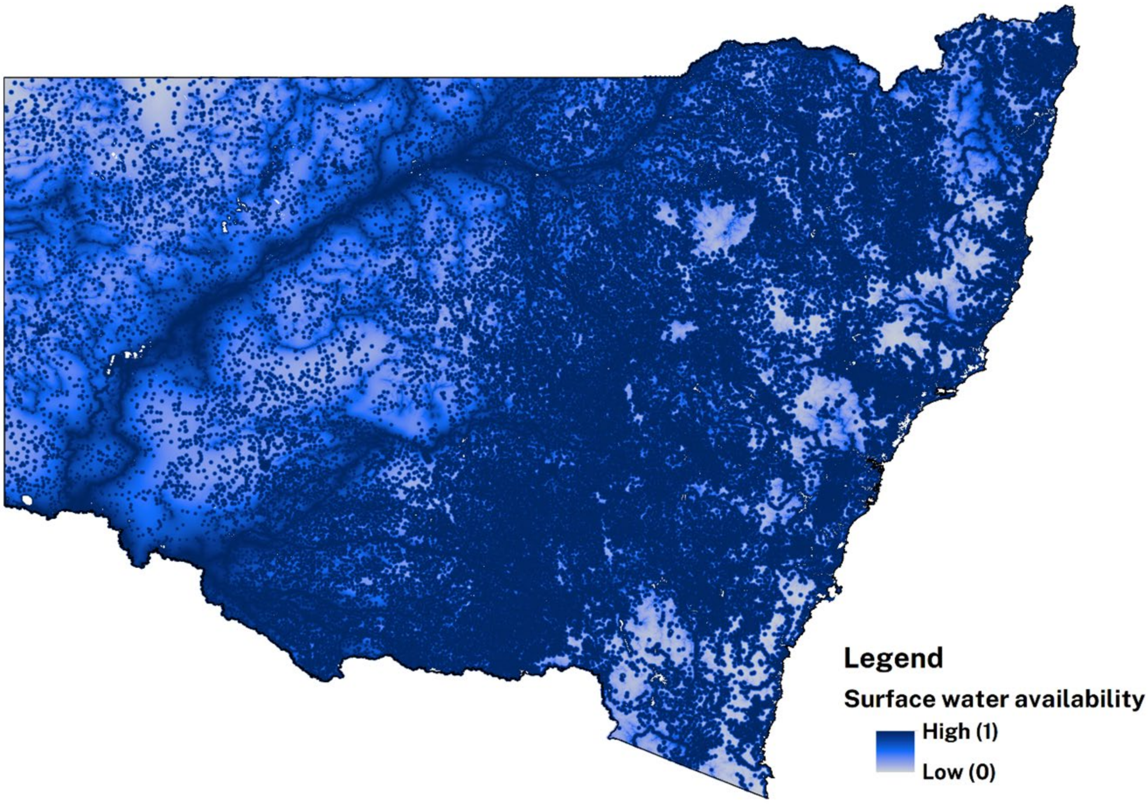


Figure 18 **Surface water availability map, used as a static layer, that is, it is held constant across the projections into future climates. Applied only for the inland region**

Ground water availability

Ground water availability (GWA) – see Equation 5 – was derived from the NSW green accumulation index (Landsat 1988–2012) which is a calculation of the area under the curve from a time-series of the green fraction from fractional cover estimates, after adjustment to cover under trees. A logistic transformation (Figure 19) was applied to better discriminate between high and low values with a midpoint of 0.3 based on visual interpretation of the data. The ground water availability map is shown in Figure 20.

Equation 4 $$GWA = \frac{1}{1+e^{-15(x-0.3)}}$$

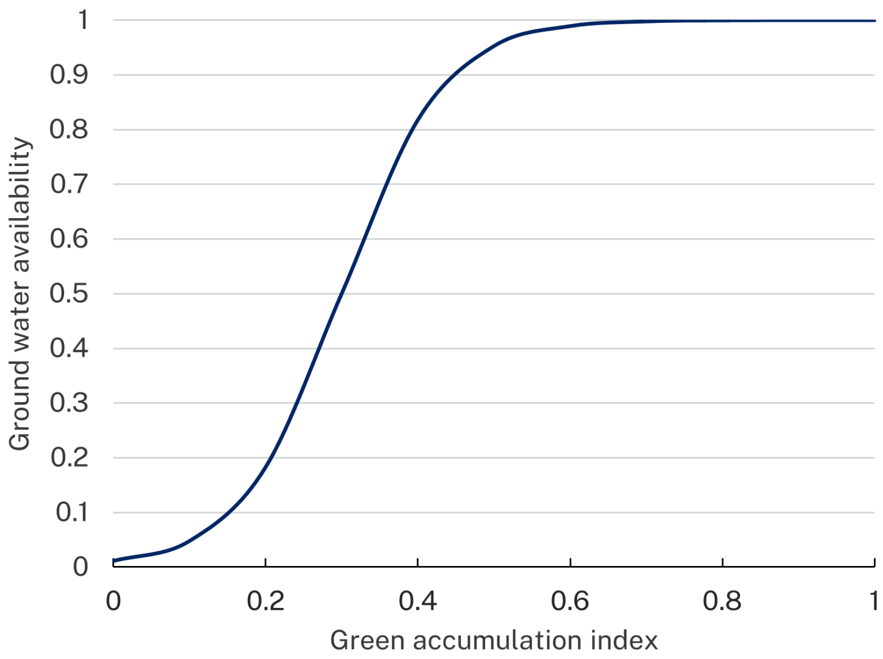


Figure 19 **Transformation function used to derive ground water availability from green accumulation index**

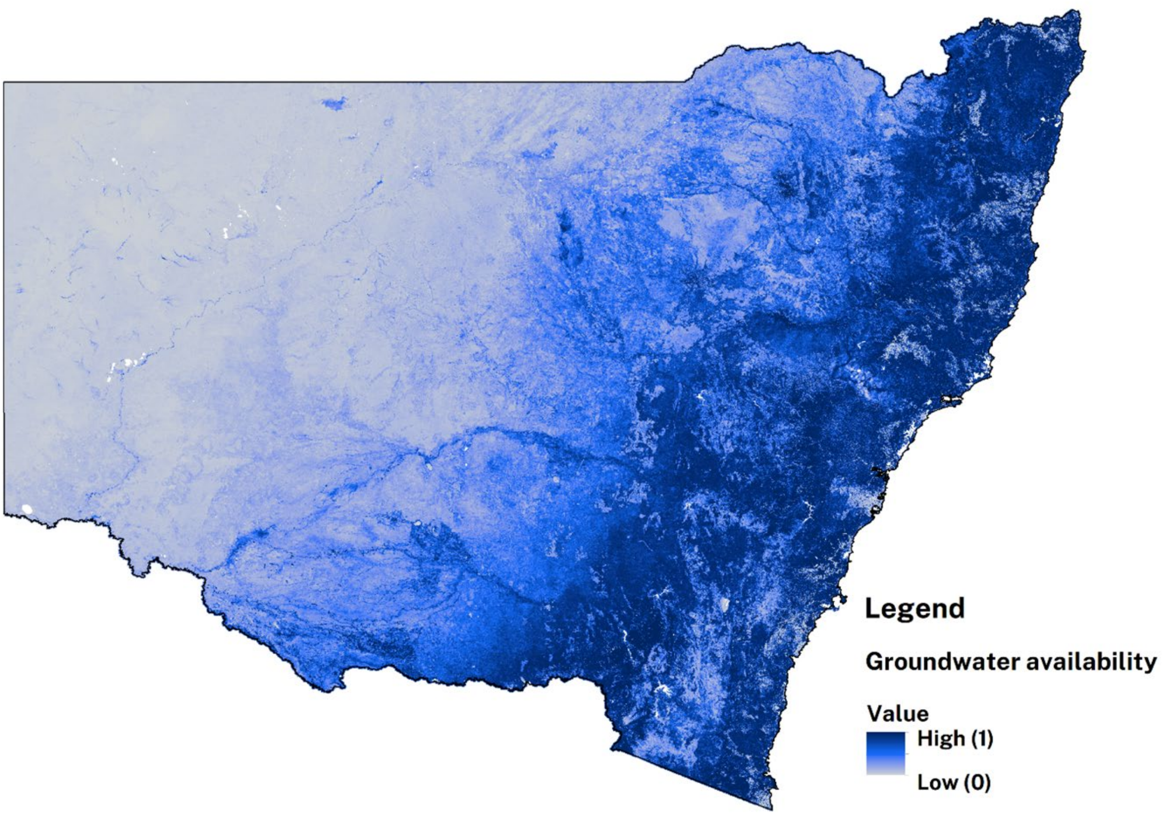


Figure 20 **Ground water availability map used as a static layer, that is, it is held constant across the projections into future climates. Applied only for the inland region**

Woody percent cover

Woody percent cover (WPCtmax) is derived from the 2017 NSW woody extent layer (Figure 21), a statewide binary classification of woody vegetation derived from multi-temporal 5 m SPOT satellite imagery. The percent of woody vegetation per pixel is calculated as the percentage of 5 × 5 m source pixels within each 90 × 90 m destination pixel that is mapped as having woody extent. This layer (WPCtmax) is kept static throughout the modelling process, that is, assume no change to woody extent into the future.

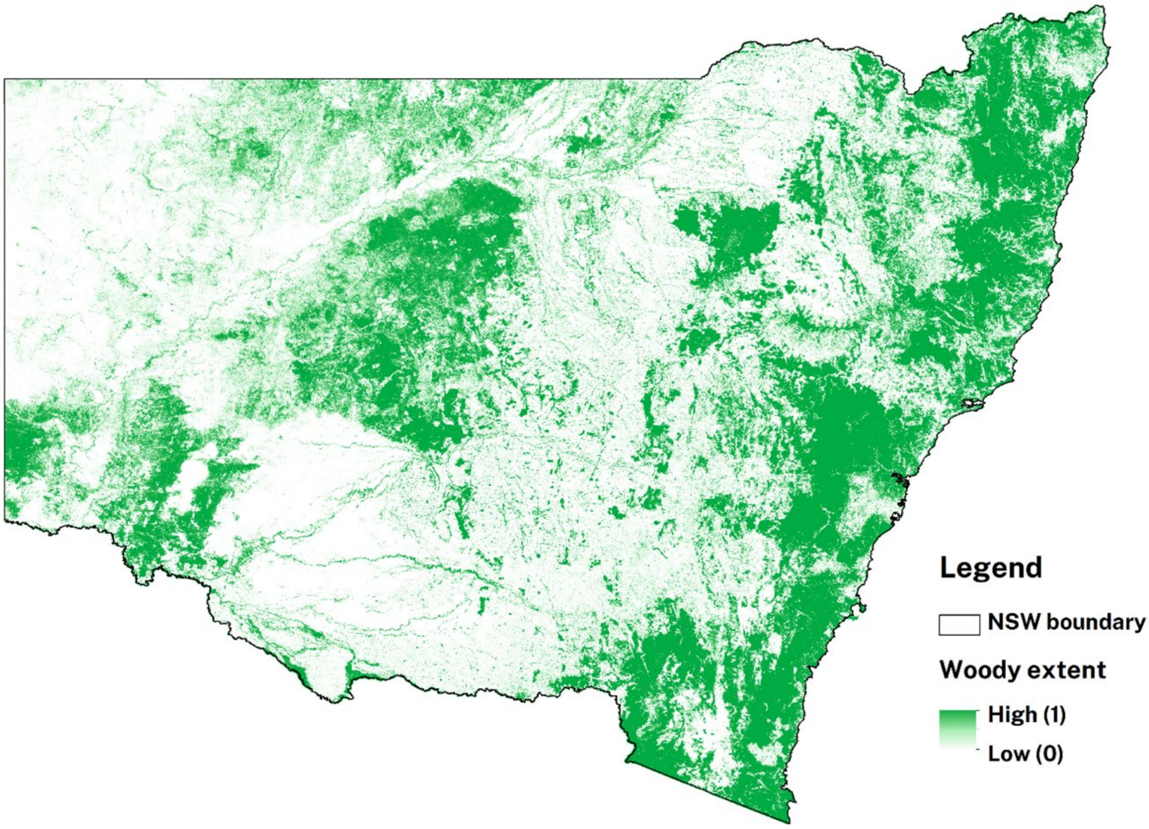


Figure 21 Woody extent map (proportion of woody vegetation per pixel)

Appendix C: Phase 2 – Landscape capacity modelling

Phase 2 of the modelling process predicts landscape capacity (P_i, otherwise known as potential occupancy, see Drielsma and Love 2021) for koalas across the study area (each 90 × 90 m pixel). It incorporates the time-series koala environment niche models (KENMs) with koala's population-level habitat area requirements and koala movement abilities.

P_i is an estimation of the proportion of time each location could be occupied, based on the habitat conditions at the site and its functional connectivity to other habitat. The concept of P_i also aligns with what has been referred to as 'habitat amount' (Fahrig 2013) and 'functional habitat'. These concepts focus on patch dynamics, and indirect habitat loss in which 'habitat is physically present but is rendered unusable (or less usable) or unattractive (or less attractive)' (Laliberté and St Laurent 2020).

The instrument used for evaluating P_i is the rapid evaluation of metapopulation persistence (REMP) methodology (Drielsma and Love 2021; Drielsma and Ferrier 2009). REMP is an ecologically driven process-based approach to assessing the capacity of a region to support populations of mobile species. It considers the quality and arrangement of habitat in a region, in relation to species' habitat needs and movement abilities. REMP extends ENMs beyond correlative modelling to include the functional requirements of populations and species' ability to access habitat across distance.

Figures for minimum viable area to support a population and movement abilities through the full range of environments for koala were collected for the Western Woodlands Way project (Taylor and Drielsma 2012; Taylor et al. 2016). These same ecological parameters were further refined using relevant literature, and through expert consultation using a SurveyMonkey online poll (see Appendix F). Parameters were derived for female koalas which we considered the limiting factor to koala population persistence.

The critical landscape characteristics used for all modelling in the Koalas in the Landscape project are provided in Table 1 (Section 2.5).

Performance parameters are used within the REMP model/methodology to help the model achieve a suitable mix of rigor and computational performance. As this project considers a single species with high iconic value, parameterisation is skewed towards rigor over performance.

The general evaluation results (averaged across projections) for P_i across epochs are provided in Figure 7 (Section 3.1). The results show a marked loss of habitat from the pre-industrial era due to clearing. From 2000 forward, additional projected loss is due solely to climate change (no further clearing or habitat construction is considered). These results are also charted as part of Figure 5 (Section 3.1).

Rapid evaluation of metapopulation persistence modelling

Rapid evaluation of metapopulation persistence (REMP) modelling produces landscape capacity (P_i) maps. These can assist species management decisions that relate to the quality and spatial arrangement of habitat. REMP modelling reports on landscape attributes, from a species population dynamics perspective. It does not consider other drivers including interspecific competition, predation, disease, direct human interference (e.g. habitat destruction and road kills), or stochastic events such as fire and storms.

A REMP P_i surface differs from an ENM by downgrading the predicted occupancy of areas with an insufficient spatial configuration of suitable habitat to support a population; and boosts the predicted occupancy of areas that do have a sufficient spatial configuration of suitable habitat to support a population, even when locally, habitat quality may be low.

The REMP method was originally developed to assess the net impacts of land-use changes on the persistence of species (and groups of species). It can be used to consider the establishment of private reserves (to offset clearing), and the clearing of native vegetation for agriculture or other developments (see Drielsma et al. 2016). The REMP method has since been applied across a range of regional assessments in NSW (Foster et al. 2017; Love et al. 2015; Taylor and Drielsma 2012; Taylor et al. 2016). Doerr et al. (2013) and then Foster et al. (2017) applied the method using a generic focal species approach. Doerr et al. (2013) applied the approach to a range of future climate and land-use scenarios.

The recent Persistence in the Landscape project (DCCEEW in prep.) represents another step in a process of continual improvement, and the first attempt to extend REMP analysis to the broader spatial scale of NSW and for a larger suite of species (more than 80). Persistence in the Landscape project modelling relies on some lower spatial resolution environmental data than previous studies (e.g. Taylor and Drielsma 2012; Taylor et al. 2016) (250 m climatic data verses 100 m granularity data used in previous studies). This limitation can be addressed in the future with the arrival of new datasets. The Koalas in the Landscape project augments the Persistence in the Landscape project to include this more rigorous modelling for koala.

REMP identifies areas of functional habitat (able to support a viable population) based on the pattern and quality of habitat represented in an ENM. REMP identifies areas that have sufficient home range scale habitat resources and dispersal scale connectivity to other areas of functional habitat. It highlights areas capable of supporting stable populations, which can recolonise vacant functional habitat patches and also indicates areas with potential habitat which could be recolonised after intermittent local extinction. For most species, this involves more than a simple spatial context calculation, as accounting for population dynamics requires integrated simulation of processes at 2 spatial scales: for localised extinctions, and broadscale dispersals.

REMP analysis is not suited to all species. Generally, for species that move at scales finer than the resolution of the data (i.e. less than a few hundred metres) and for species whose movement is not impeded by barriers such as cleared land, it provides no further information than an ENM. It does provide useful model outputs for species that are more mobile but sensitive to landscape restrictions to their movements.

The version of the REMP model (v 2.0) used in the Persistence in the Landscape and Koalas in the Landscape projects has undergone recent fundamental change, which has improved the results for models that appeared to be underpredicting occupancy (Drielsma and Love 2021).

In addition to an input ENM, REMP requires a set of ecological and performance parameters.

For connectivity analysis across geometric space, REMP integrates the cost-benefit approach (CBA) (Drielsma et al. 2007). CBA utilises the least-cost paths algorithm to calculate colonisation potential over a continuous-value grid of vegetation condition. Iterative matrix calculations based on the CBA informs a metapopulation model of local extinctions and colonisations from neighbouring populations (Hanski 1999; Hanski and Ovaskainen 2000). The CBA allows connectivity analysis by considering the composition and configuration of habitat. The measurement of the distances between potential habitat is a function of species' movement abilities, the spatial composition and condition of the prevailing landscape. The petal technique for grid sampling is used to optimise processing speed, so within each neighbourhood window, the neighbouring grid cells are aggregated into a reduced number of 'petals' to aid computation. Increased computational efficiency was achieved during the project by recoding the CBA using the CUDA platform, allowing for rapid parallel processing using graphics processing (Love unpub.). This advance has allowed increased model precision.

In order to capture the way in which extreme topography (steep slopes and cliffs) affect koala's ability to move through the landscape, a layer of ruggedness was used to modify the permeability layer used in REMP (see Equation 6 and Figure 22).

Equation 5 $$\boldsymbol{Perm.factor} = {}^{\mathbf{1}}\!/_{\boldsymbol{e}^{(\mathbf{17}\times \boldsymbol{Rugg}-\mathbf{8})}}$$

This resulted in reduced landscape capacity in the steeper parts of the eastern escarpment, such as the gorges in the Oxley Wild Rivers National Park in the north-east of NSW. In all other cases the permeability was largely unaffected where ruggedness was low to moderate. Apart from ruggedness, permeability was driven by the presence of trees (any species) within each 90 × 90 m grid cell. The permeability values were thus determined by the values in Table 1, where maximum permeability values were assigned where trees were present, and minimum values when trees were absent.

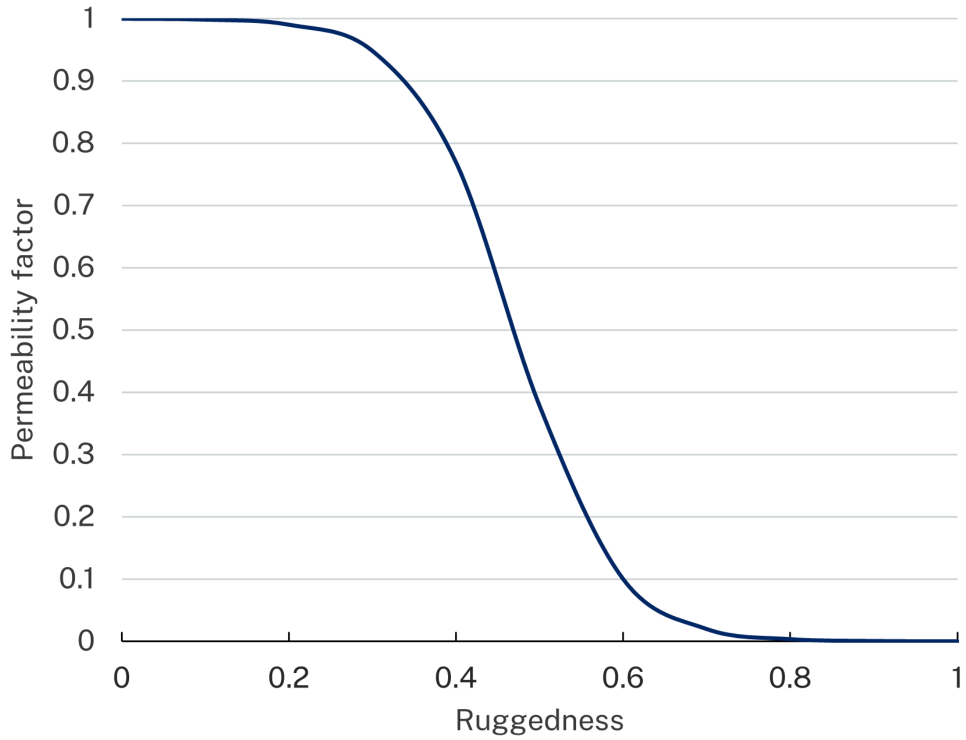


Figure 22 Function used to derive the permeability factor for ruggedness

The coastal and inland landscape capacity models were merged at the end of Phase 2 (see Section 2.5). Each model's potential influence in the combined model is decreased linearly from 100% to 0% within a distance of 50 km from the coastal KMRs. A transition between the 2 models was achieved as follows:

- Using distance up to 50 km from the western edge of the coastal region, the coastal model (which extends into the inland region) was scaled using a factor ranging from 0 (western edge of buffer) to 1 (eastern edge of buffer)
- The scaling was inversed for the inland model across the same transition zone: 1 for 50 km inside the inland region and 0 (within the coastal region)
- The merged model resulted from summing the 2 scaled models.

Appendix D: Phase 3 – Model synthesis

The model synthesis phase is where component models are combined using specific formulations to provide insights which can inform management options and help achieve conservation objectives.

These synthesised products are described in the following sections and summarised in Table 7.

Table 7 Summary of synthesised spatial products for koala

ID	Name	Description
MS01	Evaluation and trends in koala landscape capacity	Assessment of koala landscape capacity across time and trends arising from that
MS02	Model consensus	The level of consensus among the model portrayals in respect to refugia
MS03	Degree of expected change	The forecasted change in landscape capacity between 2000 and 2070
MS04	Persisting koala landscape capacity	Landscape capacity through climate change, up to 2070
MS05	Latent capacity	Additional landscape capacity, gained by increasing connectivity or through translocation of koalas to unreachable habitats
MS06	Habitat construction benefits	The level of additional landscape capacity if habitat was restored to its full potential by 2070
MS07	Koala conservation options	A single map that further synthesises project results to show a range of opportunities for conservation, enhancement and habitat construction

Synthesised spatial products

MS01 – Evaluation and trends in koala landscape capacity

See Table 2 and Figures 5 and 6 (Section 3.1) for results.

MS02 - Model consensus

See Figure 8 (Section 3.2) for results.

MS03 - Degree of expected change

See Figure 7 (Section 3.1) for results.

MS04 – Persisting koala landscape capacity map

Areas with high persisting koala landscape capacity provide habitat benefits across multiple time-steps and projections. Although some areas may remain suitable for koalas throughout foreseeable climate change and consequently are refugia in the normal sense, many other areas will provide refuge over shorter time spans – they may be declining, building or 'phasing' (that is, they are expected to build and then decline). As we cannot know habitat dynamics in advance with certainty, this map provides an overview of all areas expected to contribute to koala populations.

The persisting koala landscape capacity value h_i for grid cell i is expressed as:

Equation 6 $$h_i = \sum^p \sum^t w_t p_t$$

which is the summed passive landscape capacity across all projections (p) and epochs (t). A weight (w_t) is applied to give greater weight to future epochs. This accounts for the limited benefit to koala of areas which are already disappearing with climate change. w_t was calculated as:

Equation 7 $$w_t = \ln\left(\frac{epoch - 2000}{10} + 1\right) + 1$$

Thus, the following weights are applied for the 2000, 2030 and 2070 epochs: 1.00, 2.39 and 3.08, respectively. The final values are divided by 18.60 to normalise to a range of 0–1.0.

The higher value areas in Figure 23 provide the highest landscape capacity across epochs and alternative projections.

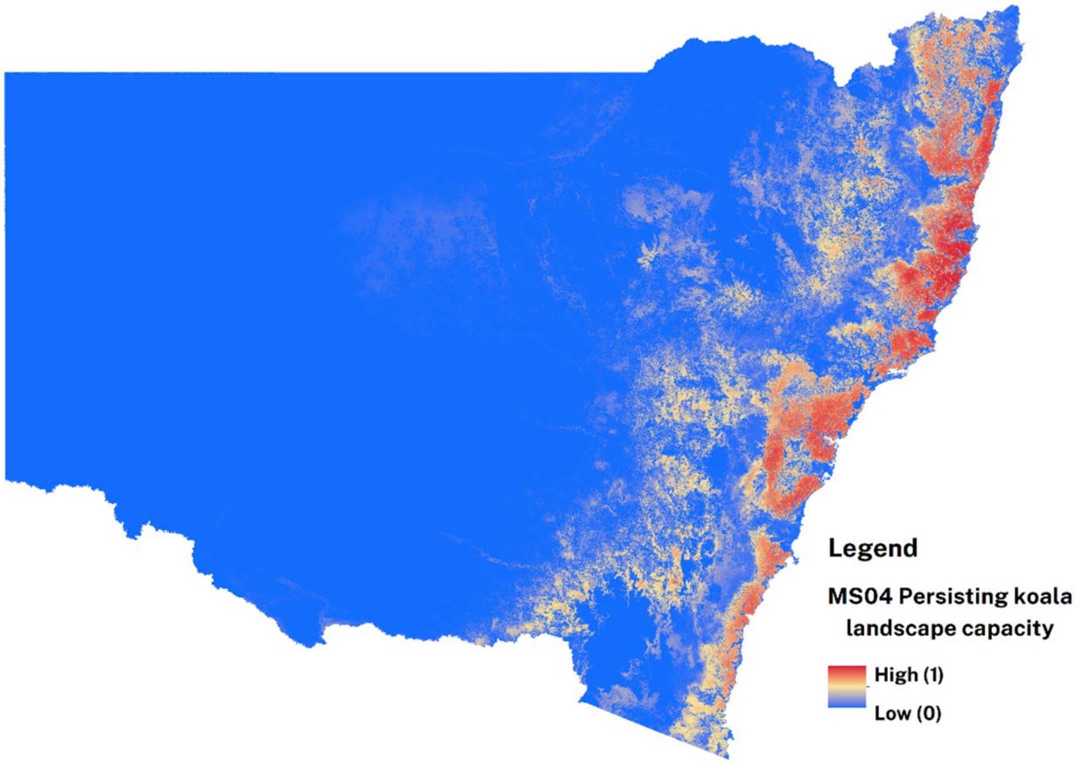


Figure 23 **MS04 Persisting koala landscape capacity for passive distribution**

The map does not include model agreement, but instead sums koala landscape capacity across all projections and all epochs from 2000 to 2070.

MS05 – Latent capacity

The latent capacity surface is a measure of what additional landscape capacity can be achieved by overcoming impediments to species accessing these areas with active management (i.e. enhancement with climate-ready koala feed tree species, improving connectivity and/or assisted relocation of individuals). Latent koala landscape capacity is calculated as the difference in landscape capacity between the 2070 passive and enhanced streams:

Equation 8 $$\boldsymbol{C_i = P_{i(e)}^{2070} - P_{i(p)}^{2070}}$$

where C_i is the latent capacity for each grid cell (i), $P_{i(e)}$ is the enhanced koala landscape capacity at 2070 (averaged across all projections) and $P_{i(p)}$ is the passive landscape capacity in 2070.

The latent koala landscape capacity map is shown in Figure 24. It shows where the greatest improvements in landscape capacity can be achieved by enhancing existing native vegetation with climate-ready koala feed trees and reconnecting areas of habitat to areas of passive koala landscape capacity.

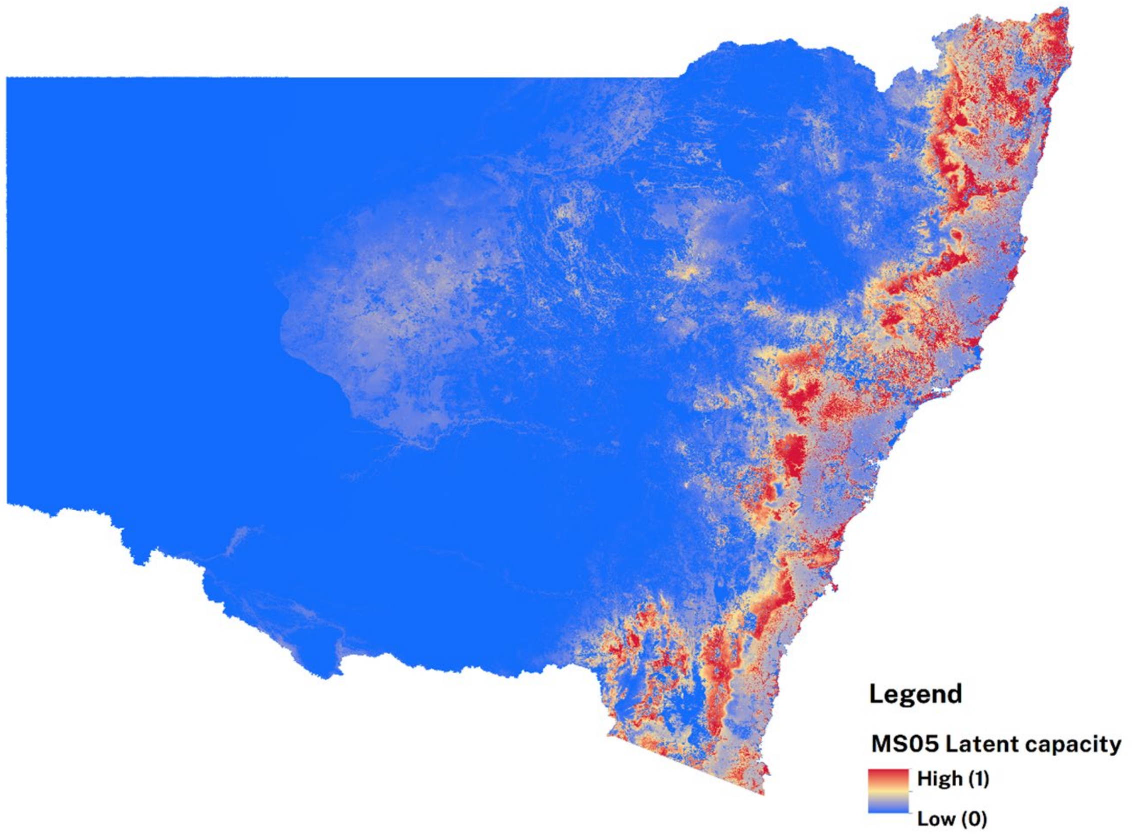


Figure 24 MS05 Latent koala landscape capacity

MS06 – Habitat construction benefits

The habitat construction benefits map provides insight into what level of (passive) occupancy is possible by 2070 at each location, if it were fully restored. The term ‘habitat construction’ refers to the establishment of climate-ready koala *Eucalyptus* food species in places that are expected to remain or become suitable for them by 2070, but which are predominantly not present now.

The process for deriving koala habitat construction benefits is shown in Figure 25. Table 8 provides a key to the naming of spatial products in the production of habitat construction benefits. The process cannot be easily represented in equations, but relies on combining habitat, landscape capacity (P_i) and P_u, which is one step back from P_i in the REMP process (Drielsma and Love 2021). P_u captures all the connectivity in a landscape but not the final integration of connectivity with actual parcels of habitat. It therefore does discriminate between well-connected areas with or without actual habitat present. By using P_u in relation to a ‘reconstructed’ 2070 scenario, it is therefore useful in identifying areas that could potentially connect to the passively viable 2070 areas.

Table 8 Key to Figure 25

Symbol	Description
t7	The epoch of the 7th decade i.e. 2070
s	Passive (or stable) model
p	Enhanced (or potential) model
pi	Landscape capacity (or potential occupancy) from REMP model
pu	Intermediate REMP product. The potential occupancy for a location, considering only the context and not the local (grid cell) habitat suitability
M	Modified scenario (with ecological condition applied)
P	Pristine scenario (no ecological condition considered)
h	ENM model

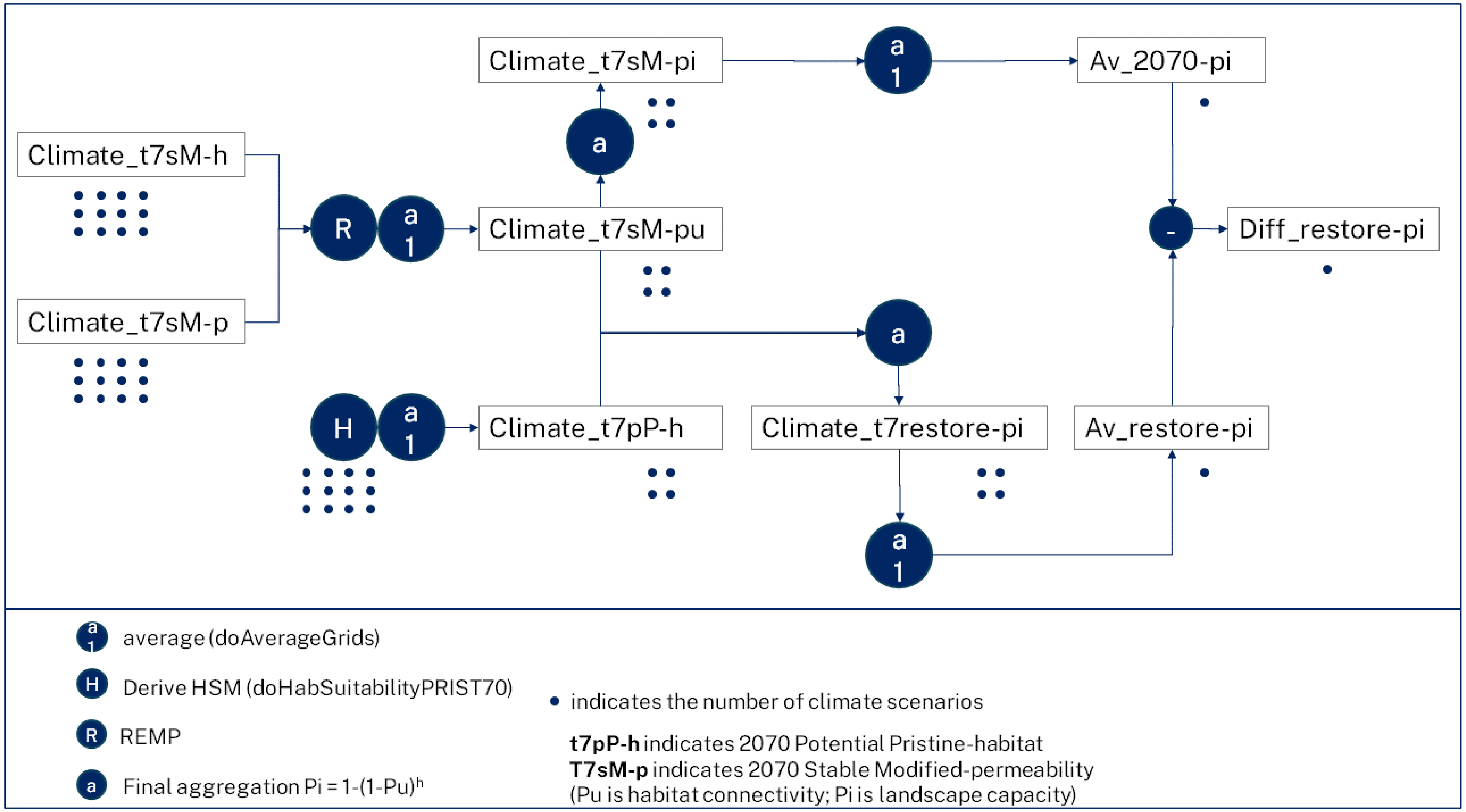


Figure 25 MS06: process for deriving habitat construction benefits

The potential benefits for habitat construction are mapped in Figure 26 and plotted in Figure 5 (Section 3.1). These show that sufficient opportunities for habitat construction remain up to 2070 despite significant impacts from climate change. The full potential for habitat construction could be reduced by over 60% due to the influence of climate change. The amount of these benefits is calculated independently, based on the projected biophysical attributes of each site and its connectivity to a passive habitat network. With significant commitments to constructing new habitat, the passive habitat network will itself expand, further benefiting koala populations.

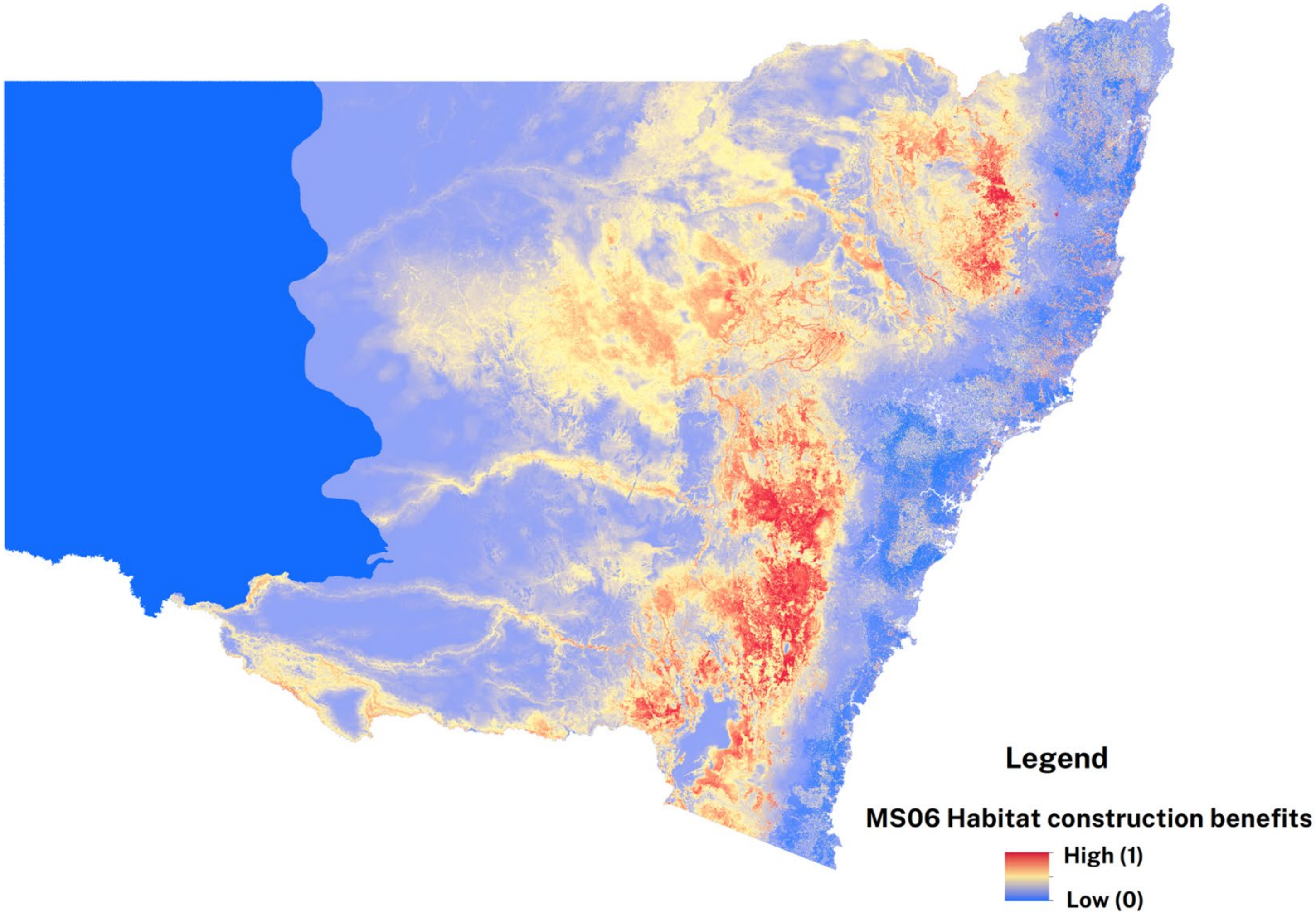


Figure 26 MS06: Koala habitat construction benefits for NSW

Because koalas have high mobility they can access and utilise much of the areas capable of becoming restored habitat in 2070, if those areas are sufficiently restored by that time.

The model suggests that the highest habitat construction benefits often are found in areas with relatively high conservation benefit in their current state. Establishing climate-ready koala tree species in these areas could further enhance their ability to support viable koala populations.

MS07 – Koala conservation options map

The integrated conservation options map (Figure 10, Section 3.3) highlights important guides to management arising from the project. These are conceptually illustrated in Figure 27. The map at Figure 10 is a composite image where the 3 principal colour bands are assigned to each of 3 surfaces relevant to climate-ready koala management:

- Band 1 (blue) – MS01 – stable, passively high koala landscape capacity in 2070, based on the average of the 12 climate projections
- Band 2 (red) – MS05 – latent capacity, additional map of NSW showing the Koalas in the Landscape study area that could potentially be made available in 2070 through enhancement of habitat with climate-ready *Eucalyptus* species; and construction of habitat connectivity and/or assisted migration
- Band 3 (green) – MS06 – habitat construction benefits, by establishing new, climate-ready *Eucalyptus* species in areas functionally connected to the Band 1 areas, including areas currently devoid of trees.

Other colours are derived where the bands overlap. The colour system used is illustrated in Figure 28.

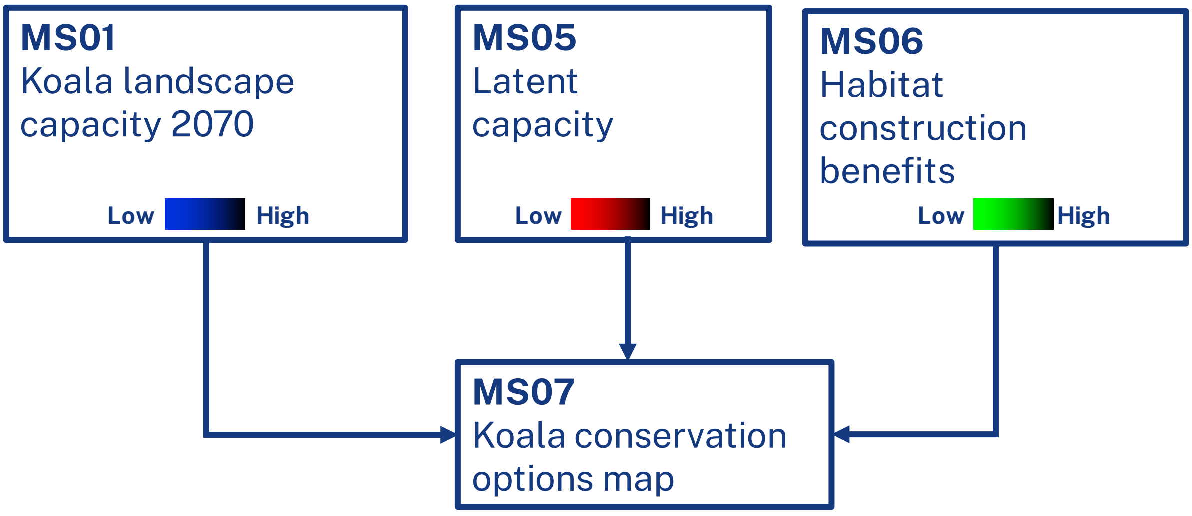


Figure 27 Flow chart for derivation of koala conservation options map

Colour saturation (inversed) indicates the contribution of each element to the conservation options map (Figure 10)

In Figure 28, the colours in circles are displayed on the model output map and the colours in the rectangles are the colour ramps for each input component (i.e. MS01, MS05 and MS06). The map uses an inverse red–green–blue (RGB) palette, that is, low values of each component yield the maximum saturation of the relevant colour. White represents unsuitable for supporting koala populations, that is, low value for all components (full saturation of red, green and blue). The darker colours represent potentially better habitat. The chartreuse colour for 'conserve and enhance' is a combination of roughly equal portions of low construct benefits (94% green saturation) and latent capacity (78% red saturation), and high value of landscape capacity (0% blue saturation).

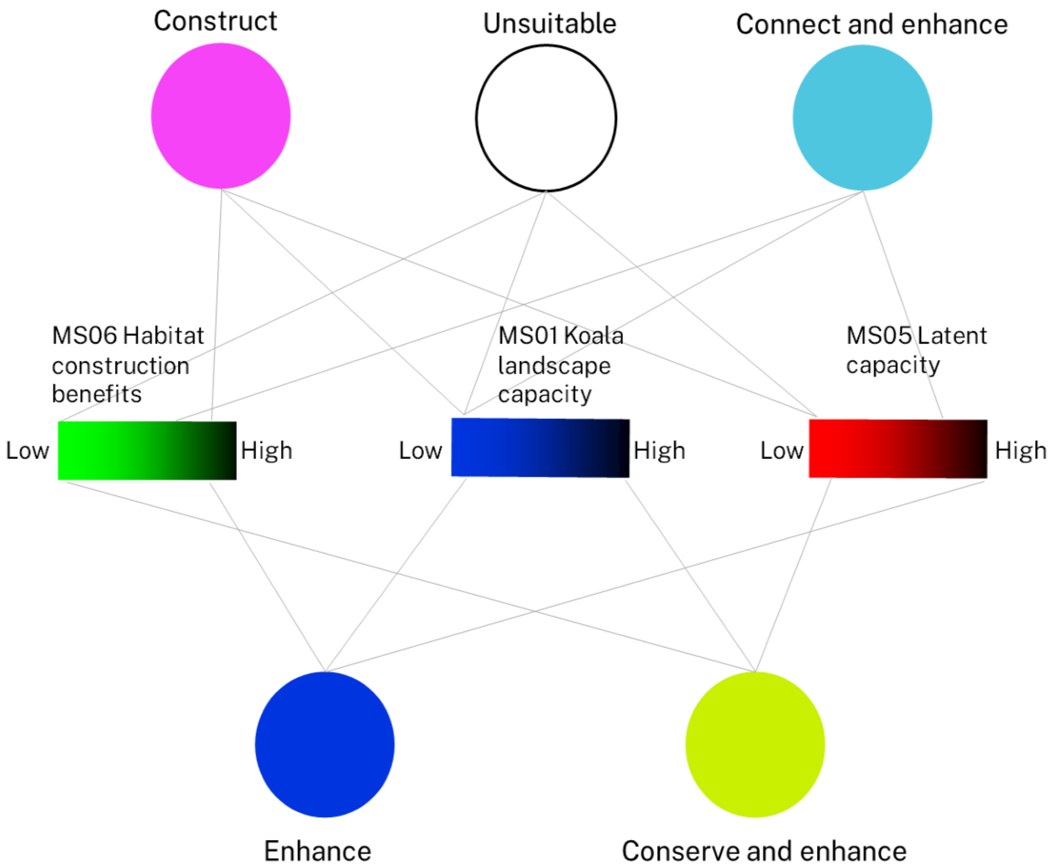


Figure 28 **Key management options in integrated conservation options map (Figure 10)**

The 3 input layers (MS05, MS01 and MS06) are represented by inverse red-green-blue (RGB) palette, respectively; that is zero saturation represents high value for each layer and maximum saturation represents low value for the layer. The 4 'key management options' of the map, depicted in Figure 9, are combinations of the 3 principal colours. These combinations are represented by lines linking the key management options colours (circles) and positions along the rectangles (centre) that represent values between low and high on each input layer's colour ramp.

Appendix E: Baseline koala environmental niche model review and validation

The koala environmental niche model (KENM) was validated through a process of expert review. Model iterations were sent to 34 koala experts with expertise in their specific regions or knowledge domains, and 24 replies were obtained. The reviewers were from different organisations including government, university and private consultancies. The experts/reviewers where selected based on their knowledge of koala biology, habitat needs and geographic distributions.

The validation of individual components of the model is covered in the relevant sections below. Climate projections and derived products are subject to high levels of uncertainty and cannot be directly validated. We took the approach of validating the 2000 baseline model only. We expect that if a reasonably parsimonious (not over-fitted) baseline model adequately represents the known historic distributions, we can have some confidence that the projected models reflect the environmental drivers of future koala distribution.

Any model of this kind will not always reflect fine-grained details. For example, it may not pick up a small patch of suitable habitat or it may predict habitat in a small area that has no habitat. Our models are intended to reflect the landscape habitat conditions, but do not consider other drivers such as predation and disease, recent fire and current seasonal conditions. The impacts of the recent fire season were not included in this review. We asked reviewers to approach the exercise using their knowledge of koala conditions before the 2019–20 fire season. The model is meant to capture general patterns, so we sought comments along those lines. Male koalas are known to wander widely. Thus, we asked our experts to focus on female koalas as they are more indicative of the health of populations.

Koala habitat baseline model key comments received

This section synthesises the key issues raised by koala experts/reviewers on the draft KENM baseline model (Figure 29).

The majority of expert reviewers responded that the koala habitat baseline map reflects their current understanding, however some of the reviewers pointed out we have under and overestimated in some geographical areas and have also given more weight to climatic variables and tree cover. Comments from across reviewers were merged as follows:

- Koala populations around Moree are not captured well by our model. Most of the Moree LGAs koala's habitat are on the scattered patches along the creek lines within the sand monkey dominated area.
- Areas along the Murray, Murrumbidgee, north of Pilliga, and south-west of Bathurst are predicted as unsuitable, but these areas are known for koala populations with high water availability.

- Model results also overpredicted in the north-east tablelands and south-west slopes including the Cobar Peneplain, which shows tree cover seems to be the strong driver.
- More than 50% decline in koala populations along the Watermark near Gunnedah as well as in other parts of the Murray–Darling Basin and in the Pilliga east were reported. Likewise, Goonoo near Dubbo also rated a suitable habitat by our model but not in reality from the ground observation.
- Model results also did not capture koalas on fragmented landscapes like on the Liverpool Plains farmland.
- Model results were also found to be overpredicted near Lightening Ridge and west along the Murry River and in Biddon near Gilgandra (which is largely dominated by cypress and this tree species is not preferred for koala habitat).
- The current model results show a little too much reliance on climate variables, we must understand the other physiological behaviour or coping mechanism.
- Tree cover seems to be a strong driver in the model. For example, the Cobar Peneplain comes out higher than it should. Koalas can cope with lower tree cover if the soil types are reasonably fertile. This would be the case for Moree, Liverpool Plains and Bathurst. Suggest considering soil fertility together with streams networks especially in the north-west, besides other climatic variables.

Key comments received from the survey questionnaires and other general comments

Two SurveyMonkey questions related to what was then called the 'koala potential occupancy model' (KPOM). The key comments and suggestions received from the experts are summarised as:

- Majority of survey questionnaires results responded the baseline habitat suitability map reflects their understanding from the groundwork, except in some geographical areas such as in Moree they are not captured well.
- Field observation indicated Gunnedah Basin and part of the Tableland was once mostly koala occupied area but in the present context these areas are unoccupied. Thus, the overall rate of change in koala population across inland NSW is occurring at a faster rate than the current model prediction.
- Streams are very important now for koalas in the north-west. The koala potential occupancy model (KPOM, now renamed koala landscape capacity model, KLCM) however seems to leave these out. Perhaps they could be weighted more highly in your habitat suitability mapping.
- As is shown by the map, the easterly concentration indicates an ever-increasing propensity for koalas to possibly transition across the landscape from west to east to possibly escape the heatwaves and ever-increasing temperatures in their previous habitat. Therefore, it is so important to see if there is a genetic link between koala populations in the tablelands, slopes and plains.

- For several years now the term KPoM has been used for koala plan of management (under the Koala SEPP) and this will be very confusing if you call the model the 'koala potential occupancy model' (KPOM). Suggest you change it to koala model of occupancy potential (KMOP) or something similar. (With the adoption of the term landscape capacity, we now call the final output the koala landscape capacity model, KLCM.)
- Koalas can cope with lower tree cover if the soil types are reasonably fertile. This may be the case for Moree, Liverpool Plain and Bathurst. Also suggested taking into consider soil fertility, greenness index etc. in the model.
- The model does not appear to discriminate areas very well at a local scale.

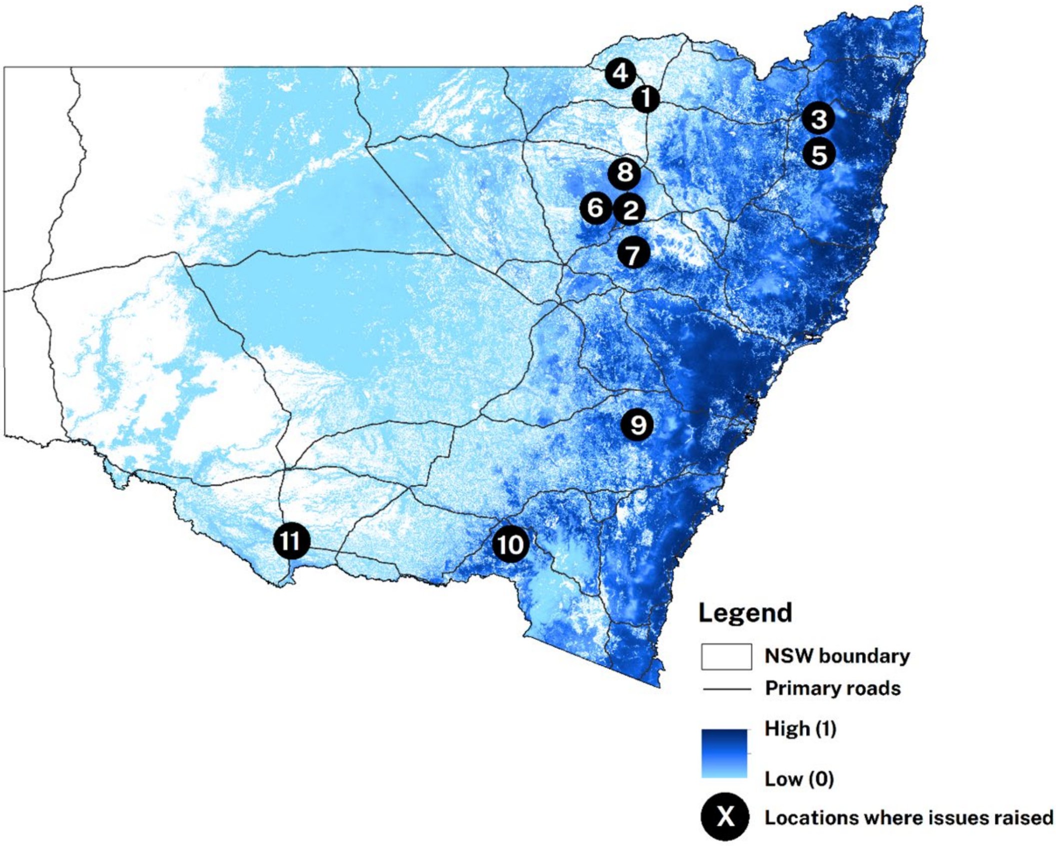


Figure 29 **Baseline koala environmental niche model results validation key comments from the experts (text below provides discussion of each numbered location on the map)**

Figure 29 shows where issues were raised with the draft 2000 baseline model, which were addressed in the later version. Each is referenced as a location on the map, as follows:

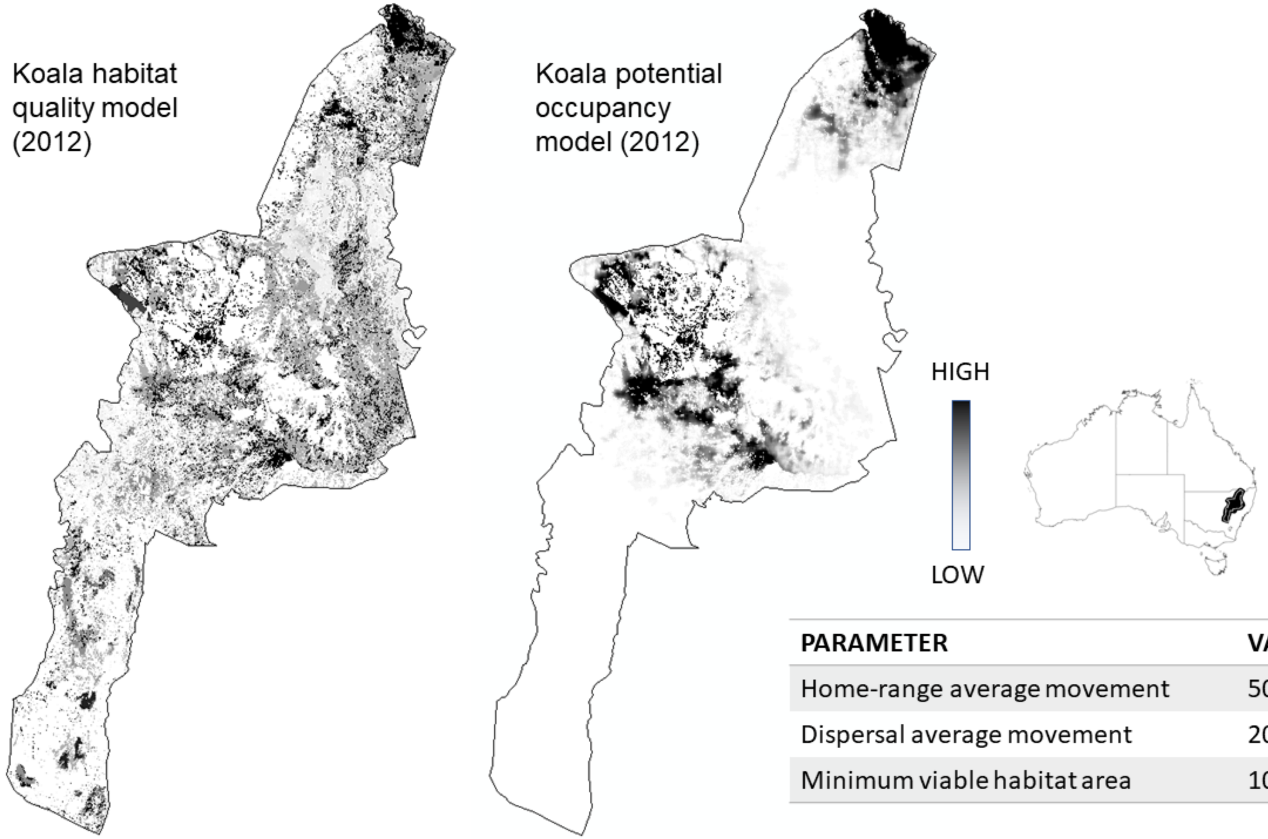
1. Koala refuges along riparian strips in 2020. Wet year in 2020 has seen more koala sightings along Gwydir, Mehi and Gil Gil streams. These features seem to require greater weighting in the model, as they exhibit a good level of connectivity.
2. This area could still be holding koalas, needs investigation. Interesting you have weighted this area highly in patches.
3. Overpredicting in many of these tableland areas. There are some notable exceptions, for example, Nowendoc where there are peppermint and snow gums, but these mostly occur on private land. Some of this is highly fragmented and koalas use paddock trees so it's not clear how such areas have been treated.
4. Gil Gil Creek has koala persistence, this area highlighted well.
5. Overprediction.
6. Koala's persistence in this Dandry area supports high habitat rating here.

7. Persistence of koalas in the Tambar Springs through the worst of drought conditions support the high rating and refuge status of this area.
8. Pilliga National Park wetlands suggest good moisture and soils, supported persistence of koalas in 2020. Perhaps underrated here.
9. Although there is much high suitability in the southern highlands and Blue Mountains (which is correct), the map does not appear to be discriminating well between different forest types. I might be wrong, but valleys in the Blue Mountains appear to be modelled as lower suitability (hard to tell even when zoomed in).
10. Koalas not really known from these high elevation forests of the south-west slopes based on past surveys, but model shows it as being high suitability.
11. River red gum areas are removed from the model, though there are known koala populations and access to water availability. Not clear why they were removed.

The following comments were received specifically in relation to the initial version of the coastal section of the model. Modifications were adopted to the subsequent version to address these concerns, where possible:

- The general consensus was that the KENM in general looked reasonable (some issues below) but that the KLCM did not seem to be accurately capturing areas where we know there is good capacity for the landscape to contain koalas.
- Important koala populations (Population of Immediate Investment in the Koala Strategy) and areas identified by experts as koala strongholds had very low capacity according to the map. This seems to be mainly a result of the low value placed on small and isolated areas.
- There is the question if small patches of high fertility land should be classed equally as valuable as large patches of remnant vegetation. If this is not possible, then it should be very explicitly stated that you made the choice to prioritise large remnants (perhaps in the Limitations section we've suggested). Providing some context for the decisions made around patch size and fragmentation would be valuable.
- Further, the woody extent mask seems to have removed habitat that is sparse trees (e.g. along rivers) but which otherwise may be good habitat
- 'Regarding the metapopulation model, it would be good if you provided some justification for the values you used. This model should probably have its own section given how much it impacts the KLCM – for example the minimum viable habitat is likely too large for areas with good soils and this has a massive impact on removing areas we know hold strong koala populations. This may also help for people to understand how the KENM is different from the KLCM. This could also be touched on in the Limitation section (e.g. that you assumed a large minimum patch size and this reduces the value of small areas of habitat that may actually be valuable).'
- 'Think about how the KLCM will affect future koala work and planning - there are implications for using large remnants/patch sizes, especially where landscape capacity doesn't align with the ARKS prioritisation.'

Appendix F: Western Woodlands Way (WWW) koala REMP model



PARAMETER	VALUE (Koala)
Home-range average movement	500 – 1,000 m
Dispersal average movement	20,000 – 50,000 m
Minimum viable habitat area	10,000 ha

Figure 30 **The Western Woodlands Way project included koala ENM (based on vegetation types) and provided initial parameter estimations for the Koalas in the Landscape REMP model**

The Koalas in the Landscape 2000 prediction is quite similar to the prediction of this region in the WWW. However, the WWW predicted less along the north-east edge north of Liverpool Plains in the central eastern part of the WWW region.

Appendix G: Data

Map projection

The koala tree suitability models, environmental niche models (ENM) and other spatial inputs were developed in the GDA 94 Geographic Coordinate System (EPSG:4283) at 0.0009DD pixel resolution, predominantly reflecting their source data. Once data were combined into the ENM, these were projected to the Australian Albers (GDA 94) equal area projected coordinate system (EPSG:3577) at a 90 m pixel resolution. Using an equal area projection, the analysis ensured that each 90 × 90 m pixel across the entire study area represented, as closely as possible, an equivalent (on-ground) area of 0.81 ha, not accounting for topographic relief.

About the koala data package

The koala spatial data package is available for internal access on DCCEEW's Information asset register (IAR), and will become available on the Sharing and Enabling Environmental Data (SEED) portal with this report.

There are 3 sub-folders within the spatial data pack v1.0 data package:

- Spatial data inputs – a list of all input data use in the project
- Modelling outputs – a list all the synthesised spatial products (MS01 – MS07 listed in table 7 of the technical report)
- Project report – final report both in PDF and word document and a excel spreadsheet of the list of spatial data.

The spatial data pack (v1.0) consists of both vector (shapefiles) and raster (GeoTiff) data, as listed in Table 9.

Table 9 List of published spatial data

Data name	Data description	Source	Projection
Koalas in the Landscape project study area.shp	Study area boundary	DCCEEW	Australian Albers (GDA 94)
Koala_site_records_1979_2019.shp	Koala occurrences site data	DCCEEW	Australian Albers (GDA 94)
Koala bioclimatic suitability model.tif	Koala bioclimatic suitability model	DCCEEW	Australian Albers (GDA 94)
Surface water availability.tif	Surface water availability	DCCEEW	Australian Albers (GDA 94)
Ground water availability.tif	Green accumulation index as a surrogate for ground water availability	DCCEEW	Australian Albers (GDA 94)

Data name	Data description	Source	Projection
Koala tree species index.tif	Koala tree suitability index	OEH 2018	Australian Albers (GDA 94)
Woody percent cover.tif	Woody extent map	NSW Woody 2017	Australian Albers (GDA 94)
MS01-Koala landscape capacity_Stable_Pi_t0.tif	Baseline *Pi* 2000	DCCEEW	Australian Albers (GDA 94)
MS01-Koala landscape capacity_Stable_Pi_t3.tif	Average *Pi* of 2030 projections for stable coupled	DCCEEW	Australian Albers (GDA 94)
MS01-Koala landscape capacity_Stable_Pi_t7.tif	Average *Pi* of 2070 projections for stable coupled	DCCEEW	Australian Albers (GDA 94)
MS01-Koala preclear1750 Potential_Pi_t0.tif	1750 reconstructed *Pi*	DCCEEW	Australian Albers (GDA 94)
MS02-2070 consensus map.tif	2070 consensus map for passive distribution at 2070	DCCEEW	Australian Albers (GDA 94)
MSO3-Degree of expected change.tif	Change in landscape capacity 2000–2070	DCCEEW	Australian Albers (GDA 94)
MS04-Persisting koala capacity.tif	Koala landscape capacity across all time-steps and projections	DCCEEW	Australian Albers (GDA 94)
MS05-Latent capacity	The additional landscape capacity that can be achieved with enhanced connectivity	DCCEEW	Australian Albers (GDA 94)
MS06-Habitat construction benefits	The level of (passive) occupancy possible by 2070 with full restoration	DCCEEW	Australian Albers (GDA 94)
MS07-Conservation options.tif	Koala conservation options map	DCCEEW	Australian Albers (GDA 94)

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More information

- AdaptNSW – Climate projections used on AdaptNSW [webpage]
- Statewide landcover and tree study method [webpage]