DEPARTMENT OF PLANNING, INDUSTRY & ENVIRONMENT

Integrated model–data fusion approach to measuring habitat condition for ecological integrity reporting

Implementation for habitat condition indicators

environment.nsw.gov.au

© 2020 State of NSW and Department of Planning, Industry and Environment

With the exception of photographs, the State of NSW and Department of Planning, Industry and Environment are pleased to allow this material to be reproduced in whole or in part for educational and non-commercial use, provided the meaning is unchanged and its source, publisher and authorship are acknowledged. Specific permission is required for the reproduction of photographs.

The Department of Planning, Industry and Environment (DPIE) has compiled this report in good faith, exercising all due care and attention. No representation is made about the accuracy, completeness or suitability of the information in this publication for any particular purpose. DPIE shall not be liable for any damage which may occur to any person or organisation taking action or not on the basis of this publication. Readers should seek appropriate advice when applying the information to their specific needs.

All content in this publication is owned by DPIE and is protected by Crown Copyright, unless credited otherwise. It is licensed under the Creative Commons Attribution 4.0 International (CC BY 4.0), subject to the exemptions contained in the licence. The legal code for the licence is available at Creative Commons.

DPIE asserts the right to be attributed as author of the original material in the following manner: © State of New South Wales and Department of Planning, Industry and Environment 2020.

Authorship and citation

This document was prepared by Jamie Love[1,3], Michael Drielsma[1,3], Kristen Williams[2], Rajesh Thapa[3]

[1] Department of Planning, Industry and Environment, Sydney
[2] Commonwealth Scientific and Industrial Research Organisation (Land and Water), Canberra
[3] University of New England, Armidale

This document should be cited as: Love J, Drielsma MJ, Williams KJ & Thapa R 2020, *Integrated model–data fusion approach to measuring habitat condition for ecological integrity reporting: Implementation for habitat condition indicators*, Biodiversity Indicator Program Implementation Report, Department of Planning, Industry and Environment NSW, Sydney, Australia.

Published by:

Environment, Energy and Science
Department of Planning, Industry and Environment
4 Parramatta Square, 12 Darcy Street, Parramatta NSW 2150
Phone: +61 2 9995 5000 (switchboard)
Phone: 1300 361 967 (Environment, Energy and Science 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

Report pollution and environmental incidents
Environment Line: 131 555 (NSW only) or info@environment.nsw.gov.au
See also www.environment.nsw.gov.au

ISBN 978-1-922318-52-7
EES 2020/0101
February 2020

Find out more about your environment at:

www.environment.nsw.gov.au

Contents

Acknowledgements vii

Acronyms and abbreviations vii

Context viii

Summary ix

Key findings x

1. Introduction 1
   - 1.1 Habitat condition indicators 1
2. Measuring ecological condition 4
   - 2.1 Adapting the NVM condition model 5
   - 2.2 Source data 7
   - 2.3 Model inputs 9
   - 2.4 Ecological condition model 9
   - 2.5 Spatial precision 12
   - 2.6 Data gaps 13
   - 2.7 Extended ecological condition 14
3. Measuring ecological connectivity and ecological carrying capacity 16
   - 3.1 Multi-scale habitat connectivity modelling 17
   - 3.2 Ecological connectivity model 20
   - 3.3 Ecological carrying capacity model 22
   - 3.4 Combining habitat connectivity across scales 25
4. Reporting habitat condition indicators 27
5. Further work 30
   - 5.1 Measuring indicator confidence 31
   - 5.2 Measuring indicator change 32
   - 5.3 Forecasting indicator change 32
   - 5.4 Comparing indicators with existing similar products 33

Appendix A Indicator workflow diagrams 34

Appendix B Ecological condition model data processing 38
   - 1.1 GDM of NSW Keith class probability grids (Uncon3) 38
   - 1.2 SPOT woody FPC 2011 and woody change data (5–10 m) 2011–2013 38
   - 1.3 Biometric vegetation cover benchmarks 39
   - 1.4 National parks and public conservation tenure 39
   - 1.5 TSR proportion 40
   - 1.6 Terrain ruggedness 41
   - 1.7 Weighted distance to water 41

1.8 Relative foliage projective cover 42
1.9 Soil resilience index 43
1.10 Natural woodiness 45
1.11 Stable green vegetation 46
1.12 Nativeness 47
1.13 Ecological condition model raster calculations 49
Appendix C. Maps of ecological condition inputs for New South Wales 50
Appendix D. Lower bound FPC thresholds 55
Appendix E. Nativeness land-use classification 59
Glossary 64
References 69

List of tables

Table 1 Source data used to derive inputs for the model of ecological condition. 8
Table 2 Inputs into the model of ecological condition and their descriptions. 9
Table 3 Parameters used for multi-scale analysis sampling, spatial links parameters used for ecological connectivity and context analysis parameters used for ecological carrying capacity 19
Table 4 Foliage projective cover (FPC) factors applied to 2011 FPC data to account for change between 2011 and 2013 38
Table 5 '*tenureNP*' values used as an input to condition component models 40
Table 6 Soil properties (OEH 2017a) and their ranges allocated to scores used to develop the simplified *nswSRI* 44
Table 7 Fractional cover time series metrics 46
Table 8 Condition weights applied to classes of *nativeness* for woody and non-woody condition components and where the *nativeness* input is used to constrain stable green vegetation's contribution to the non-woody component 48

List of figures

Figure 1. Nested structure used to arrange and link indicators for measuring biodiversity and ecological integrity in New South Wales. This implementation report covers indicators in the habitat condition indicator family (shown by the darker grey box). viii
Figure 2 Ecological condition, ecological connectivity and ecological carrying capacity indicators for terrestrial habitat in New South Wales as of 2013. xi

Figure 3 Remaining ecological carrying capacity (brown) due to loss of ecological condition (light grey), and additional loss of capacity due to fragmentation (dark grey), for all New South Wales, NPW reserves, other tenures, and bioregions. xii

Figure 4 The overarching Biodiversity Indicator Program’s monitoring framework outlining how habitat condition indicators are related to other ecological integrity and biodiversity indicators. 3

Figure 5 The ecological condition indicator model for New South Wales estimating the ecological condition of habitat, as of 2013. 10

Figure 6 Expression tree of the ecological condition model. 11

Figure 7 Ecological condition (grey = low to red = high) over satellite imagery showing identifiable landscape features in the far north-west (top left), north-east (top right), south-west (bottom left) and south-east (bottom right) of New South Wales produced at 1:50,000 scale. This scale is unsuitable for indicator use and these maps are only provided to demonstrate the model’s spatial precision. 13

Figure 8 Data gaps (‘holes’) present in source data and propagated through the model of ecological condition. These were filled using the Biodiversity Impacts and Adaptation Project condition layer (see section 2.7: Extended ecological condition). 14

Figure 9 Extended ecological condition using the Biodiversity Impacts and Adaptation Project condition layer (OEH 2016) to provide context outside New South Wales. 15

Figure 10 The relationship between ecological condition (habitat quality at each location), ecological connectivity (accumulated path connectivity) and ecological carrying capacity (spatial context) for the same area. 17

Figure 11 The power law and fractal perspective applied to resample the original 90-metre resolution data (grid cells in grey) to coarser analysis resolutions (grid cells in blue). The 5760-metre resolution was only used for spatial links analysis. 18

Figure 12 Example of multi-scale analysis sampling showing the same single cell location (blue) in each of the 16 overlapping pixel offsets for the 360-metre analysis resolution relative to the original 90-metre resolution raster cells shown in black. 18

Figure 13 Distance decay function applied to calculate path permeability from the effective distance of paths, scaled using the distance in cells and shown for paths consisting entirely of pristine (solid blue) and cleared (dashed red) habitat value. 21

Figure 14a (top) Distance decay function applied to calculate path permeability ($\boldsymbol{wij}$) from accumulated cell permeabilities (p) scaled using the distance in cells and shown for paths consisting entirely of pristine (solid blue) and cleared (dashed red) habitat value. 24

Figure 15 The ecological connectivity indicator model for New South Wales estimating each location’s contribution to habitat connectivity and the ecological carrying capacity of surrounding locations, as of 2013. 26

Figure 16 The ecological carrying capacity indicator model for New South Wales estimating the intactness and naturalness of terrestrial habitat at each location considering the effect of surrounding habitat loss and fragmentation, as of 2013. 26
Figure 17 Ecological condition for 2013 averaged for each of the 571 Mitchell landscapes in New South Wales. 28
Figure 18 Ecological carrying capacity for 2013 averaged for each of the 571 Mitchell landscapes in New South Wales. 28
Figure 19 Histogram showing the distribution of ecological carrying capacity values in NPW reserves (left) and other tenures (right). 29
Figure 20 The agreement between ecological condition on the y axis and 33 desktop-based assessments of habitat condition, performed using satellite imagery to evaluate the habitat condition assessment system (Donohue [CSIRO] 2018, pers. comm.) 31
Figure 21 Vegetation stability indices calculated from fractional cover time series data (2007–2016) shown for the Liverpool Plains area in New South Wales with satellite imagery included for reference (top left). 47
Figure 22 Currency of land-use data (from 2003 to 2017) in New South Wales used to derive ecological condition's *nativeness* input. 48
Figure 23 Ecological condition model showing woody and non-woody components, their inputs and weights. 49
Figure 24 *tenureNP* input layer identifying national parks and other public conservation areas (as used to report on NPW reserves). 50
Figure 25 *propTSR* input layer with the proportion of each 90-metre grid cell that is travelling stock reserve (TSR). 51
Figure 26 *ruggedness* input layer showing local variation in elevation. 51
Figure 27 *distWater* input layer showing the distance to water weighted by stream order. 52
Figure 28 *relFPC* input layer showing foliage projective cover (FPC) scaled relative to thresholds for intact vegetation types. 52
Figure 29 *woodiness* input layer showing the amount of natural woody cover predicted to have originally occurred prior to the industrial era. 53
Figure 30 *nativeness* input layer providing an estimate of the nativeness of vegetation based on land use. 53
Figure 31 *nswSRI* input layer showing soil resilience derived from land systems and key soil properties. 54
Figure 32 *stblGrnVeg* input layer showing the amount and stability of green vegetation. 54
Figure 33 Example of FPC transformations (equation 8) shown for vegetation formations. 55

Acknowledgements

The authors would like to acknowledge those who have made valuable contributions to this work. This includes the NSW Government for funding, and Commonwealth Scientific and Industrial Research Organisation (CSIRO) for leading the Biodiversity Indicator Program. The remote-sensing expertise of Randall Donohue (CSIRO), Tim Danaher (Department of Planning, Industry and Environment, DPIE), Tony Gill (DPIE) and the Native Vegetation Information Science team (DPIE). Megan McNellie (DPIE) for her ongoing contributions to the Biodiversity Indicator Program. Becky Schmidt (CSIRO) and Clare Gambley (CSIRO) for invaluable contributions to the outlook report, also Joanne Wilson, Laura Babian, Mark Littleboy, Greg Summerell, Jeremy Black and Jo White for their support.

DPIE reviewers: Tom Barrett, Murray Ellis and Ian Oliver; and external reviewers: Phil Gibbons (Australian National University) and Bertram Ostendorf (University of Adelaide). Tim Cooney (DPIE) and Darren King (CSIRO) for assisting in workflow and data management, and all those who contributed to the original native vegetation management condition model or source data products used here and in any previous work in this field. Thanks to Donella Andersen, Nature Edit, for her great work editing and formatting this report.

Acronyms and abbreviations

ACT	Australian Capital Territory
ALUM	*Australian Land Use and Management Classification* (Australian Government 2006)
BIAP	Biodiversity Impacts and Adaptation Project
CBA	Cost benefit approach
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEM	Digital elevation model
FPC	Foliage projective cover
GDM	Generalised dissimilarity model
NARCliM	NSW and ACT Regional Climate Modelling project
NHA	Neighbourhood habitat area
NPW	National park and wildlife
NPWS	National Parks and Wildlife Service
NSW	New South Wales
SQI	Soil quality index
SRTM	Shuttle radar topographic mission
TSR	Travelling stock reserve
VAST	Vegetation assets, state and transitions

Context

The New South Wales (NSW) Government has introduced new legislation for biodiversity conservation and native vegetation management, including the *Biodiversity Conservation Act 2016* (the BC Act) which commenced on 25 August 2017. The goals of the BC Act include the conservation of biodiversity at bioregional and state levels, a reduction in the rate of species loss, and effective management to maintain or enhance the integrity of natural habitats. To contribute to assessing the performance of the new legislation, the former Office of Environment and Heritage established the Biodiversity Indicator Program to report on the status of biodiversity and ecological integrity at regular intervals. The responsibility of implementing this program now rests with the Department of Planning, Industry and Environment.

Monitoring of *all* known biodiversity in New South Wales is impractical. Surrogates intended to best represent biodiversity are often relied on, however, monitoring remains a large, complex task that requires novel approaches to data collection and use, including the application of models to help measure status and track change. This indicator implementation report details how three ecological integrity indicators for measuring status and change in habitat condition are developed and applied using existing and new approaches to analysing and modelling spatial data and associated information.

The overarching monitoring framework, which outlines how indicators are related and derived, is detailed in *Measuring Biodiversity and Ecological Integrity in New South Wales: Method for the Biodiversity Indicator Program* (OEH & CSIRO 2019) and summarised in Figure 1.

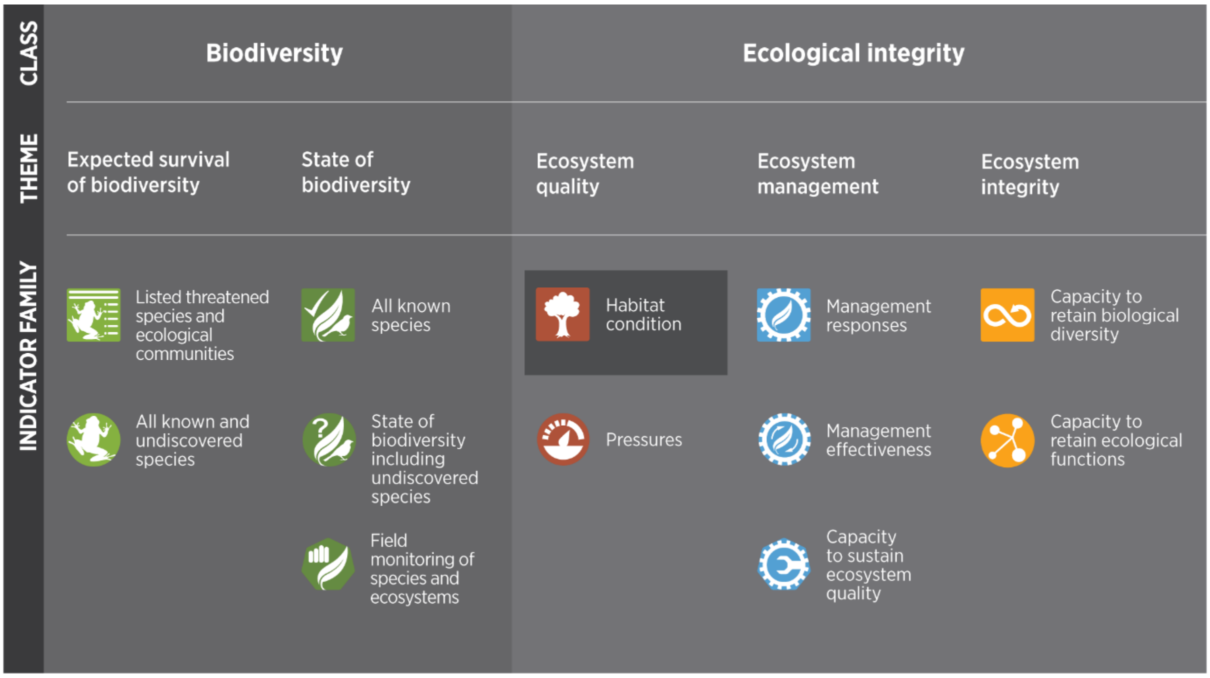


Figure 1. **Nested structure used to arrange and link indicators for measuring biodiversity and ecological integrity in New South Wales. This implementation report covers indicators in the habitat condition indicator family (shown by the darker grey box).**

The method for the Biodiversity Indicator Program establishes a nested design within which all **indicators**, as they are developed, have a place. Each indicator is nested with others of its type in an **indicator family**, and each family is nested within one of five **themes** which are associated with either the biodiversity or ecological integrity **class** of indicators (as shown in Figure 1).

The key results and highlights are presented in one of several report cards in the first *NSW Biodiversity Outlook Report* (DPIE 2020). The indicators detailed in this report sit within the nested framework as follows:

Class: **Ecological integrity**

Theme: **3. Ecosystem quality**

Indicator family: 3.1 Habitat condition

Indicator: 3.1a Ecological condition of terrestrial vegetation

The ability of terrestrial habitat at each location to support its biodiversity

Indicator: 3.1b Ecological connectivity of terrestrial vegetation

The contribution each location makes to connectivity of terrestrial habitat by way of its ecological condition and relative position in the landscape (e.g. as part of a habitat corridor or a stepping stone)

Indicator: 3.1c Ecological carrying capacity of terrestrial vegetation

Each location’s capacity to support native species and ecosystems, considering its ecological condition and the effect of surrounding habitat loss and fragmentation

The **habitat condition** indicator family is an overall measure of the capacity of habitats to support the original complement of native plants and animals. By considering the condition and position of each habitat and its connection with other surrounding habitats across a region, the remaining capacity of an area to support its native plants and animals can be inferred. In the future, the terrestrial indicators will be complemented by other indicators for freshwater, coastal and marine habitats.

Summary

- **Ecological condition** measures the general quality of habitat for biodiversity at each location.
- **Ecological connectivity** measures the value that the general quality of habitat at each location contributes to habitat connectivity.
- **Ecological carrying capacity** measures the ability of habitats to support the persistence of their original biodiversity (that which existed prior to any clearing or degradation of habitats in the industrial era) and combines the measure of each location’s habitat quality with its connectivity to, and the quality of, surrounding habitat.

The two measures of general habitat quality (i.e. ecological condition and ecological carrying capacity) are intended to be used with predictions of biodiversity distributions for particular biological groups to measure the proportion of species or ecosystems retained or likely to persist, all else being equal.

Ecological condition and ecological carrying capacity can be reported for individual locations and different regions including the whole of New South Wales. At this stage, ecological connectivity can be reported for individual locations. Methods for appropriately aggregating and reporting the value of ecological connectivity within different regions are under development.

The methods used to measure these three indicators build on work published in peer reviewed reports and literature. Previous assessments were updated using the best available high-resolution data applied across New South Wales using 90-metre raster grids. Improvements in data processing and workflow have significantly streamlined throughput and reduced computation times, aiding repeat applications for future assessments of these indicators.

Varying time periods of source data (principally remote-sensing data and land-use mapping) used in these indicators support approximating their status as of 2013. Ongoing data acquisition programs within New South Wales will enable future reporting closer to the legislative baseline of August 2017, and future time periods.

The results and findings of this analysis are presented in the first *NSW Biodiversity Outlook Report* (DPIE 2020) and can be summarised by the following key findings.

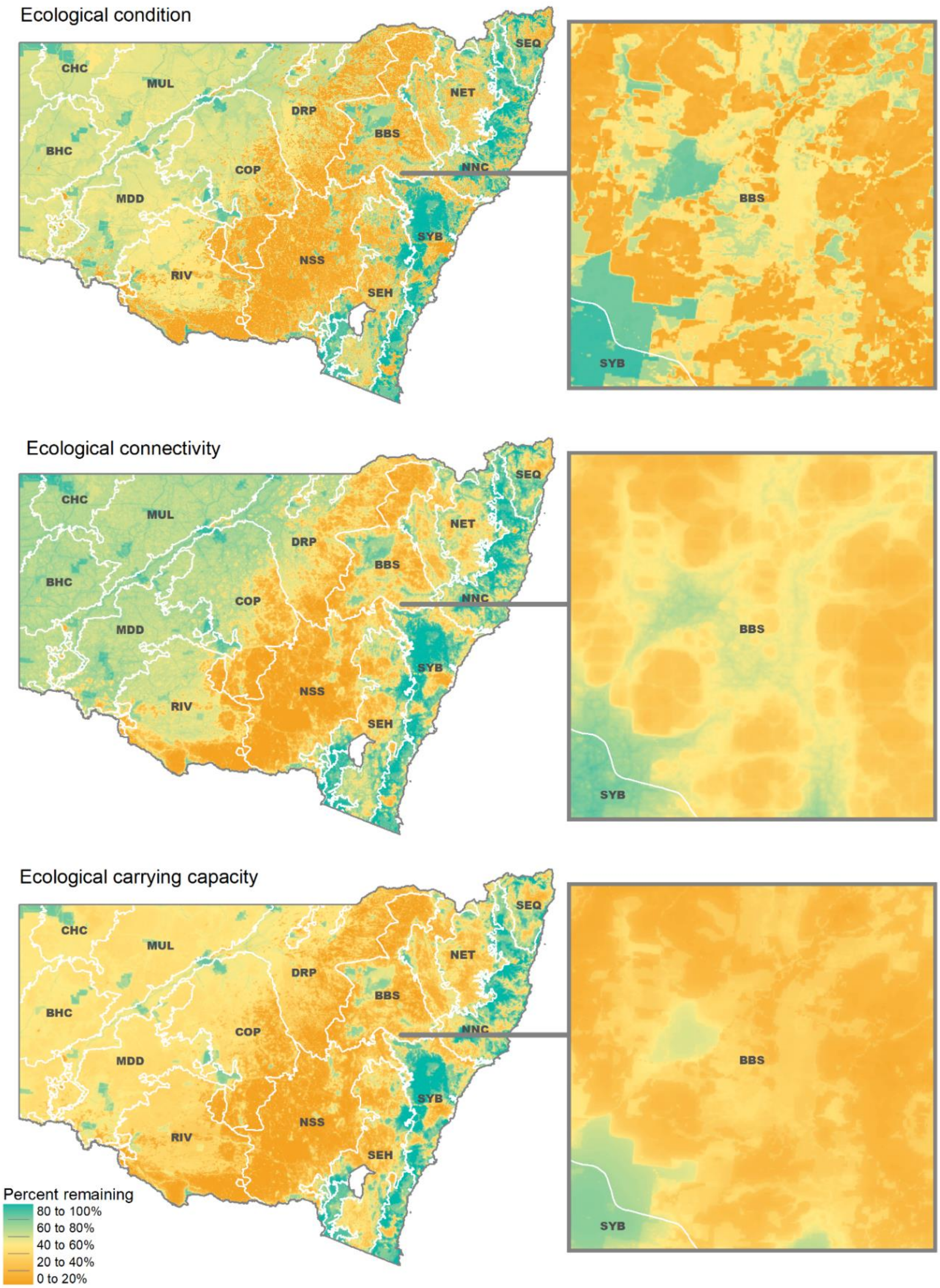
Key findings

The status of ecological condition, connectivity and carrying capacity presented here are measures for 2013. Data required to enable a mid-2017 assessment (i.e. at commencement of the BC Act) are currently in development.

- Clearing and degradation of habitat since the pre-industrial era is estimated to have reduced **ecological condition** in New South Wales from 1.0 to 0.44.
- Taking account of both ecological condition and habitat fragmentation, the **ecological carrying capacity** of remaining habitat in New South Wales is estimated to have been reduced from 1.0 to 0.33.
- Due to lost **ecological connectivity**, the fragmentation of remaining habitat alone has reduced its **ecological carrying capacity** by 25% (from 0.44 to 0.33).
- Maps of these three habitat condition indicators for New South Wales are shown in Figure 2. Ecological condition and ecological carrying capacity are reported for the whole of New South Wales, inside and outside of national park and wildlife (NPW) reserves (i.e. public reserves established in perpetuity under the *National Parks and Wildlife Act 1974*), and NSW bioregions in Figure 3.
- Patterns of habitat loss and fragmentation vary significantly. As of 2013, the Australian Alps, South East Corner, and NSW North Coast bioregions have the highest remaining ecological carrying capacity (0.53 to 0.62) while the NSW South Western Slopes, Brigalow Belt South and the Riverina bioregions have the lowest (0.15 to 0.25). See Figure 3.

Future assessments of the indicators

- Work is under way to improve the accuracy and validation of these three habitat condition indicators using field collected vegetation integrity measures that are being developed to underpin the *Biodiversity Assessment Methodology* (OEH 2017a) and new remotely sensed vegetation cover time-series products.



Ecological condition

Ecological connectivity

Ecological carrying capacity

Figure 2 **Ecological condition, ecological connectivity and ecological carrying capacity indicators for terrestrial habitat in New South Wales as of 2013.**

The grey line points to the location of detailed example insets (right). Each indicator's potential range of values is from 0 (dark orange) where habitat has been completely removed and where no connectivity to other habitat exists, to 100 (dark teal) where habitat remains intact and well-connected relative to a pre-industrial state.

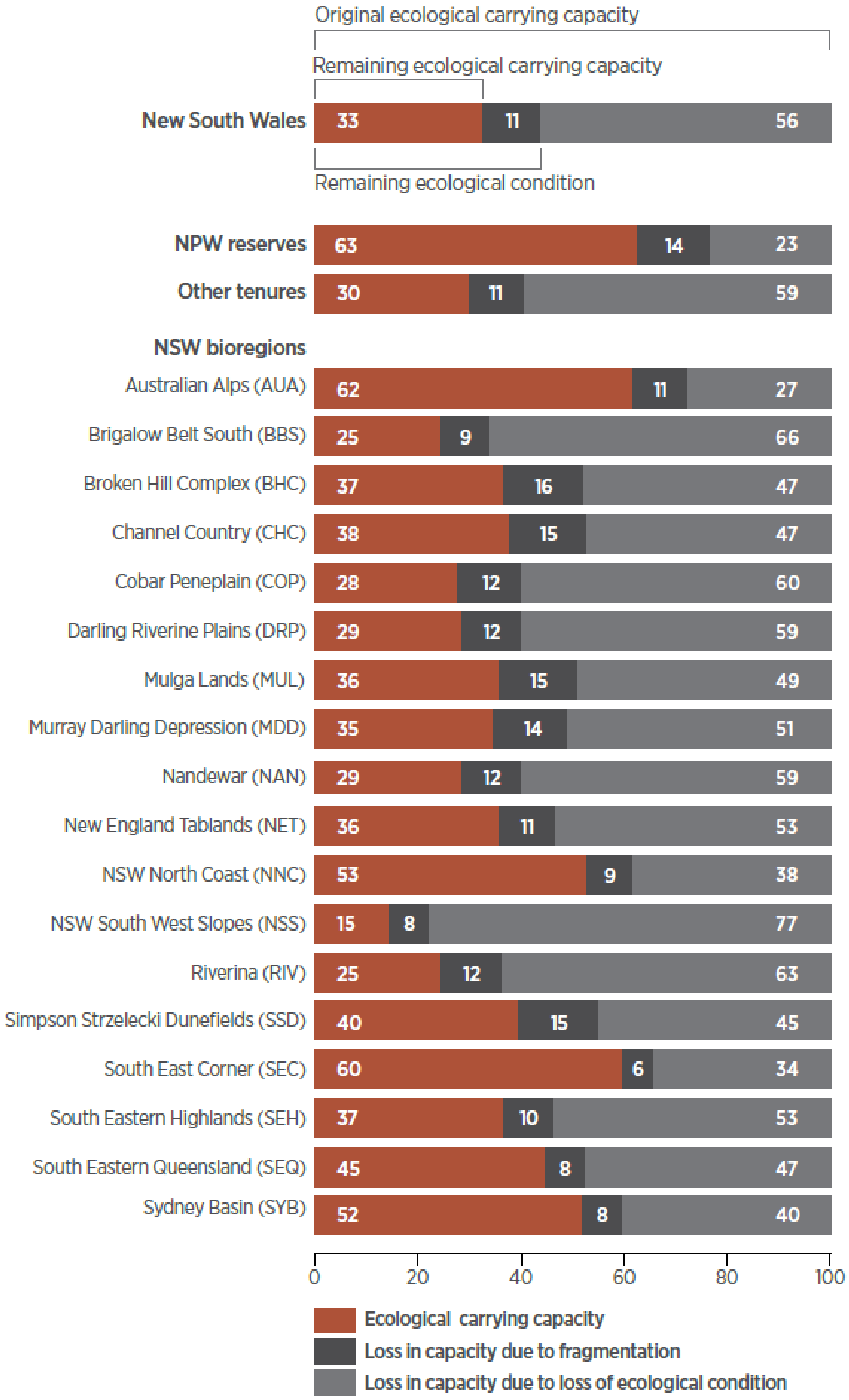


Figure 3 **Remaining ecological carrying capacity (brown) due to loss of ecological condition (light grey), and additional loss of capacity due to fragmentation (dark grey), for all New South Wales, NPW reserves, other tenures, and bioregions.**

The chart summarises the status of habitat condition in New South Wales and how this varies between NPW reserves (i.e. public reserves established in perpetuity under the National Parks and Wildlife Act) and other tenures, and for the different bioregions across the state.

1. Introduction

The former Office of Environment and Heritage NSW collaborated with the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Macquarie University and the Australian Museum to develop a method for the collection, monitoring and assessment of biodiversity information in New South Wales at regional and statewide scales (OEH & CSIRO 2019). The technical implementation of the method specifically detailed in this report establishes a 'first assessment' (as of 2013) for indicators in the habitat condition indicator family.

Habitat condition is one of several families of indicators related to ecosystem quality and used for reporting ecological integrity in New South Wales. The three indicators of habitat condition reported here: ecological condition, ecological connectivity and ecological carrying capacity, are all measures of terrestrial habitats. Additional indicators are being developed to measure aquatic habitats. The habitat condition indicators are also used as inputs to several biodiversity indicators (Drielsma et al. 2020; Nipperess et al. 2020).

1.1 Habitat condition indicators

The condition of terrestrial habitat in New South Wales varies both spatially and temporally as contributing factors differ between locations and change over time. Its status ranges from areas where habitat remains intact relative to an estimated original, potential, or pre-industrial state, through to areas where natural habitat has been completely removed or replaced. It is largely a function of how habitat has been managed over time; however, naturally occurring events and environmental conditions also contribute to varying degrees.

Habitat that remains intact and well-connected is expected to retain a greater proportion of its original or potential diversity, thereby contributing to the integrity of ecosystems and the persistence of biodiversity. It provides the resources native species need to persist, as individuals and together as populations and ecosystems, and allows them to adapt to changes in their environment or respond to threats, through evolutionary processes or by moving within and beyond their current distribution ranges.

The ecosystem quality theme of ecological integrity indicators (Figure 4) includes four component measures of habitat condition, three of which are developed here. Together, these indicators estimate the capacity of existing habitat to maintain the ecological processes needed to support terrestrial species and ecosystems native to New South Wales. The three habitat condition indicators implemented here are:

- **Ecological condition of terrestrial native vegetation**

  The generalised quality of terrestrial habitat for biodiversity at each location

  This indicator is a measure of the intactness and naturalness of terrestrial habitat at each location without considering the indirect influence of surrounding habitat loss and fragmentation. It can be reported for individual locations and averaged for regions including the whole of New South Wales.
- **Ecological connectivity of terrestrial native vegetation**

  The contribution each location makes to the connectivity of terrestrial habitat by way of its ecological condition and relative position in the landscape

  This indicator measures each location's contribution to the connectivity of habitat (and therefore the ecological carrying capacity of surrounding locations) by way of its habitat quality and its relative position in the landscape (e.g. as part of a habitat corridor or as a stepping stone). Ecological connectivity is measured across multiple ecological scales and can be reported for individual locations.

- **Ecological carrying capacity of terrestrial native vegetation**

  Each location's capacity to support native species and ecosystems, considering its ecological condition and the condition and connectivity of surrounding habitat

  This indicator measures the ability of habitats to support the persistence of their original biodiversity (genes, species and ecosystems). It combines the ecological condition at each location with measures of its connectivity to, and the quality of, surrounding habitat across multiple ecological scales. It estimates the effect surrounding habitat loss and fragmentation has on biological movements, such as foraging, dispersal and migration. This indicator represents the ability of an area to maintain self-sustaining and interacting populations of all species naturally expected to occur. It can be reported for individual locations and averaged for regions including the whole of New South Wales.

Indicators in the habitat condition family (*sensu* OEH & CSIRO 2019) use remote-sensing, land-use and other relevant spatial products together with semi-inferential modelling to estimate the extent of habitat loss (see section 2: Measuring ecological condition), and mechanistic modelling to assess the ecological process implications of habitat loss and fragmentation (see section 3: Measuring ecological connectivity and ecological carrying capacity). These three indicators depict different aspects of the capacity of habitats to support native plants and animals, and the complex ecosystems they form. The implementation of these indicators is summarised by workflow diagrams (Appendix A) and further detailed in the following sections of this report.

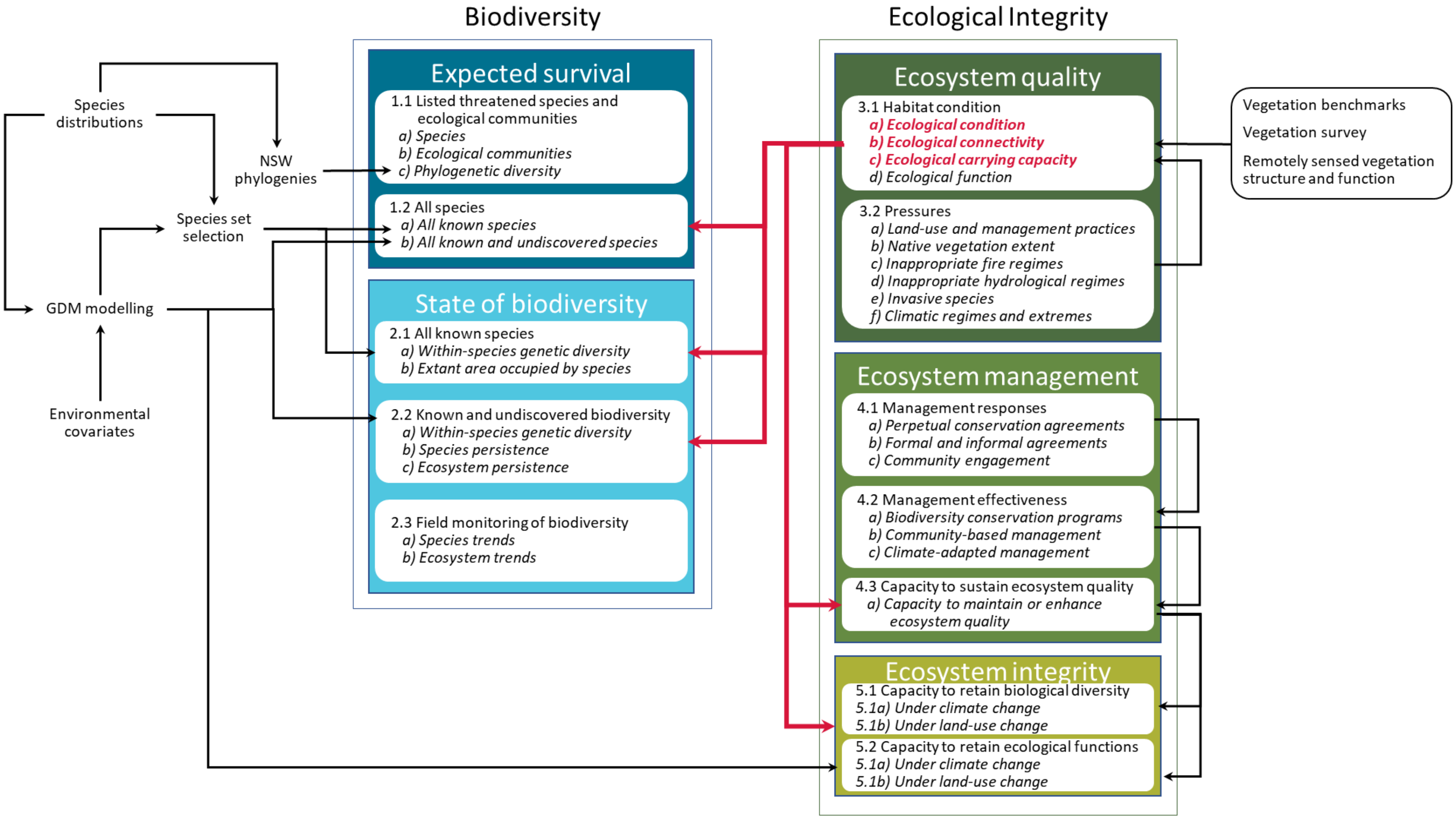


Figure 4 **The overarching Biodiversity Indicator Program's monitoring framework outlining how habitat condition indicators are related to other ecological integrity and biodiversity indicators.**

The red arrows point to indicators that depend on habitat condition. Nested structure: classes are in columns, themes are the coloured boxes within columns, and indicator families are the white boxes within coloured boxes. Adapted from OEH & CSIRO (2019).

2. Measuring ecological condition

Ecological condition of terrestrial habitat can be measured in a variety of ways (Hak & Comer 2017; Lawley, Lewis, Clarke, & Ostendorf, 2016, Drielsma et al. 2012, Newell et al. 2006). Methods are rapidly evolving as data availability and quality increases, and as new technologies are trialled and operationalised (e.g. McNellie et al. 2014; Harwood et al. 2016).

Measures of ecological condition are best determined from attributes that are relevant to the scale of reporting. Site-scale field assessments can be used to report detailed attributes at individual locations, such as native vegetation cover for different growth forms or strata, species richness, exotic species abundance and other structural, functional and compositional characteristics (OEH 2017a). These measures can be monitored over time, scaled against benchmarks attained from reference sites (OEH 2017c) or based on estimated potentials, and combined to report a location's overall measure of ecological condition. Obtaining consistent coverage of site-scale attributes across large heterogeneous regions is generally impractical; However, when sufficiently sampled, site information can be used to train and validate predictive models. Such work is progressing in New South Wales and will likely contribute to future indicator measures when available.

At regional scales, reporting on remotely observable spatial attributes such as the extent, cover, size and spatial context of habitat can provide accurate, yet less detailed (coarser grained), measures relating to ecological condition. Regional scale attributes are routinely measured from remotely sensed products. These include foliage projective cover and various other vegetation indices (OEH 2017d; Tehrany, Kumar & Drielsma 2017). Other attributes such as understorey and ground-cover disturbance or exotic species presence can be inferred, however imperfectly, from data such as land-use, land-cover and tenure mapping, or from other mapped or modelled attributes considered to influence or reflect characteristics of ecological condition. Existing approaches to habitat condition assessment applied in New South Wales have been better suited to measuring attributes of woody habitat (Dillon, McNellie & Oliver 2011; Drielsma, Howling & Love 2012); However, emerging sensor technologies (e.g. satellite-based radar, light detection and ranging, and hyperspectral), combined with an improved understanding of the relationships with field and remotely measurable attributes of condition, are improving the ability to reliably monitor, model and report the ecological condition of all habitat types across whole diverse regions (Harwood et al. 2016; Lausch et al. 2017; Vihervaara et al. 2017) such as New South Wales.

Here, the Ecological condition of terrestrial habitat indicator is derived using a semi-inferential approach to estimate the intactness and naturalness of habitat. Ecological condition combines direct remotely sensed measures of vegetation cover with inferred measures from a range of relevant sources. The approach addresses the challenge of quantifying the complexity and multi-facetted nature of ecological condition across large, heterogeneous regions by synthesising multiple lines of evidence. In some instances, characteristics are directly measured, such as the loss of natural vegetation cover, using remotely sensed products. In other cases, characteristics are only inferred from proxy information, such as understory disturbance, or the presence and influence of different land-use and management regimes. The approach provides a complete statewide estimate of ecological condition, but is limited by the currently available data. Reliability will vary across space, spatial scales, environments, and habitat characteristics present at any location.

A 90-metre spatial raster is used to assign ecological condition values to every location (90-metre grid cell) across New South Wales using data sources of varying scale and resolution, combined with expert interpretation of their relationships to condition. The approach is based on the most recent statewide vegetation condition model for New South Wales (Drielsma et al. 2012) that was designed to assess the biodiversity benefits of native vegetation management. This earlier model, the native vegetation management condition model (henceforth 'NVM condition model') was itself partially informed by the State of the

Catchment vegetation condition model for New South Wales (Dillon et al. 2011) that applied the vegetation assets, state and transitions (VAST) framework (Thackway & Lesslie 2006) to ALUM-classified land-use mapping (see Australian Government 2006 and Appendix B, 1.12) and vegetation cover. The NVM condition model also incorporated novel methods for scaling remotely sensed vegetation cover relative to benchmark conditions expected for intact vegetation, that were developed to model native vegetation condition for the Great Eastern Ranges (Drielsma et al. 2010).

2.1 Adapting the NVM condition model

The integrated model–data fusion approach, used previously to model NVM condition, and adopted here for ecological condition, is applied in a context of scarce and incomplete data. Thus, the approach draws on multiple lines of available evidence, combining them using expert understandings of what each data input can provide and the quality of that data.

The original NVM condition model provided an estimate of vegetation condition at every 250-metre grid cell across New South Wales, as an input to statewide biodiversity assessment models (Drielsma et al. 2012). The NVM condition model has since underpinned numerous state and regional biodiversity evaluation and prioritisation projects (Drielsma et al. 2012; Drielsma et al. 2015; Foster et al. 2016; Lentini et al. 2013; OEH 2016). The development of the ecological condition indicator aimed, as far as possible, to reflect the data, knowledge and processes used in the NVM condition model. However, wherever possible, accuracy, currency and spatial resolution have been improved.

While the process for modelling the ecological condition of habitat across New South Wales is both similar to, and builds on, prior approaches used to model vegetation condition (Dillon et al. 2011; Drielsma et al. 2012). It is important to note that it differs conceptually to vegetation condition models that resolve quantities or qualities relating to specific attributes of vegetation structure, function and composition which are commonly measured separately and combined into a proxy for habitat condition (Eyre et al. 2015; OEH 2017a). Rather, its intent is to directly estimate a single generalised measure of the quality of habitat for all native species and ecosystems from relevant available spatial information.

Development of the original NVM condition model involved a series of consultative workshops and expert peer reviews with the former Department of Environment and Climate Change NSW and Catchment Management Authority (now Local Land Services) staff between 2009 and 2011 (Drielsma et al. 2012). Expert review was initially sought in relation to the structure of the model, the selection of data sources, and then in relation to the weights used to combine data from different sources; including land-use and tenure mapping, remotely sensed vegetation cover and other contributing landscape attributes. In each case, the weightings applied to both discrete and continuous data inputs were a combination of the expert-informed intrinsic strength of the relationship between each input and native vegetation condition (here, ecological condition), and the confidence held in the accuracy of the layers.

The NVM condition model used an aggregation of three separately modelled condition components (i.e. woody vegetation, non-woody vegetation and soil resilience), with the contribution from each apportioned by a model of natural woodiness. The NVM condition model's primary focus was on predicting the structural intactness of native vegetation across the state; whereas Ecological condition indicator is primarily focused on modelling the intactness and naturalness of terrestrial habitat.

At the time, the NVM project recognised that:

> Much work remains to be done in the area of vegetation condition mapping to ensure the ongoing improvement in the provision of state-wide biodiversity assessment capacity (Drielsma et al. 2012).

This remains the case today. Nonetheless, the NVM-adapted ecological condition model detailed in this report provides, to date, the most detailed and complete statewide estimate of ecological condition for New South Wales.

In adapting the NVM condition model to measure ecological condition, the ongoing need for further development is acknowledged:

- Quantitative validation is planned but not yet implemented due to a lack of suitable site data. In the interim, qualitative assessment indicates the model is suitable for statewide and regional scale reporting, however, a formal process undertaken in future will allow a more explicit assessment of model accuracy e.g. using in situ vegetation integrity observations (OEH 2017c).
- The data underlying the model need updating. The original NVM condition model used NSW land-use mapping and remotely sensed land-cover products that are no longer current. While ecological condition uses the most recently available data, in many cases these are representative of periods prior to the August 2017 baseline. Data capture techniques are also advancing significantly, but new techniques were not operational in time for this application.
- Advances in vegetation modelling may engender new approaches. Emerging data-driven methods using statistical models and field observations of condition for training and validation have the potential to provide more robust condition assessments (Harwood et al. 2016; Tehrany et al. 2017). However, more work on remote-sensing variables (Jarihani et al. 2014), suitable observation-based training data and modelling approaches is needed to prove these methods before they can be routinely applied.

These factors influenced the decision to proceed with adapting the NVM condition method as a practical starting point for improving our general knowledge of ecological condition across New South Wales. Approaches to modelling habitat condition (Harwood et al. 2016), blending of remote-sensing variables (Jarihani et al. 2014) and in situ vegetation integrity observations (OEH 2017c) in New South Wales are examples of new developments presently under way that are expected to contribute to future assessments of this indicator (OEH & CSIRO 2019). The NVM method is flexible, and can be adapted to account for such developments in both spatial data and analysis capabilities. In this case of ecological condition, new spatial data products such as LandSat fractional cover time series metrics (Donohue, Lingtao & Williams 2017) and NSW digital soil mapping (OEH 2017b) are incorporated. The NVM-adapted ecological condition model also incorporates the most recent land-use and remotely sensed vegetation cover data available for the whole of New South Wales.

The NVM method can be readily updated using new spatial data as it’s developed and enables ‘snapshot’ monitoring of change in ecological condition between two points in time, given data that are representative of both epochs. The currency of updated source data used here ranges from 2003 to 2017 resulting in a model that is most representative of ecological condition in 2013. Compared with the former 250-metre NVM condition model, the new ecological condition layer improves data currency (closer than previous products to the time of commencement of the BC Act), level of detail, spatial precision and resolution. Used here to model ecological condition, the NVM method provides a current knowledge baseline against which to assess future improvements in habitat condition monitoring and allows related knowledge gaps to be identified and prioritised, helping to optimise future work.

While ecological condition currently provides our best estimate of generalised habitat condition status across New South Wales, the NVM-based model is expected to improve through ongoing review and refinement of data inputs and the expert-derived weights assigned to those inputs. These inputs may in future be calibrated or replaced using new statistical analyses directly informed by site observation data. As new in situ condition observation data become available (e.g. through consistent, on-ground monitoring and assessments using the vegetation integrity method by programs initiated under the BC Act), the model may lend itself to optimisation or machine learning approaches (e.g. Harwood et al. 2016; McNellie et al. 2014). This may improve the model's predictive capacity through statistical selection and weighting of ecological condition predictors.

It is expected that over time, the adapted NVM condition model used here for the Biodiversity Indicator Program's ecological condition indicator will become a valuable part of greater efforts aimed at improving our knowledge of the ecological condition of habitat, and the ways in which it is monitored in New South Wales. The data will have utility in other programs of work such as the Biodiversity Conservation Trust, environmental offsetting or program planning by the *Saving our Species* program; or wherever there is a need for comparative measures using estimates of habitat condition to rank the ecological costs or benefits of alternative management actions.

2.2 Source data

The Biodiversity Indicator Program's ecological condition indicator relied on multiple sources of information from which inputs to the model were derived. Source data (Table 1) were initially obtained from the former Office of Environment and Heritage's corporate and Science Division databases, or developed in collaboration with the CSIRO. Spatial data required relatively complete and consistent coverage for New South Wales. However, collated source data had some unavoidable spatial irregularities, mostly at the state boundary, and especially along the coast. Additionally, no extrapolation or other filling of gaps in source data was undertaken, therefore, the final coverage of indicator products was based on the common coverage across all source datasets.

Source data were obtained in either GDA94 geographic or NSW Lamberts projection. All vector (polygon/line) source data were raster-converted at approximatley 90 metres ($0.0008\dot{3}$° or 3 second), or finer where spatial detail warranted and then aggregated to 90 metres. Rasterised data sources were aggregated up to 90 metres where the source resolution was finer, or resampled to 90 metres where coarser. Bilinear resampling was used for continuous data and nearest neighbour resampling used for categorical data. While some spatial error and loss of information is inevitable when raster-converting, resampling or reprojecting spatial data, methods for developing model inputs (see Appendix B) were selected to minimise the loss of information and precision, and the resulting spatial accuracy of indicator products was considered appropriate for their scale (see section 2.5: Spatial precistion).

Table 1 Source data used to derive inputs for the model of ecological condition.

Ecological condition data source	Type	Retrieved from	Version or date retrieved	Reference
NSW SRTM Level 2, 1 second (30 m) DEM v1.0 (SD09001)	30-m raster	OEH Corporate: P:\Corporate\Grids\Land\Elevation\LCC\DEM30m_SRTM\dem30m	V1.0 Retrieved 27/03/17	Geoscience & Australia and CSIRO Land & Water 2010
GEODATA TOPO 250K series 3 rivers (stream ordered) (SD09002)	Vector	OEH Science internal: LMDS_Data_Store\Study_Area_NSW\Data\Rivers\stream_order\river_250topo_ordered.shp	Retrieved 02/08/2017	Geoscience Australia 2006
GDM of NSW Keith class probability grids (Uncon3) (SD09003)	250-m raster	OEH Science: NSW NVM Benefits Project	V3.0 Retrieved 18/10/2017	Drielsma et al. 2012
SPOT woody FPC 2011 (Metric1) (SD09004)	30-m raster	Supplied by CSIRO: WoodyFPC_2011_Metric1.rst	Retrieved 22/05/2017	OEH 2014
LandSat fractional cover 2007–2016 Metrics (SD09005)	30-m raster	Supplied by CSIRO: FracCover_bare_2007-2016_Metric (1-3).rst	Retrieved 22/05/2017	Danaher et al. 2010; Donohue et al. 2017
SPOT woody change data 2011–2014 (SD09006)	Vector	OEH Corporate: SLATS_Change2008_2014.gdb	Retrieved 21/08/2017	OEH 2014
Interim cover benchmarks for the BioMetric Tool (SD09007)	Table	OEH Science: NSW NVM Benefits Project	Retrieved 01/03/2017	Ayers et al. 2005
2017 NSW land use (SD09008)	Vector	OEH Corporate: Final_Landuse_2013.gdb	Retrieved 12/09/2017	OEH 2017f
NPWS estate (SD09009)	Vector	OEH Corporate: P:\Corporate\Layers\Tenure\CrownEstate\NPWS_Estate_P	Retrieved 08/11/2017	OEH 2017g
Travelling stock routes (SD09010)	Vector	OEH Corporate: P:\Corporate\Layers\Tenure\CrownEstate\TravelingStockRoutes_P	Retrieved 16/10/2017	DECCW 2009
NSW digital soil mapping (SD09011)	100-m raster	OEH Corporate: https://iar.environment.nsw.gov.au/dataset/digital-soil-maps-for-key-soil-properties-over-nsw	Retrieved 03/08/2017	OEH 2017b
Attribution of Western Land Systems/Mitchell landscapes (SD09012)	Vector	OEH Science: NSW NVM Benefits Project	Retrieved 16/11/2017	D Robson and M Drielsma [OEH] 2011, pers. comm.

Notes: Unique Biodiversity Indicator Program identifiers are shown in **bold** and relate to workflow diagram objects shown in Appendix A.
SRTM = shuttle radar topographic mission; DEM = digital elevation model; FPC = foliage projective cover; GDM = generalised dissimilarity model;
OEH in the ‘Retrieved from’ column = the former Office of Environment and Heritage, previous division names and database structures; NPWS = National Parks and Wildlife Service.

2.3 Model inputs

A set of model inputs (Table 2) that are intermediate raster data products derived from the source data products listed in Table 1, were used to develop condition component models (see section 2.4: Ecological condition model). All inputs were standardised to a 90-metre grid. Where possible, the processing of source data reflected the methods used in the original NVM condition model. Each input, its rationale for inclusion, dependent source data and the processing required are detailed in Appendix B. Maps of inputs are shown for New South Wales in Appendix C. Processing of source data to derive model inputs required the development and application of a suite of python scripts using Esri's ArcPy library, and raster operations performed using ArcGIS^{TM} 10.4. These were adapted from the original NVM condition model's ArcView 3.X Avenue scripts where available. The stable green vegetation input (Appendix B, 1.11) and updated soil resilience index (Appendix B, 1.9) were not part of the original NVM condition model and were developed specifically for modelling ecological condition. All other inputs reflect those used in the original NVM model, although their data currency, resolution and level of detail have been improved.

Table 2 Inputs into the model of ecological condition and their descriptions.

Input name	Input ref. (ID)	Input type	Input description
National parks and public conservation	$tenureNP$ (DD09001)	Categorical	National parks and other public conservation areas (i.e. NPW reserves)
TSR proportion	$propTSR$ (DD09002)	Continuous	Proportion of each 90-metre grid cell that is travelling stock reserve (TSR)
Terrain ruggedness	$ruggedness$ (DD09003)	Continuous	Local variation in elevation
Weighted distance to water	$distWater$ (DD09004)	Continuous	The distance to water weighted by the stream order class of the nearest mapped waterway
Relative foliage projective cover	$relFPC$ (DD09005)	Continuous	Foliage projective cover scaled relative to thresholds for intact vegetation types
Soil resilience index	$nswSRI$ (DD09006)	Continuous	Soil resilience derived from land systems and key soil properties
Natural woodiness	$woodiness$ (DD09007)	Continuous	Predicted original woody cover expected to have occurred at each grid cell location
Stable green vegetation	$stblGrnVeg$ (DD09008)	Continuous	The amount and stability of green fractional cover over a 10-year period
Nativeness	$nativeness$ (DD09009)	Categorical	Estimate of vegetation 'nativeness' based on land use

Notes: The process of deriving inputs from source data is detailed in Appendix B.
Input references (Input ref.) are used to refer to products and processes throughout the model, and IDs relate to workflow diagram objects in Appendix A.

2.4 Ecological condition model

Initially, three ecological condition components were modelled separately: woody vegetation, non-woody vegetation and soil resilience; matching those used in the original NVM condition model. Following peer review of components and a critical evaluation of draft products, a decision was made to incorporate the information contained exclusively in the soil resilience component (primarily the model's NSW soil resilience index input) into the model's non-woody component resulting in only the woody and non-woody condition components contributing to the final model.

Both continuous value and categorical inputs were used. Values for all continuous inputs are 32-bit floating point numbers ranging from 0 to 1 with lower values representing a greater expected loss or reduction in ecological condition. Categorical inputs were either allocated values reflecting their influence on ecological condition in the same way that continuous input values were applied, or were used to categorically moderate other inputs whose influence was considered dependent.

Using ArcMap's raster calculator, woody and non-woody component models were generated from model inputs separately (Appendix B, 1.13), then combined into a single raster layer containing ecological condition values ranging from 0 to 1 for each location in New South Wales (Figure 5). The natural woodiness input (Appendix B, 1.10) and its complement (natural non-woodiness) were used to apportion the contribution from each component so that the woody component did not contribute to locations predicted to be grasslands; both woody and non-woody components contributed to woodlands; and forests were predominantly informed by the woody component. The natural woodiness input relied on a generalised dissimilarity (GDM) model of pre-industrial vegetation class distributions (Appendix B, 1.1; Appenix C, Figure 28) and woody cover benchmarks (Appendix B, 1.3), to estimate the natural woodiness of pre-industrial vegetation at each location.

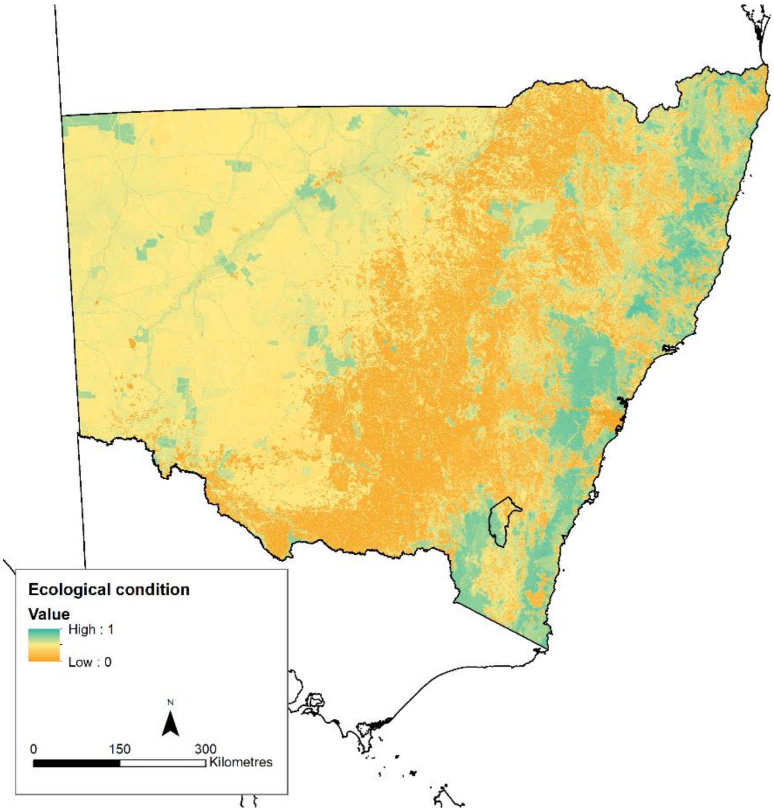


Figure 5 The ecological condition indicator model for New South Wales estimating the ecological condition of habitat, as of 2013.

Locations with high ecological condition are shown in teal and low ecological condition is shown in orange.

The assembling of the condition model is shown in Figure 6 as an expression tree. The root's left branch represents the model's woody component and its right branch represents the non-woody component. Each component is itself an expression of model inputs and associated weights. Categorical inputs were employed as conditional operators and discrete classes were either allocated constant weights or used to moderate the contributions of other inputs. Continuous inputs with values ranging from 0 to 1 were multiplied by weighting factors that determine their potential influence in the model then added to the difference between the factor and one. The greater an input's weighting factor, the more influence it has when considered in isolation, and the lower the minimum possible ecological condition value that may result (equal to one minus the factor). The weighted results for all inputs were then multiplicatively combined.

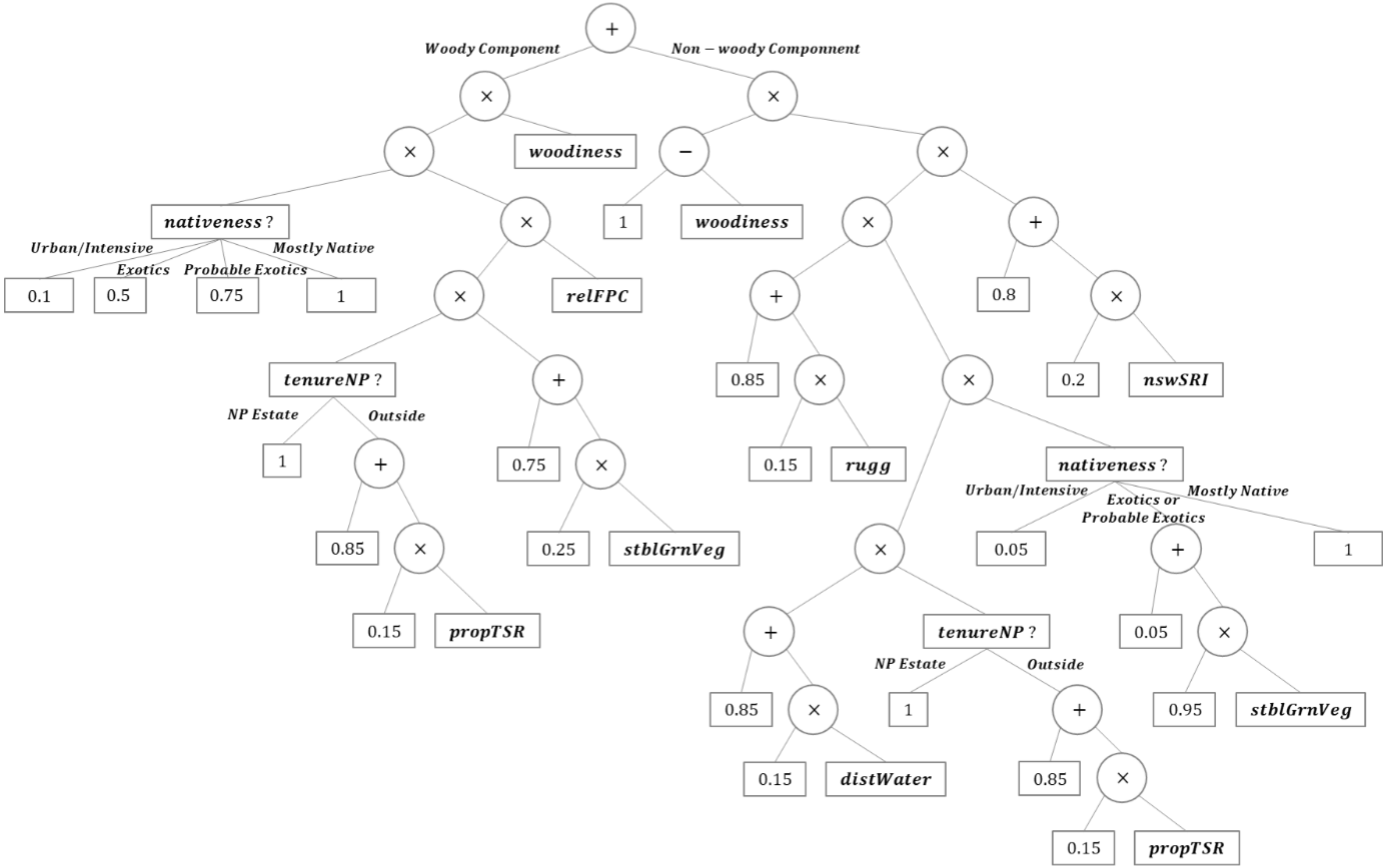


Figure 6 **Expression tree of the ecological condition model.**

The root’s left branch represents the model’s woody component and its right branch, the non-woody component. Leaf nodes are either continuous inputs (Appendix B) with values ranging from 0 to 1, or constant expert-derived weights. Non-leaf nodes are either commutative operators (except 1-woodiness in the non-woody component), or categorical inputs (Appendix B) shown with question marks and used as conditional operators.

Apart from the addition of stable green vegetation and the inclusion of the soil resilience index in the non-woody component (rather than as a separate soil resilience component), the weightings applied to both categorical and continuous inputs align closely with those adopted for the original NVM condition model (Drielsma et al. 2012). Acknowledging that habitat with good ecological condition occurs both inside and outside NPW reserves (i.e. public reserves established in perpetuity under the *National Parks and Wildlife Act 1974*), and following a review of draft results, down-weighting of areas outside national parks estate (based on gazettal's prior to commencement of the BC Act) in the original NVM model was reduced, thus allowing other non-tenure based inputs to make a proportionally greater contribution. As a result, the national parks estate input (*tenureNP*) was only used to moderate contributions from the travelling stock reserve (TSR) input (*propTSR*) with other inputs now weighted independent of tenure.

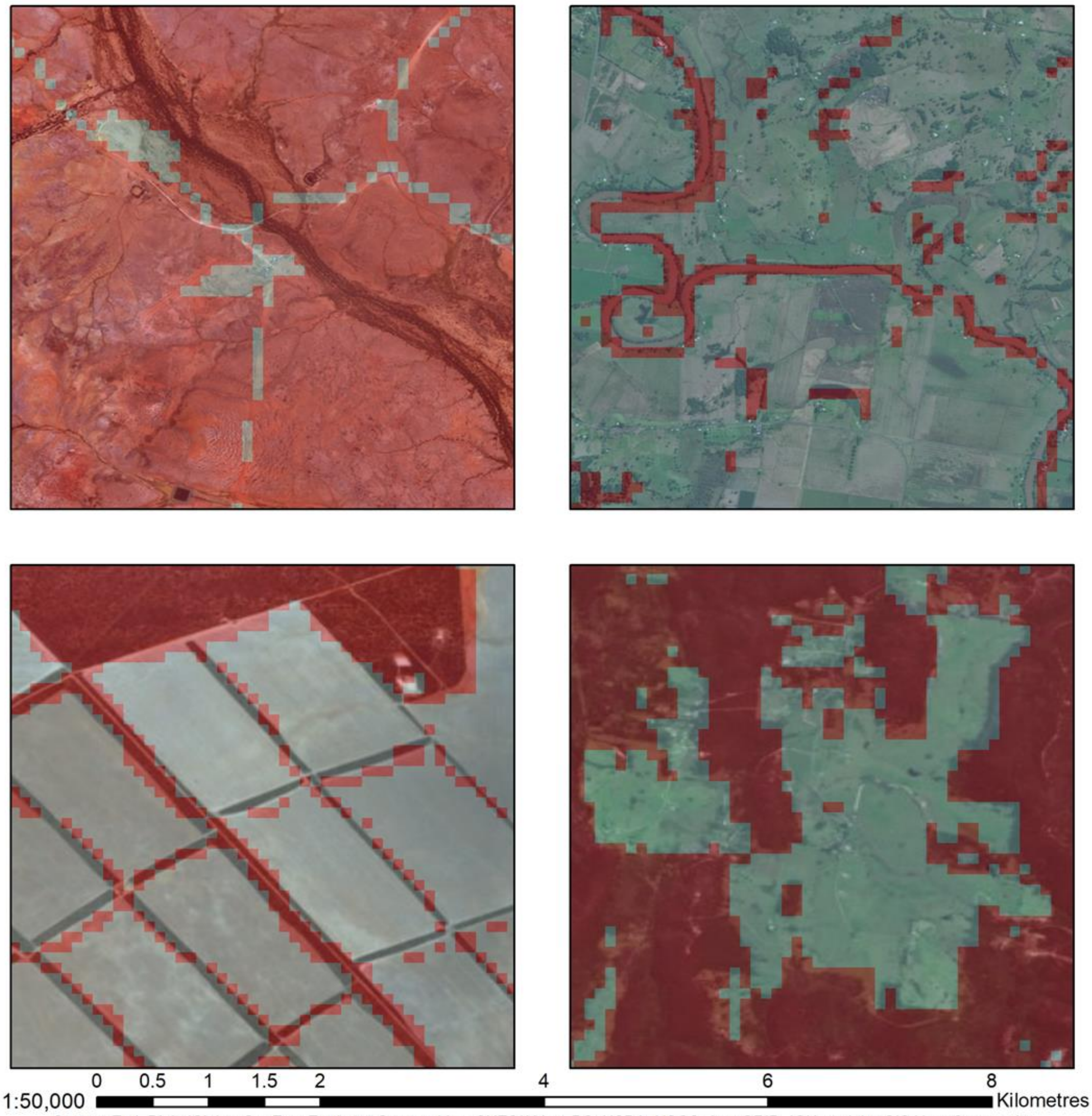
For the woody component, the greatest contributions to ecological condition are from estimated naturalness and relative foliage projective cover, with remaining contributions from stable green vegetation and TSRs outside of NPW reserves. For the non-woody component, stable green vegetation provides the greatest proportional contribution outside of areas mapped as urban/intensive or mostly native. Ruggedness, distance to water, TSR proportion and soil resilience also make contributions to the non-woody component.

2.5 Spatial precision

As the ecological condition model is reliant on multiple data sources, its spatial precision is influenced by that of each source dataset and will vary depending on the features each represent. Figure 7 shows the spatial precision of ecological condition for four areas, in the north-west (top left), north-east (top right), south-west (bottom left) and south-east (bottom right) of New South Wales, produced at 1:50,000 scale. This scale is unsuitable for the use of ecological condition and these maps are only provided to demonstrate the product's spatial precision. Indicators are most appropriately used for aggregated reporting at state and regional scales and best viewed using map scales of 1:250,000 or greater. The observed spatial error is typically less than a single 90-metre grid cell across the state, but may be greater or less due to differences in source data precision which varies from location to location depending on the features present.

Linear features with sub-pixel widths, such as roads and waterways, are not always well represented by raster data and gaps in these features may result from vector to raster conversion or nearest neighbour sampling. Smaller features with sub-pixel areas, such as paddock trees, will contribute to ecological condition where they are represented in source data (such as 5-metre foliage projective cover) through averaging finer-resolution (source) data up to the 90-metre analysis resolution. The contribution will be in proportion to the feature's size relative to a 90-metre grid cell. While potentially contributing to ecological condition, the representation of individual paddock trees and other sub-pixel features is considered beyond the scope of these state-scale habitat condition indicator products.

The spatial precision of ecological condition is carried through to the ecological connectivity and ecological carrying capacity indicators. While all habitat condition indicators are suitable for statewide and regional scale analysis and reporting, they should be supplemented with additional finer-scaled information where available to support attribution of the drivers of condition, especially when used for fine-scale regional or subregional analysis. This use needs to be assessed case-by-case. Where analysis warrants more detailed or finer-scaled information, these three indicators (condition, connectivity and carrying capacity) are likely to provide valuable context not available in region-specific datasets, and their inclusion should also be considered where possible.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 7 **Ecological condition (grey = low to red = high) over satellite imagery showing identifiable landscape features in the far north-west (top left), north-east (top right), south-west (bottom left) and south-east (bottom right) of New South Wales produced at 1:50,000 scale. This scale is unsuitable for indicator use and these maps are only provided to demonstrate the model's spatial precision.**

2.6 Data gaps

There were multiple data gaps across the source dataset(s). These gaps (Figure 8) include waterbodies and other small areas of missing data. No attempt was made to extrapolate source data, or derived spatial inputs, to fill these data gaps, which therefore propagate through to the final product. However, for some uses these gaps need to be filled. 'No Data' holes were therefore filled using the Biodiversity Impacts and Adaptation Project's (BIAP) vegetation condition layer (OEH 2016), which was also used to extend the ecological condition model across the complete 'NARCliM' project extent (see section 2.7: Extended ecological condition and Figure 8). The NARCliM project is the NSW and ACT (Australian Capital Territory) Regional Climate Modelling project.

Figure 8 shows the locations within New South Wales that are assigned 'No Data' (in red) in the ecological condition model and where values in the extended ecological condition layer are derived from the BIAP vegetation condition layer. The resulting 'hole-filled' extended ecological condition product is therefore complete, allowing its use in downstream analysis, such as developing the ecological connectivity and ecological carrying capacity indicators which include an analysis of neighbourhoods extending beyond New South Wales.

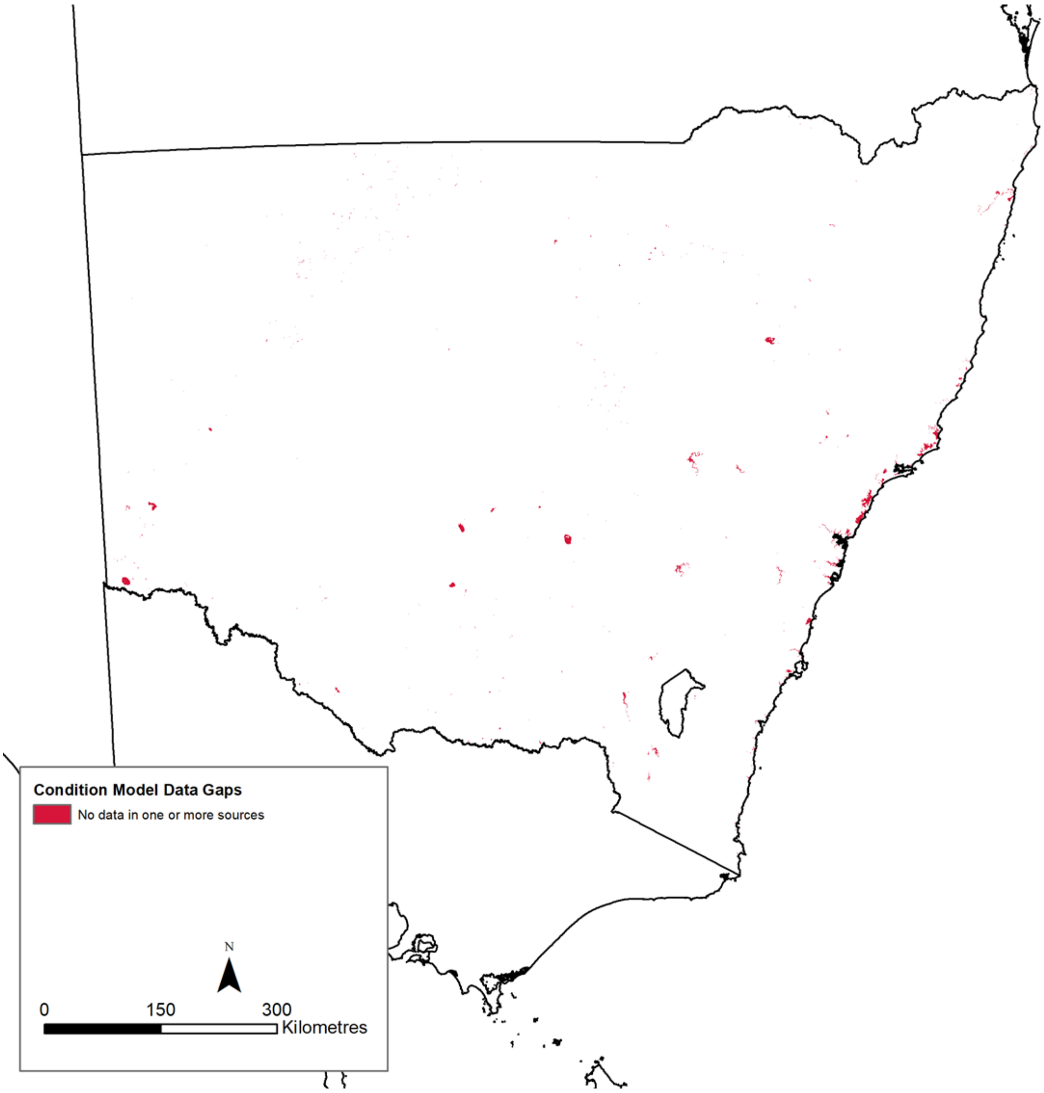


Figure 8 **Data gaps ('holes') present in source data and propagated through the model of ecological condition. These were filled using the Biodiversity Impacts and Adaptation Project condition layer (see section 2.7: Extended ecological condition).**

2.7 Extended ecological condition

Calculating ecological connectivity and ecological carrying capacity (section 3) at any single location in New South Wales requires evaluating habitat connections within a neighbourhood window or specified distance. To minimise edge effects along state boundaries and artefacts resulting from data gaps, it is necessary to fill locations that are missing data and to extend ecological condition into other jurisdictions by a distance greater than the maximum distance of influence for any focal cell. To achieve this, data from the 250-metre gridded BIAP condition layer (OEH 2016) was used to extend the ecological condition model out to the entire NARCliM study region (Figure 9) (Evans et al. 2014).

The BIAP condition layer was bilinearly resampled to match the ecological condition's 90-metre resolution before combining the two layers using ArcMap's conditional function. The resulting extended ecological condition layer consists of ecological condition within New South Wales, and BIAP condition outside the state and additionally where data gaps occur (see section 2.6: Data gaps). As values for areas outside New South Wales are only required to provide analysis context, it is not essential that this data be developed with the same process or rigour as that used for reporting within New South Wales, and the BIAP layer was considered suitable for this purpose. Inconsistencies between the two products are most noticeable along the north-west boundaries of New South Wales (Figure 9). Values between the two products are more consistent along the north-east and southern state boundaries where the two products have greater agreement. Inconsistencies inevitably effect values of ecological connectivity and ecological carrying capacity at locations along the borders of New South Wales, however, due to the relative homogeneity of ecological condition values in these areas, their influence is considered marginal.

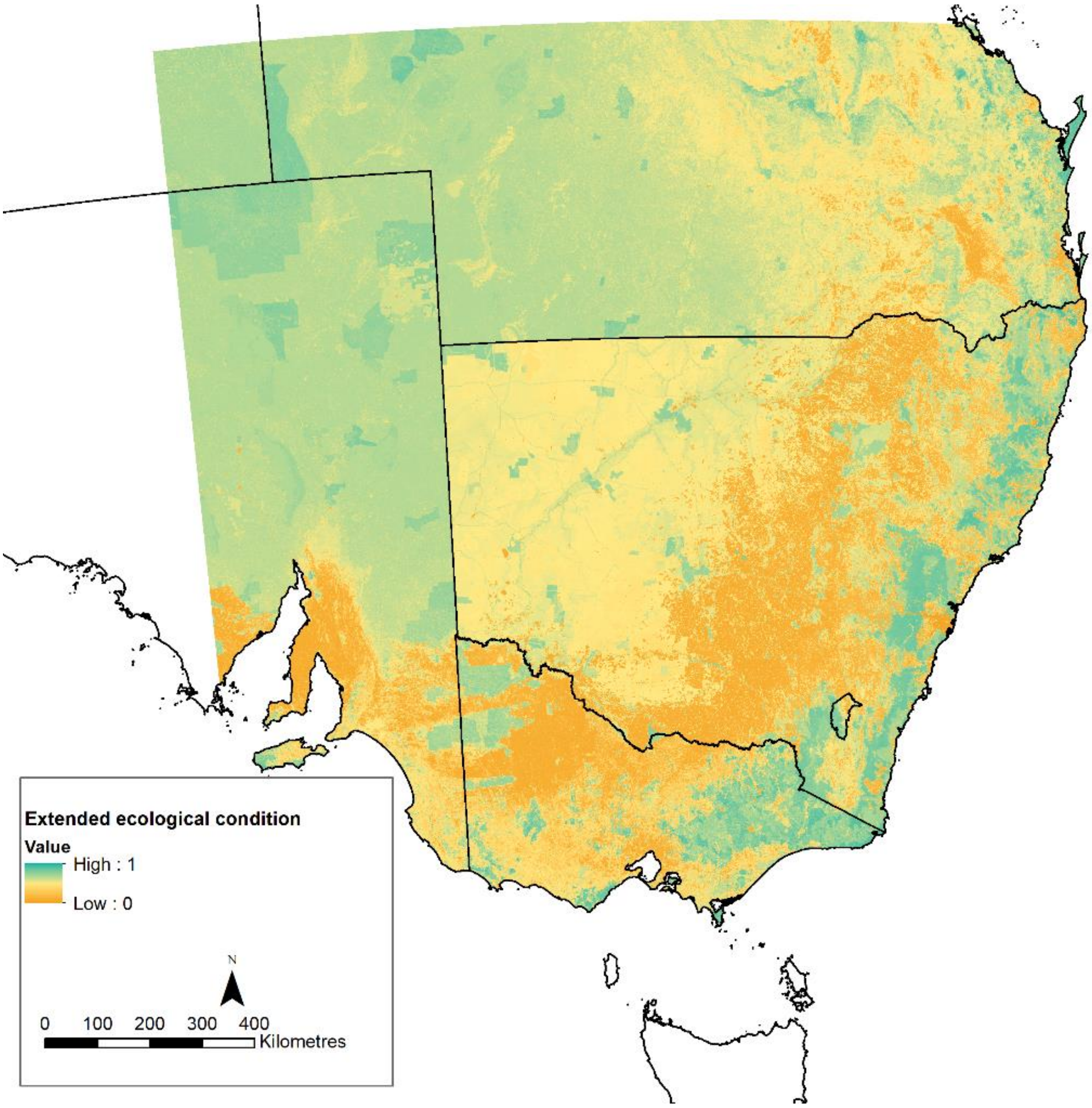


Figure 9 **Extended ecological condition using the Biodiversity Impacts and Adaptation Project condition layer (OEH 2016) to provide context outside New South Wales.**

3. Measuring ecological connectivity and ecological carrying capacity

The connectivity of habitat is an emergent property of habitat amount, quality and locality. It is arguably the major factor influencing ecological function, especially for mobile and space-demanding fauna where fragmentation can reduce the availability of suitable habitat (Baguette et al. 2013; Noss 1987). Well-connected habitat facilitates the processes that individuals, populations and ecosystems need to persist, including foraging for food, searching for a mate, dispersing to other habitat, migrating with the seasons, or shifting distributions in response to changes in the environment or habitat-altering events. Connectivity is also increasingly recognised as having an additional role in aiding biodiversity to adapt to the impacts of climate change (Mackey & Hugh 2010; Mackey, Watson & Worboys 2010).

Ecological connectivity and ecological carrying capacity indicators use related methods to report on the connectivity of habitat.

- **Ecological connectivity** measures the value that each location contributes to the connectivity of habitat in a region by way of its ecological condition and relative locality.
- **Ecological carrying capacity** measures how well-connected habitat at each location is to other surrounding habitat.

The observable difference between these two indicators is shown in Figure 10. Conceptually, the underlying algorithms for both indicators are nearly identical apart from their parameterisation and the accumulation of connectivity values. Planned refinements aim to fully integrate the analysis used to produce both these indicators.

Ecological connectivity measures the effectiveness of each location as a connector of contemporary habitat across ecological scales. It estimates each location’s contribution to the ecological carrying capacity of surrounding habitat (see ecological carrying capacity indicator, below) and is determined for each location by its ecological condition, as well as ‘least cost path’ (Cormen 2014; Dijkstra 1959) connections between habitats that traverse that location. Ecological connectivity values are allocated using the ‘spatial links tool’ (Drielsma, Manion & Ferrier 2007) to generate least cost paths between site pairs, accumulating their connectivity values at every location they traverse. In this way, locations that are more frequently traversed by least cost paths, or are traversed by least cost paths with higher connectivity value or those that connect habitats with higher ecological condition, are considered to provide a greater contribution to habitat connectivity and are therefore allocated higher ecological connectivity values.

Ecological carrying capacity on the other hand, uses the ‘cost benefit approach’ (Drielsma, Ferrier & Manion 2007) to measure spatial context, integrating ecological condition at each location with measures of its connectivity to, and the condition of, surrounding habitat across ecological scales. Spatial context analysis is performed using a least cost paths algorithm similar to ecological connectivity, with differences in how connectivity values are accumulated. Where ecological connectivity values are determined at each location from the accumulation of traversing paths, context analysis accumulates connectivity values at each path’s source by treating each location as a focal cell from which paths to surrounding habitat originate. In this way, a measure of how well connected each location is to its surrounding habitat is derived without explicitly mapping least cost paths (as is the case with ecological connectivity).

Both indicators are intended to be scale agnostic, avoiding a preference towards any particular spatial or temporal scale at which only a subset of ecological processes may operate. They are also designed to be generic across all habitat types, only considering the quality of habitat and not its suitability for any particular species or ecosystem. The approaches are therefore intended to be a generic, unbiased evaluation of habitat connectivity independent of specific taxa, movement processes (foraging, dispersal and migration) or timeframes (single and cumulative movements, by individuals and across generations). The analysis design is kept tractable, despite this inherent complexity, by adopting a simple set of design rules that minimises arbitrary parameterisation decisions.

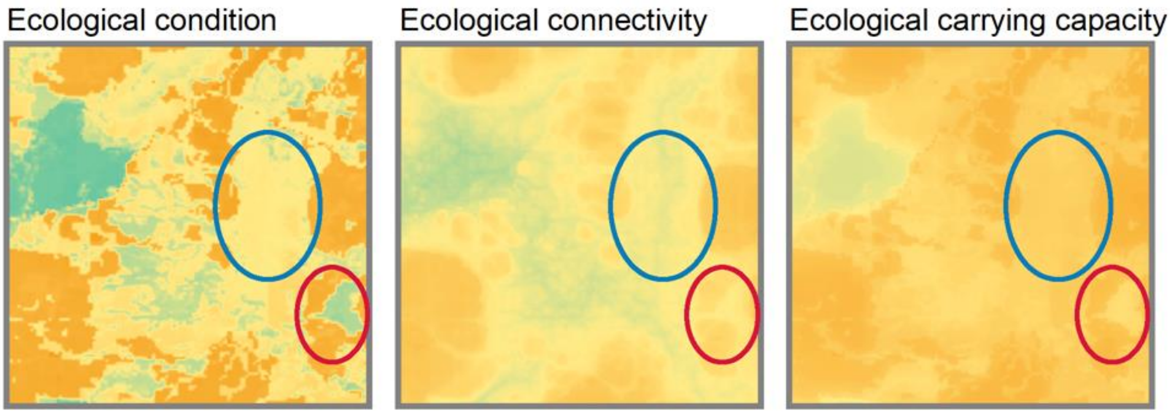


Figure 10 **The relationship between ecological condition (habitat quality at each location), ecological connectivity (accumulated path connectivity) and ecological carrying capacity (spatial context) for the same area.**

Locations of low (orange) to moderate (yellow) ecological condition and carrying capacity may have higher (dark teal) ecological connectivity where they contribute to important corridors between other habitats (larger, blue circle). Smaller areas of moderate to high ecological condition may have lower ecological connectivity and carrying capacity where they are isolated or their surrounding habitat is highly fragmented (smaller, red circle).

3.1 Multi-scale habitat connectivity modelling

Both ecological connectivity and ecological carrying capacity are designed to consider habitat connectivity across spatial and temporal scales at which different ecological processes operate. The analysis adopts a systematic approach to raster geometry that generates a simple schema of analysis across ecological scales using a fractal perspective on ecological complexity (Brown et al. 2002) and the power law. This helps bring order to otherwise seemingly overwhelming chaos. To achieve this, a multi-scale analysis approach (Drielsma et al. 2012) is used, with multiple analysis resolutions and proportionally scaled analysis parameters (Table 3) as proxies for different ecological scales. Analysis is performed for each ecological scale separately, with its resolution inversely proportional to scale (i.e. as the distances being analysed doubles, the analysis resolution is halved). The analysis outputs across all resolutions are then combined at the highest resolution to produce the final indicator products.

The spatial links tool and the cost benefit approach (CBA) require spatial inputs for habitat value, provided here by the extended ecological condition dataset, and measures of landscape permeability used to solve least cost paths. To perform the multi-scale analysis, these spatial inputs are sampled from their original 90-metre resolution data to each resolution at which the multi-scale analysis is performed (Table 3). Spatial inputs are sampled to coarser resolutions as proxies for larger ecological scales by halving the analysis resolution at each scale (doubling the cell size, see Figure 11) and using multiple pixel offsets to account for the loss of detail that occurs when aggregating data to coarser resolutions. Using multiple pixel offsets also reduces spatial artefacts that result when resampling coarser data back to the finer-resolution output scale.

Python scripts were used to resample data inputs for both indicators. Figure 11 and Figure 12 show how data were resampled to coarser resolutions using multiple pixel offsets under the multi-scale analysis approach, and Table 3 lists the number of pixel offsets and offset size used at each analysis resolution. To derive coarser offset analysis inputs, raster extents were shifted by each offset multiplied by the offset size in both the x and y directions before the original 90-metre cell values were aggregated into their associated coarser cells using their mean values. Spatial links and the CBA are performed for each of the sampled pixel offsets at each analysis resolution separately. Once analysis of all resolutions and offsets was complete, all outputs were resampled to match the 90-metre resolution for combining into the final indicator product (see section 3.4: Combining habitat connectivity across scales).

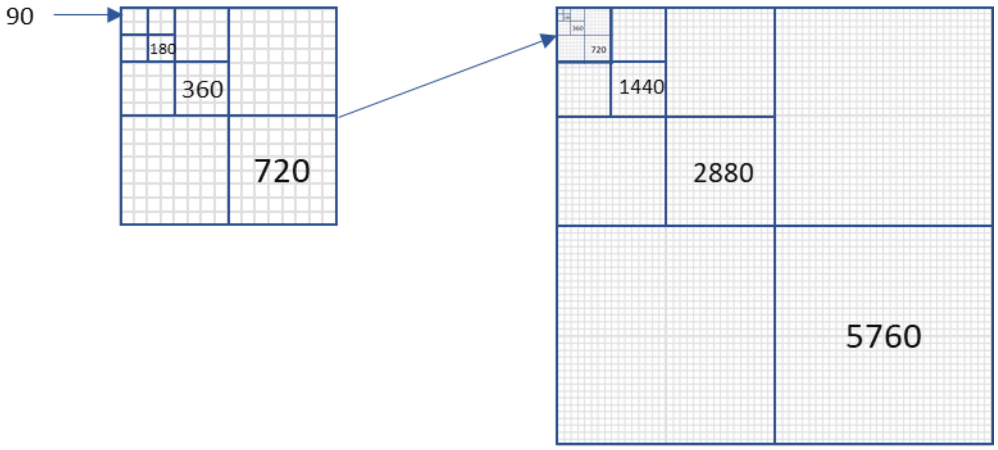


Figure 11 **The power law and fractal perspective applied to resample the original 90-metre resolution data (grid cells in grey) to coarser analysis resolutions (grid cells in blue). The 5760-metre resolution was only used for spatial links analysis.**

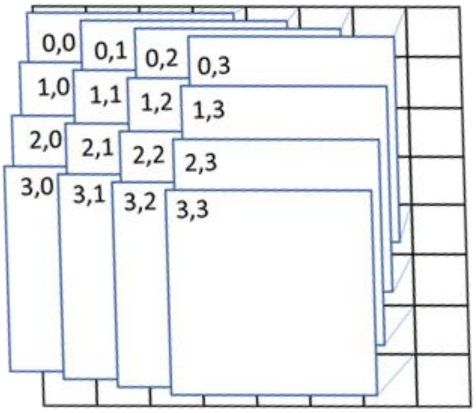


Figure 12 **Example of multi-scale analysis sampling showing the same single cell location (blue) in each of the 16 overlapping pixel offsets for the 360-metre analysis resolution relative to the original 90-metre resolution raster cells shown in black.**

For each offset, the extent is shifted in both the x and y directions by a multiple of the pixel offset size (90 metres here). Values of the original 90-metre resolution cells (in black) are then aggregated into their respective 360-metre resolution cell (in blue). This is repeated for the number of pixel offsets of each analysis resolution.

Table 3 Parameters used for multi-scale analysis sampling, spatial links parameters used for ecological connectivity and context analysis parameters used for ecological carrying capacity

Multi-scale analysis parameters				Spatial links parameters				Context parameters	
Analysis resolution cell size (m)	**Cell size (ha)**	**Number of pixel offsets**	**Pixel offset size (m)**	**Minimum effective cell distance (EDmin)**	**Maximum effective cell distance (EDmax)**	**Average movement distance and search radius (m)**	**Maximum path cost (dmax)**	**Minimum 1/α (p_{min}=0.5)**	**Maximum 1/α (p_{max}=0.7)**
90x90	0.81	1	0	90	225	2,250	5,625	130	250
180x180	3.24	4	90	180	450	4,500	11,250	260	500
360x360	12.96	16	90	360	900	9,000	22,500	520	1,000
720x720	51.84	16	180	720	1,800	18,000	45,000	1,040	2,000
1440x1440	207.36	16	360	1,440	3,600	36,000	90,000	2,080	4,000
2880x2880	829.44	16	720	2,880	7,200	72,000	180,000	4,160	8,000
5760x5760	3317.76	16	1440	5,760	14,400	144,000	360,000		NA

Notes: Context analysis was only performed for the first six resolutions.
The multi-scale analysis parameters are used to derive spatial links and context analysis raster inputs for each of the pixel offsets at each of the analysis resolutions.
Spatial links and context analysis parameters are used to derive the connectivity values of least cost paths as described in the following sections.

3.2 Ecological connectivity model

Ecological connectivity is measured using the spatial links tool (Drielsma, Manion & Ferrier 2007) that applies Dijkstra's least cost path graph search algorithm (Cormen 2014; Dijkstra 1959) to rasterised spatial data. Ecological connectivity modelling refines the 'landscape value' methodology used to inform native vegetation management benefits across New South Wales (Drielsma et al. 2012). Like landscape value, ecological connectivity avoids preferencing any particular ecological scale. Unlike ecological connectivity, landscape value considered differences in habitat type by modelling connectivity separately for three different vegetation structure classes (Drielsma et al. 2012). In contrast, ecological connectivity is a single, generalised, multi-scaled measure of connectivity, considering only habitat quality and locality and the resulting contribution this makes to connectivity for all habitat types.

Spatial links is applied using a complete all-pairs strategy. This improves on earlier applications of spatial links (Scotts & Drielsma 2002; Drielsma, Manion & Ferrier 2007; Drielsma et al. 2012; Drielsma et al. 2015) that relied on a heuristic sampling strategy, referred to here as the 'sampled links' approach. Using sampled links, least cost paths are sampled between locations that are within a specified distance of each other and randomly selected from a predefined pool of candidates probabilistically distributed towards areas of higher ecological condition. Instead of heuristically selecting path source and destinations, the complete links approach generates least cost paths between every pair of locations within the bounds of parameterised search constraints.

The all-pairs approach allows for a consistent and controlled analysis of the entire analysis domain. This prevents a sampling imbalance that can occur when performing the sampled links approach in regions with an uneven distribution of habitat, between parts of the region that have more intact habitat, therefore more candidates, and areas with less intact habitat that consequently have less candidates. This imbalance can under-value the important contributions that remnant habitat in highly cleared parts of the landscapes make to the connectivity of remaining habitat, such as stock reserves or paddock trees in the NSW wheat-sheep belt. By solving all possible paths, the all-pairs strategy allows the algorithm to resolve complete patterns of habitat connectivity consistently and more efficiently than the previous approach.

The parameterised constraints used by the all-pairs approach include:

1. search radius and maximum path cost parameters, scaled relative to the analysis resolution and beyond which least cost paths are not generated (listed in Table 3)
2. a minimum habitat (ecological condition) threshold, below which locations are not considered as path sources or destinations.

For ecological connectivity, an ecological condition of 0.3 is used as the minimum habitat threshold for all analysis resolutions. This parameter represents a trade-off between ecological rigour and processing time. As the minimum habitat condition threshold is decreased, the number of low-valued paths connecting habitat with low ecological condition increases, resulting in diminishing contributions to ecological connectivity at the expense of increased processing time. A minimum habitat condition threshold of 0.3 ensures connectivity is modelled between habitat with a range of ecological condition values (>0.3) and was found to provide adequate path sampling without significant loss of information, while also maintaining practical computer processing times.

To solve least cost paths, spatial links uses a 'cost' raster with cell values representing each location's effective distance (ED). Effective distance is the relative cost of traversing a location, derived from the analysis cell size inversely weighted by its ecological condition. Equation 1 is used to derive cost rasters of effective distance (ED) at each location (i). A factor between 1 and 2.5 linearly scaled by the complement of ecological condition is applied to the analysis cell size, effectively making locations with an ecological condition of zero, 2.5 times costlier to traverse (ED_{max}) than those with an ecological condition of one, where effective distance is set to the Euclidian distance (ED_{min}). The factor of 2.5 has been determined appropriate for generalised connectivity analysis through previous work in New South Wales (Drielsma et al. 2012; Drielsma, Manion & Ferrier 2007).

$$ED_i = (1 - h_i) \times (ED_{max} - ED_{min}) + ED_{min} \qquad \text{equation 1 (P09504)}$$

For each analysis resolution and pixel offset processed, least cost paths are generated sequentially between every pair of locations with ecological condition above the minimum habitat condition threshold of 0.3 and within the search radius and maximum path cost specified (Table 3). The cost of a path traversing between any two neighbouring locations is calculated as the sum of half their effective distance with diagonal traversal accounted for by applying a factor of $\sqrt{2}$. The accumulated cost (d) for each path is calculated as the sum of the costs associated with traversing all locations in the path. As least cost paths are solved between every pair of locations (i and j) that are within the search constraints, a logistic decay function (equation 2) is applied to calculate the path's connectivity value (w_{ij}) from its accumulated cost (d_{ij}). The decay function uses an average movement distance parameter (α) that is scaled relative to each resolution (Table 3) and a parameter s of $5/\alpha$ to define the slope of the curve consistently across all resolutions. The average movement distance, like the related ED factor is based on previous generalised connectivity modelling work in New South Wales (Drielsma et al. 2012; Drielsma, Manion & Ferrier 2007).

$$w_{ij} = \frac{e^{-s(d_{ij}-\alpha)}}{1+e^{-s(d_{ij}-\alpha)}} \qquad \text{equation 2 (P09505)}$$

The decay function, when applied to the accumulated cost of traversing each path, results in connectivity values between those shown in Figure 13. The function is shown for the number of cells traversed by paths consisting entirely of locations with ED_{max} (cleared locations with highest cost) in red (dashed) and ED_{min} (pristine habitat with lowest cost) in blue (solid). This shows how path connectivity (w) decreases more rapidly when traversing higher cost locations (dashed red, low ecological condition values) than it does when traversing locations with lower cost (solid blue, high ecological condition values).

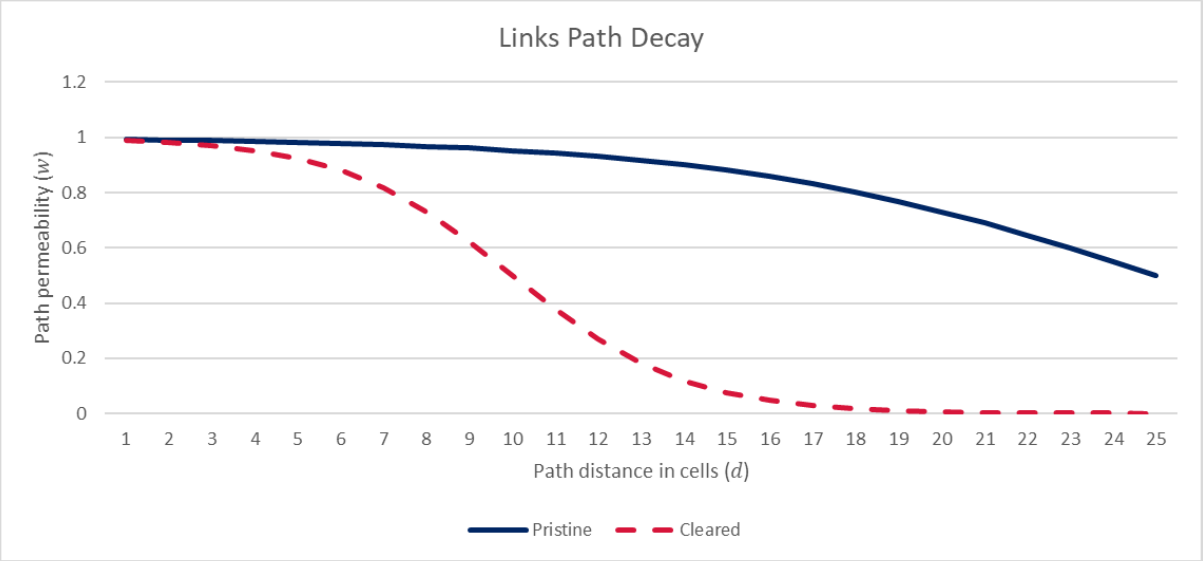


Figure 13 **Distance decay function applied to calculate path permeability from the effective distance of paths, scaled using the distance in cells and shown for paths consisting entirely of pristine (solid blue) and cleared (dashed red) habitat value.**

To map ecological connectivity, each path's connectivity value is multiplied by the ecological condition at its source and destination, and the result added to the accumulating connectivity values at every location it traverses. The resulting connectivity value of each location, as the sum of connectivity values from all traversing paths, accounts for the number of traversing least cost paths, their connectivity value and the amount and quality of habitat they connect. This therefore reflects the location's contribution to habitat connectivity and its contribution to the ecological carrying capacity of other connected habitats at each analysis scale.

3.3 Ecological carrying capacity model

The cost benefit approach (CBA) (Drielsma, Ferrier & Manion 2007) used to model ecological carrying capacity calculates the neighbourhood habitat area (NHA) for each location as a measure of spatial context, inversely proportional to habitat fragmentation. Like the spatial links approach, CBA is an adaptation of Dijkstra's least cost path graph search algorithm (Cormen 2014; Dijkstra 1959) and is used to solve single-source shortest path trees (Wu & Chao 2004) over rasterised spatial data. CBA is used to simulate ecological processes including foraging, dispersal (relevant to both flora and fauna) and migration across continuous valued rasterised representations of complex landscapes.

CBA typically relies on an optimisation strategy of aggregating all cells within a neighbourhood window and centred on a focal cell, into coarser analysis units termed 'petals' (Drielsma et al. 2007a). Petals decrease in resolution as the distance to the focal cell increases, and are used as least cost path analysis units, greatly reducing the graph search space required at each location. For ecological carrying capacity, software optimisations (Love, Drielsma & Welch in prep) permit a one to one mapping of cells to petals negating the need for coarser aggregated analysis units, while maintaining window sizes suited to the ecological scales being assessed. A neighbourhood window of 25 by 25 cells is used at each resolution. Therefore, the area that each neighbourhood cell and search window represents, increases with each coarser analysis resolution accordingly. After reviewing draft results, an additional analysis at the original 90-metre resolution was performed using a window size of 13 by 13 cells to better capture local patterns of habitat fragmentation surrounding each location.

To derive ecological carrying capacity, CBA is applied using generalised parameters (Table 3) and spatial inputs scaled to multiple spatial resolutions that, like ecological connectivity, account for processes operating across a range of ecological scales. To reflect the continuous and evolving nature of ecological processes, and account for indirect influences of change in other parts of the landscape, CBA is performed over three iterations for each spatial resolution and at each pixel offset sampled where the habitat input of each iteration is multiplicatively moderated by the NHA output of the last.

To solve single-source shortest path trees, CBA uses measures of each location's permeability that are accumulated multiplicatively as paths traverse. Permeability rasters are derived from a single original 90-metre resolution raster using the same multi-scaled sampling used to aggregate ecological condition (see section 3.1: Multi-scale habitat connectivity modelling). The original fine-scale permeability raster that acts as the source for all sampled rasters is derived directly from the original 90-metre resolution extended ecological condition input by applying equation 3 to each cell.

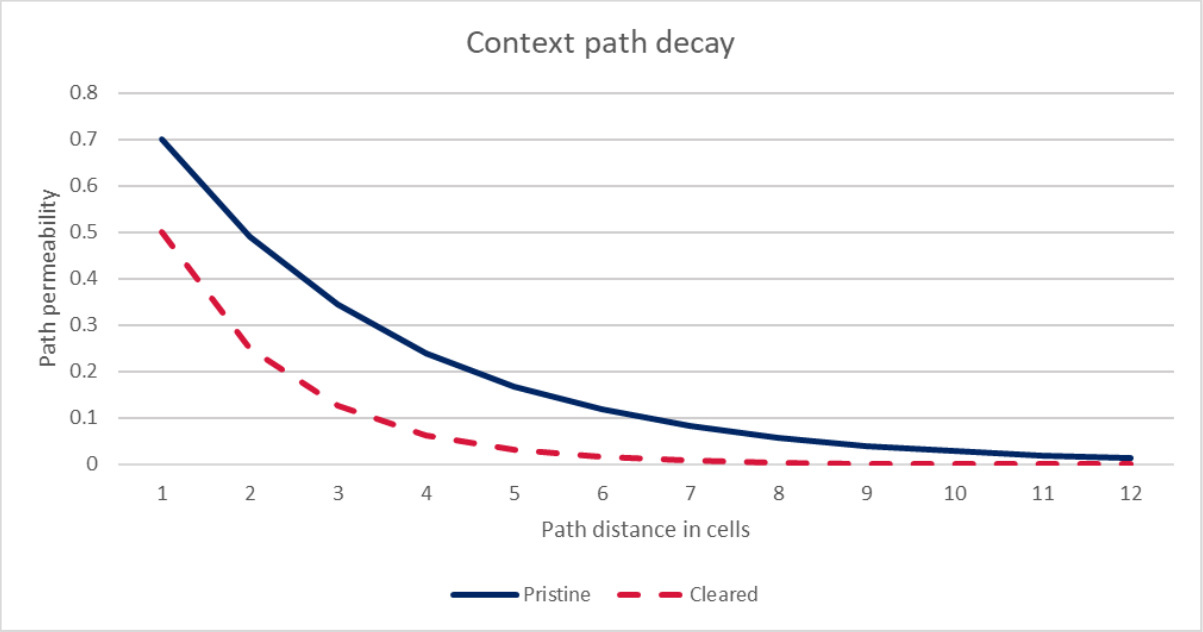
$$p_i = condition_i \times (p_{max} - p_{min}) + p_{min} \qquad \text{equation 3 (P10004)}$$

Potential permeability values (p) for each analysis resolution are based on generic minimum and maximum average movement distances (1/α) (Table 3) and range from p_{min} of 0.5 for cells where ecological condition equals 0, through to p_{max} of 0.7 for cells where ecological condition equals 1. 1/α are less than average movement distances used to model ecological connectivity reflecting the differences in the least cost paths distances and resulting patterns of connectivity considered by each analysis. Values were chosen that result in a minimum of 95% decay for a path of maximum distance across maximum quality habitat, that is, the window size and path lengths were matched. Using these constant parameters suited to generalised habitat connectivity analysis (Drielsma et al. 2012; Drielsma, Manion & Ferrier 2007) ensures cell and path permeabilities (Figure 14a) are appropriately scaled for each resolution.

CBA is performed by iterating equation 4 through every cell in the analysis domain as a focal cell. First, the permeability of the shortest path from the focal cell (i) to each location, in this case cell j, in its search window is calculated. Given permeability values (p) for each cell in the search window, the accumulated permeability of a path between cell i and j comprising of intermediate cells indexed by k is derived multiplicatively (Figure 14a). Once the least cost path to every location in the search window is solved, their permeabilities are multiplied by their respective ecological condition values (H_j) then summed to calculate the NHA of the focal cell (Γ_i).

Figure 14b shows how NHA accumulates at an increasing rate for radii less than 1/α then at a decreasing rate beyond this distance. Following the process used to calculate metapopulation capacity described in Drielsma and Ferrier (2009), the calculation of NHA (Γ_i) at each resolution and pixel offset is repeated three times, and at each iteration all ecological condition values (H_j) are multiplicatively weighted by NHA (Γ_i) from the previous iteration, after it is first scaled to between 0 and 1.

$$\Gamma_i = \sum_j H_j \prod_{k=i}^{j} p_k \qquad \text{equation 4}$$



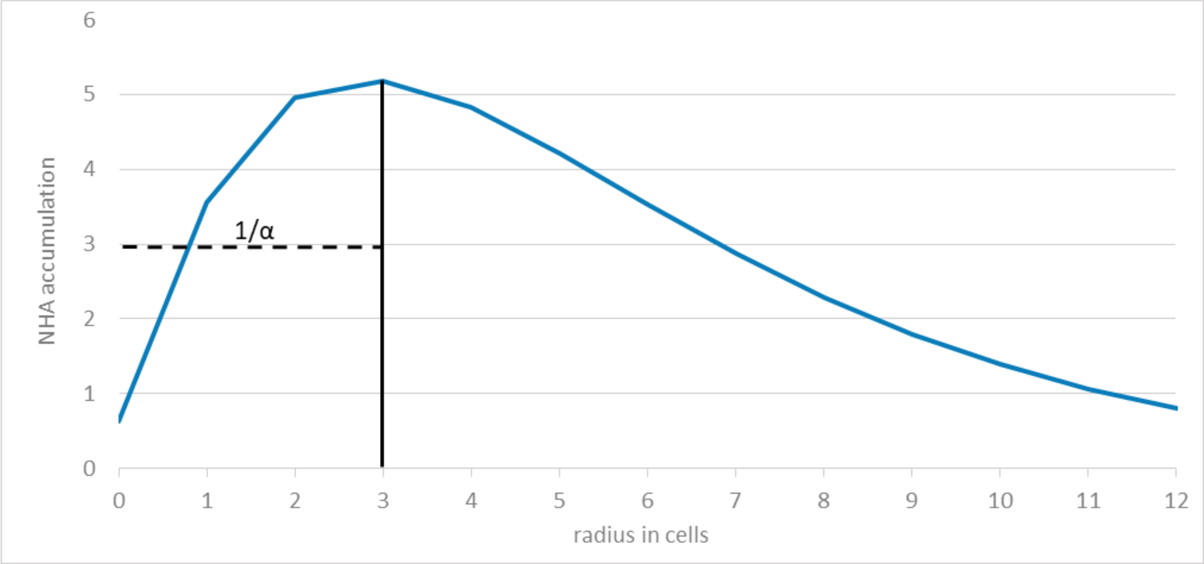


Figure 14a (top) Distance decay function applied to calculate path permeability (w_{ij}) from accumulated cell permeabilities (p) scaled using the distance in cells and shown for paths consisting entirely of pristine (solid blue) and cleared (dashed red) habitat value.

Figure 14b (bottom) Neighbourhood habitat area (NHA) accumulates at an increasing rate for radii less than 1/α then at a decreasing rate beyond this distance.

3.4 Combining habitat connectivity across scales

To derive ecological connectivity (Figure 15) and ecological carrying capacity (Figure 16) indicators for New South Wales, the multi-scale outputs from both the spatial links analysis and the context analysis for all resolutions and pixel offsets (Table 3) were combined into their respective indicator products. This use of multiple offsets at each resolution not only ensures the loss of data is minimised when resampling inputs to coarser analysis resolutions, but also minimises artefacts reflecting coarser cell boundaries in outputs when resampling back to the finer original 90-metre resolution. As parameters for both indicators were scaled relative to each analysis resolution, analysis outputs across all resolutions have the same range of values. No additional transformations beyond those required to account for the different number of pixel offsets processed at each resolution were necessary to ensure values from each scale were weighted equally.

To derive a single raster layer measuring the ecological connectivity of habitat across multiple scales, outputs from the spatial links analysis at each sampled resolution and pixel offset were combined with equal weighting. This is performed in ArcMap by setting the analysis extent and resolution to that of the original 90-metre ecological condition layer, then the spatial links outputs from each resolution and pixel offset were summed. To weight each analysis resolution equally, the 90-metre and 180-metre outputs were first multiplied by factors of 16 and 4 respectively, due to their lower number of pixel offsets processed. This aligns their range of values when summing with that of the summed outputs from coarser resolutions. The combined sum of all outputs is then masked back to the reporting extent of New South Wales and range standardised to between 0 (lowest ecological connectivity) and 1 (highest ecological connectivity).

To produce a single measure of the ecological carrying capacity of habitat at each location in New South Wales, the NHA outputs from each analysis resolution and pixel offset were combined with ecological condition. NHA raster outputs were first rescaled to between 0 and 1 by dividing each raster by 59.665 (the pre-calculated largest potential NHA value representing a completely connected and intact search window) and the results summed at the original 90-metre resolution for each analysis resolution separately. Summed outputs from each resolution and ecological condition were then averaged with equal weighting and masked back to the reporting extent of New South Wales to derive the final ecological carrying capacity indicator product containing values ranging from 0 (lowest ecological carrying capacity) to 1 (highest ecological carrying capacity).

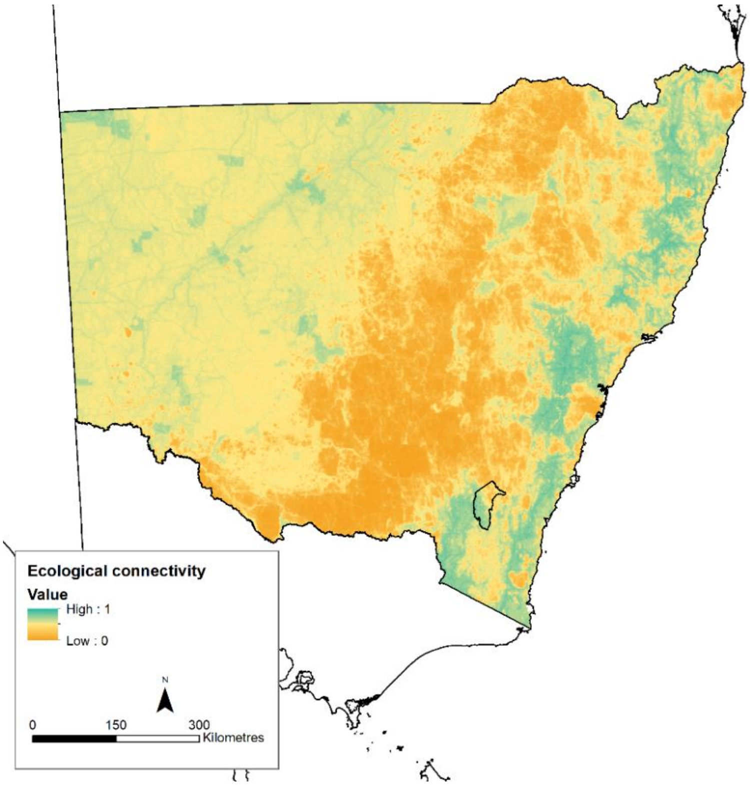


Figure 15 The ecological connectivity indicator model for New South Wales estimating each location's contribution to habitat connectivity and the ecological carrying capacity of surrounding locations, as of 2013.

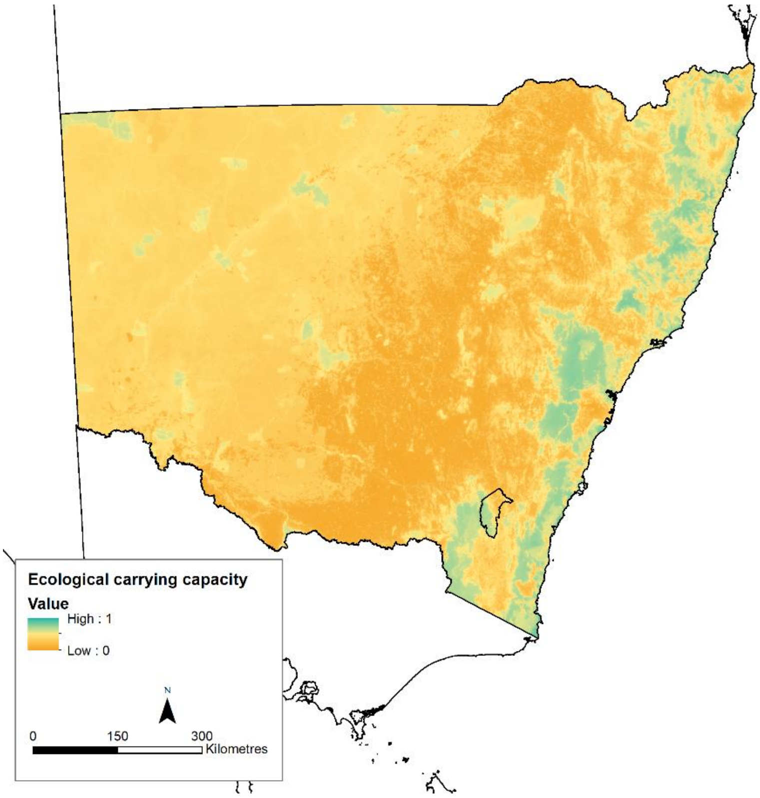


Figure 16 The ecological carrying capacity indicator model for New South Wales estimating the intactness and naturalness of terrestrial habitat at each location considering the effect of surrounding habitat loss and fragmentation, as of 2013.

4. Reporting habitat condition indicators

The three habitat condition indicators emphasise different but related aspects of ecosystem quality and are therefore packaged together for reporting. Together, these indicators estimate the capacity of existing habitat to maintain ecological processes supporting terrestrial species and ecosystems native to New South Wales. The key results and messages from these habitat condition indicators are summarised and presented along with the current suite of biodiversity and ecological integrity indicators in the first *NSW Biodiversity Outlook Report* (DPIE 2020). These indicators are measures for 2013. Data required to enable a mid-2017 assessment (i.e. at commencement of the BC Act) are currently in development and will allow indicator trends over this period to be reported for any thematic region, including New South Wales as a whole.

Ecological condition and ecological carrying capacity enable comparative reporting for New South Wales as a whole, and for individual bioregions (Figure 3) by averaging cell values within reporting regions. When available data permit, these indicators may also be compared for reporting regions between any two points in time. Additionally, these two indicators can be reported as averages for any given reporting unit, such as public reserves and other tenure (Figure 3), and the 571 Mitchell landscapes (Mitchell 2002; OEH 2017e) in New South Wales (Figure 17 and Figure 18). Mapping indicators for Mitchell landscapes demonstrates how these indicators can be used to measure and report on highly detailed classifications, such as plant community types (Sivertsen 2009) currently being mapped in New South Wales. The histogram of ecological carrying capacity for NPW reserves and other tenures (Figure 19) demonstrates how the distribution of values within different stratifications can be compared to inform more detailed reporting.

Overall, New South Wales has an average ecological condition of 0.44 which is the proportional quality of remaining habitat after considering past clearing and other land utilisation impacts. The ecological carrying capacity of habitats across New South Wales is less (0.33) because fragmentation interferes with ecological processes by limiting dispersal, and therefore how resources are shared between systems to maintain all species of plant and animal. Fragmentation throughout New South Wales is shown to have reduced the ecological carrying capacity of remaining habitats by 25% (0.11 of 0.44). As can be seen in Figure 3, the pattern of habitat loss and degradation across New South Wales and between bioregions varies significantly. As of 2013, the Australian Alps, South East Corner, and NSW North Coast bioregions have the highest remaining ecological carrying capacity (0.53 to 0.62) while the NSW South Western Slopes, Brigalow Belt South and the Riverina bioregions have the lowest (0.15 to 0.25).

Ecological connectivity differs from ecological condition and ecological carrying capacity in that it provides a measure of each location’s relative contribution to the connectivity of extant habitat, rather than an absolute measure of its quality or connectivity status. While ecological connectivity values can be mapped across regions and reported on for individual locations, they cannot easily be reported for larger units with values compared over time, as positive changes in one location may result from the removal of habitat at another. Ecological carrying capacity is more appropriate for reporting how well connected habitat is within an aggregate reporting region. Ecological connectivity can however be used to report on each individual location’s contribution to the connectivity of contemporary habitat, and how that might change over time or under different management regimes. This characteristic can be relevant to evaluating or prioritising actions that result in changes to habitat within a broader framework of land management.

It is important to note that, as habitat in one part of the landscape is removed or becomes degraded, the relative contribution that nearby remaining habitat makes to habitat connectivity may increase without increasing in condition, depending on its position, and especially if connecting to larger remaining areas of higher quality habitat. An individual location may contribute to habitat connectivity purely due to its location relative to other habitat, independent of its own ecological condition or carrying capacity. Any reporting unit can therefore make a greater contribution to the connectivity of remaining habitat (with higher ecological connectivity) due to the removal of other habitat, and increases in ecological connectivity values at a single locaiton do not necessarily indicate that any improvement has occured in the ecological condition or ecological carrying capacity of habitat, or overall habitat connectivity.

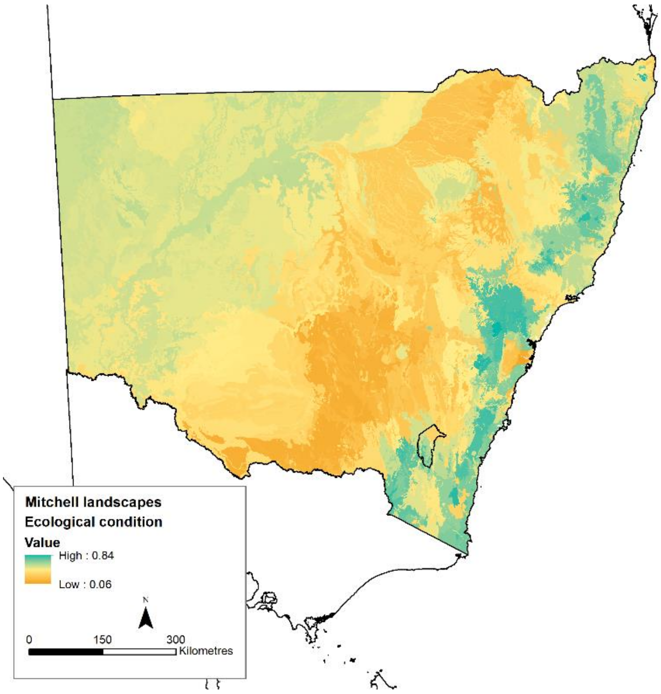


Figure 17 Ecological condition for 2013 averaged for each of the 571 Mitchell landscapes in New South Wales.

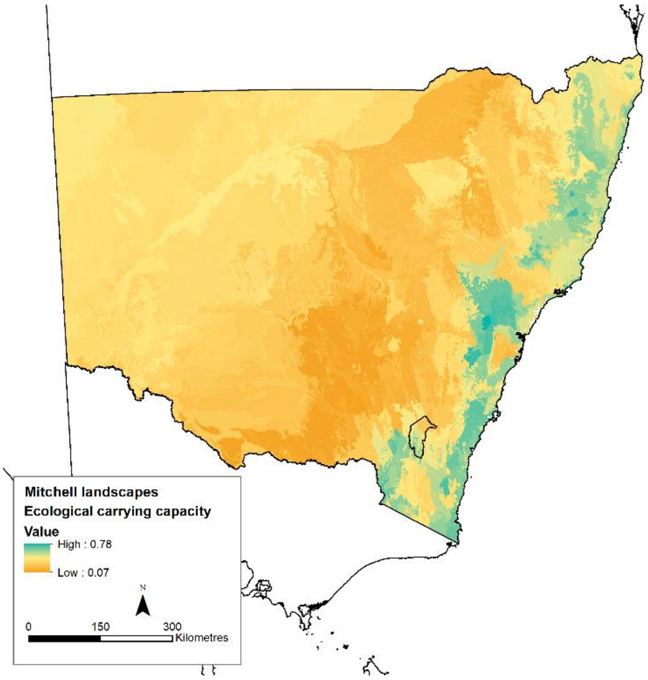


Figure 18 Ecological carrying capacity for 2013 averaged for each of the 571 Mitchell landscapes in New South Wales.

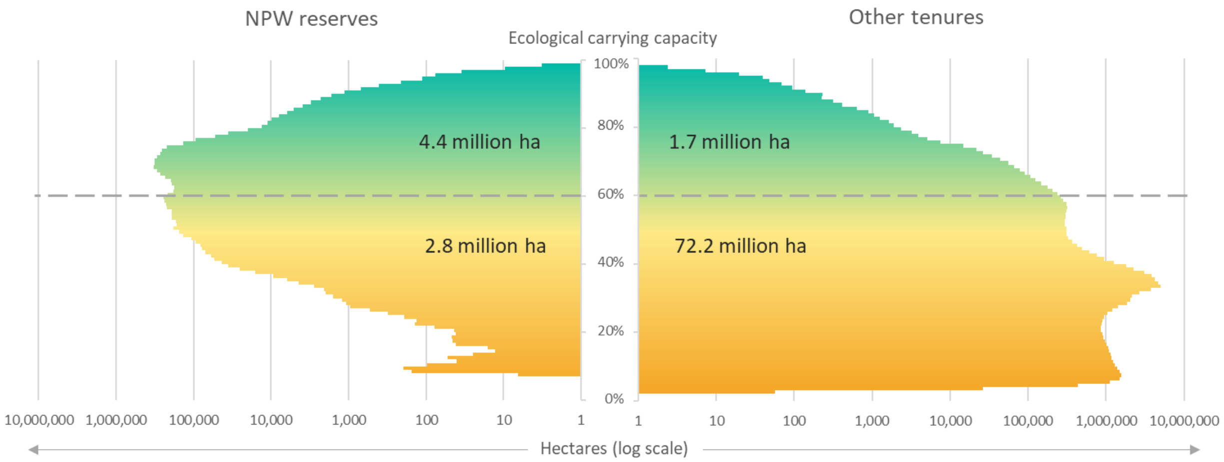


Figure 19 **Histogram showing the distribution of ecological carrying capacity values in NPW reserves (left) and other tenures (right).**

Area on the horizontal axis is in $\log_{10}$ scale and ecological carrying capacity on the vertical axis. NPW reserves (i.e. public reserves established in perpetuity under the National Parks and Wildlife Act) are primarily managed for conservation and have over 4.4 million hectares (62% of NPW reserves) with an ecological carrying capacity of 0.6 (60%) or higher, whereas other tenures have 1.7 million hectares (2% of other tenures) that are 0.6 (60%) or higher. Although a much smaller proportion of the total area of other tenures has ecological carrying capacity equal to or above 0.6, this is equivalent in size to 33% of the area with the same range of values in public reserves, indicating that large quantities of good quality habitat exist both inside and outside of public reserves.

5. Further work

There are many challenges associated with developing indicators of habitat condition across regions as large and diverse as New South Wales and much work remains to be done to gain a rigorous understanding of how habitat condition changes across the state, within regions, under different management regimes and over time. Our understanding of how habitat condition can be interpreted from available data, and our ability to do so, is constantly improving, and the best techniques for measuring or modelling the condition (or related attributes) of habitat at different scales will consequently evolve. The indicators presented here are a starting point defining our current knowledge of statewide habitat condition in New South Wales and provide a basis for including other relevant information as it becomes available. While this product is developed using the most up-to-date data, ongoing work will be needed to develop an assessment closer to when the BC Act commenced in August 2017. Future assessments of these indicators may further leverage new techniques that are currently in development but have not yet been fully operationalised.

Currently available remote-sensing products can provide accurate measures of vegetation cover relating to habitat condition for specific points in time but are unable to provide a complete measure of habitat condition (comprehensively inclusive of all contributing characteristics for example, as required for ecological condition or vegetation integrity assessments). Information from other sources can be costlier to collect or produce, especially repeatedly, across large regions such as New South Wales. As a result, it is difficult to accurately relate available information to the condition of habitat at any particular point in time. This highlights the need for committed and consistent approaches to collecting data from across a range of sources, including remotely sensed vegetation, land-use and vegetation type mapping, site observations and survey data, to improve our ability to assess and monitor habitat condition across the state.

While remote sensing presently provides valuable information on structural aspects of habitat condition (Tehrany et al. 2017), current sensors are limited to mapping of vegetation canopy, or what can be seen from above. New satellite missions and reduced cost of sensors attached to unmanned vehicles may in the future lead to more attributes of habitat condition being observed at larger scales. Other techniques requiring additional sources of data are needed to accurately predict the condition of understorey and ground-cover characteristics that contribute to habitat condition. These may rely on observed condition attributes and the modelled relationships between these and other observable predictors or proxies. Additional work is also required to better understand the relationships between these proxies, such as those between soil and landform variables and habitat condition, especially in the west of the state where less natural woody habitat exists and earlier remote-sensed woody vegetation cover products such as foliage projective cover are less directly related to habitat condition.

New remote sensing-based products such as the stable green vegetation (Appendix B, 1.11) input to ecological condition, seasonal cover disturbance index (OEH 2017d) and the habitat condition assessment system (Harwood et al. 2016) that rely on consistent time-series data may improve the mapping of habitat attributes beyond that which can presently be achieved. This is especially the case where the condition of habitat can be reflected in how measured indices change over time. More work is needed to develop consistent data and refine these products before they can be systematically incorporated into measures of ecological condition. Once developed and tested, these remote sensing-based methods, as well as predictive vegetation integrity modelling (McNellie et al. 2014; OEH 2017a), are expected to contribute to future iterations of this indicator.

5.1 Measuring indicator confidence

Available data and existing methods do not currently allow for the confidence in these indicators to be reported quantitatively. However, accuracy of the indicators is expected to increase when results are aggregated for reporting at larger scales, such as across whole regions or statewide. Accuracy also depends on how well different habitat attributes are represented. For example, the canopy of native woody habitat such as forests and closed woodlands can be captured well by remote-sensing products, whereas less information is available below the canopy to capture understorey and ground-cover disturbance and for non-woody habitat types, such as herbs and grasses.

While the accuracy at individual locations may vary widely and is highly dependent on the accuracy of source data and methods used to infer indicator measures, the patterns of change in habitat condition, when observed at larger scales, are well described by these indicators. Measurements of ecological condition and ecological carrying capacity averaged across regions and the state are therefore given a confidence level of ‘somewhat adequate’ based on a qualitative desktop appraisal of the model, prior applications of the approach and knowledge of source data.

The NSW *Biodiversity Assessment Method* (OEH 2017a) has developed a consistent approach to field assessing site-scale vegetation integrity against a set of best-on-offer condition attribute benchmarks that can be applied to new observations and existing site data. When available, site-scale measures of vegetation integrity will allow a rigorous measure of confidence in these indicators to be reported. While data required to comprehensively validate ecological condition remain in development, an initial comparison was made against desktop-based habitat condition assessment data (R Donohue [CSIRO] 2018, pers. comm.) undertaken to evaluate applications of the habitat condition assessment system (Harwood et al. 2016; Lyon et al. 2016).

The habitat condition assessment system evaluation data was developed through expert elicitation of habitat condition for multiple transects in Australia using Google Earth ™ satellite imagery (R Donohue [CSIRO] 2018, pers. comm.). Thirty-three transect sites fell within New South Wales and their comparison with ecological condition is shown in Figure 20. While the sample size is small, the R^2 of 0.6757 indicates a moderate level of agreement between the ecological condition model and the independent expert-based desktop assessments of habitat condition. The three greatest outliers have been assessed as resulting from inconsistencies in the land-use mapping of native forestry and pine plantation, or spatial precision where one site falls on the boundary between nature reserve and pine plantation. Additional such data collection following the expert elicitation methodologies of Dickson et al. (2016) will allow a rapid evaluation of ecological condition in New South Wales, while also implementing a process for collecting reliable in situ observations of vegetation integrity.

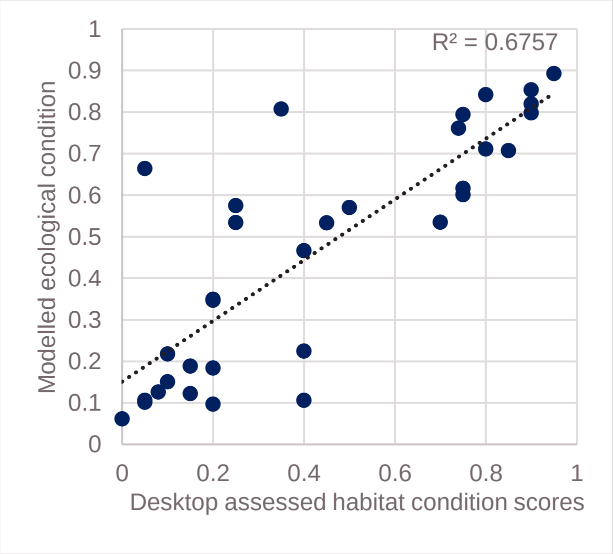


Figure 20 The agreement between ecological condition on the y axis and 33 desktop-based assessments of habitat condition, performed using satellite imagery to evaluate the habitat condition assessment system (Donohue [CSIRO] 2018, pers. comm.)

5.2 Measuring indicator change

The goals of the BC Act include the conservation of biodiversity at bioregional and state levels, a reduction in the rate of species loss, and effective management to maintain or enhance the integrity of natural habitats. To help assess the performance of new legislation for biodiversity conservation and native vegetation management, the habitat condition indicators presented here have been designed to provide a mechanism for monitoring and reporting on the status of ecological integrity in New South Wales at regular intervals, and to allow trends in these indicators to be reported.

The methods used to develop habitat condition indicators have been designed to enable monitoring and reporting over time, however, data available for New South Wales, such as remotely sensed foliage projective cover and land-use mapping do not currently provide the temporal consistency or temporal coverage needed to measure changes in these indicators over any past period. With ongoing improvements in data collection, the methods presented here, given consistent and accurate data representative of multiple points in time, can be used to monitor changes in the status of biodiversity and ecological integrity at regular intervals, and will allow trends in habitat condition indicators to be reported.

While some of the inputs used to model the ecological condition indicator are not expected to change significantly over periods of time relevant to the BC Act, other inputs to ecological condition are representative of dynamic habitat characteristics. Inputs that can be considered dynamic, such as those dependent on remotely sensed vegetation or those used in the current model to infer the influence of habitat management such as land-use and tenure mapping, can be updated frequently, where source data availability permits. This in turn allows changes in vegetation cover, and to some degree the effects of changes in management, to be captured by the model.

Within the current habitat condition modelling framework, the collecting of annual remotely sensed foliage projective cover and land-use and tenure-change mapping, would allow monitoring of how these indicators trend over time, however, to accurately measure change, these products need to be collected regularly and consistently over a period of time. New products like the MODIS-LandSat blended fractional cover currently being developed for New South Wales as well as annual land-use change products will contribute to addressing this need.

5.3 Forecasting indicator change

Accurately forecasting temporal change in ecological condition, and the subsequent change in ecological connectivity and ecological carrying capacity, and pre-empting consequences for biodiversity enables a better understanding of potential policy outcomes, supports the prioritising of investment, helps in managing risks and facilitates more effective planning for the future. Drielsma and Ferrier (2006) present a method for dynamic modelling of temporal change in vegetation condition that considers an initial state, and the probabilities and consequences of threatening processes occurring over a defined period of time.

Applying the Drielsma and Ferrier approach, probabilities of threatening processes occurring are spatially derived through association with existing data that are generally reflective of native vegetation management where the consequences are typically related to the types of vegetation that occur. The regenerative capacity of native vegetation is also considered, allowing for improvements in condition given threat abatement or combined with hypothetical management actions, such as restoration and revegetation, which can act to influence the rate of change in regenerative capacity.

As knowledge and information improves, models such as this can be used to forecast change in these indicators, and may be calibrated with measures of change in vegetation management and general ecological responses observed using remotely sensed time-series data (Harwood et al. 2016; OEH 2017d) or site-based vegetation integrity assessments (OEH 2017c). Ongoing commitments to the delivery of these products will lead to a greater understanding of how habitat changes over time, and how management influences those changes, enabling more-targeted decisions and ultimately maintaining and enhancing habitat quality to sustain more of New South Wales' biodiversity.

5.4 Comparing indicators with existing similar products

While underlying methods have evolved and data have improved, the measures of ecological condition align reasonably well with previous similar measures in New South Wales, however, these products are not directly comparable due to differences in how they were derived. In 2010, the NSW State of the Catchment reported an overall vegetation condition index of 0.52 based on land-use and land-cover mapping available up to 2008 (Dillon et al. 2011). The 2012 NSW Native Vegetation Management Benefits Project's condition layer was derived using remote-sensing and land-use data up to 2008 and similar methods to the ecological condition indicator and measured an average vegetation condition across New South Wales of 0.56 (Drielsma et al. 2012). Vegetation condition modelled for the Biodiversity Impacts and Adaptation Project (OEH 2016) in 2016 was derived from an extrapolation of the NSW NVM condition model and measured an average condition of 0.52 for New South Wales.

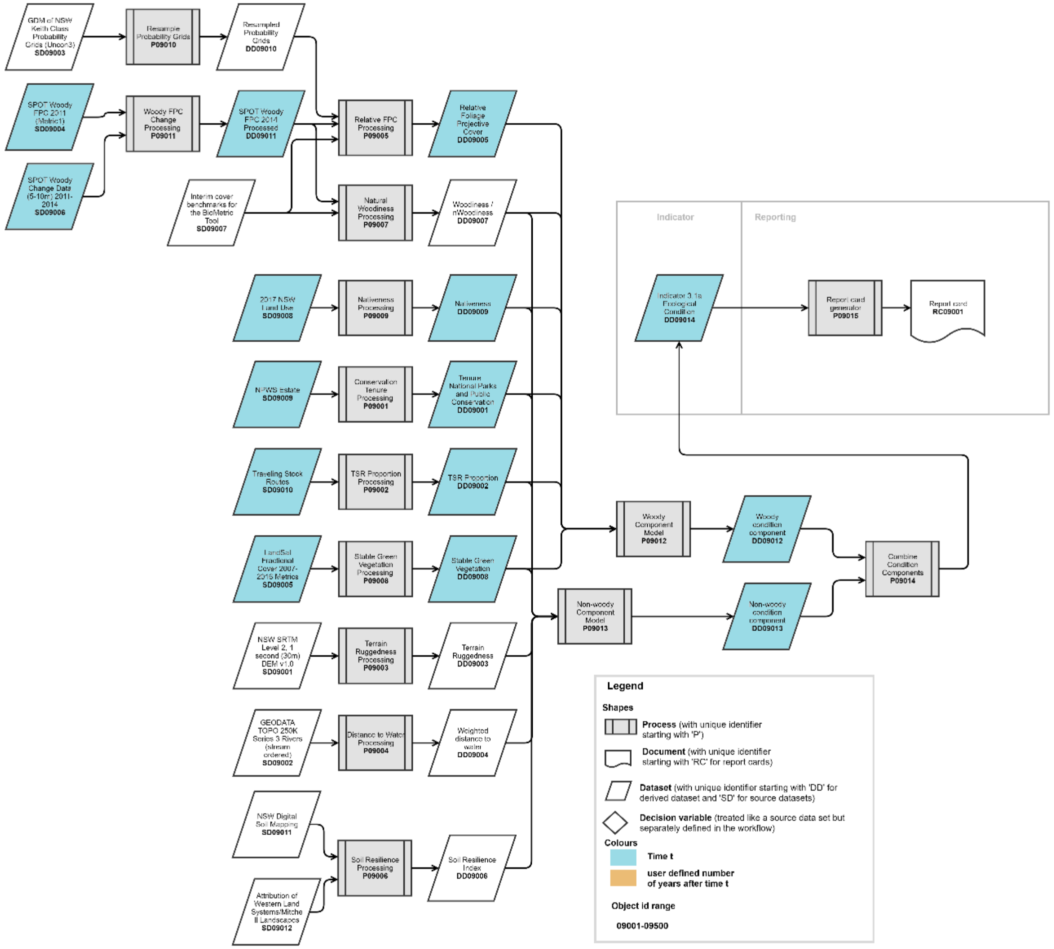
While some of the differences between earlier products and these indicators may potentially be attributed to changes in native vegetation extent and condition occurring over this period, and captured through improved data currency, a large and unmeasurable proportion of the differences between products would be due to differences in the methods applied, the resolution and quality of underlying data, and weightings applied to individual inputs. Therefore, while direct comparison between these products is not valid and cannot be made, some common design elements make these comparisons worth noting. In future, the derivation of consistent remotely sensed time-series products, such as the MODIS-LandSat blended fractional cover and temporal land-use datasets will enable a trajectory showing the history of change in habitat condition indicators to be derived.

Appendix A Indicator workflow diagrams

The following figures present workflow diagrams showing both data and processes used in the development of the three habitat condition indicators: ecological condition, ecological connectivity and ecological carrying capacity. The ecological connectivity and ecological carrying capacity indicators will remain relatively static as these processes are considered to be in a mature state. However, the processes and data used to derive ecological condition are expected to evolve as new products and techniques are operationalised. It will be important that consideration is given to the need to track historical trajectories in order to support the reporting of change and trends (e.g. reduction in the rate of loss of effective supporting habitat for biodiversity). Therefore, any new methods adopted, and their data dependencies, will need to support hindcasting to the commencement of the BC Act, on 25 August 2017.

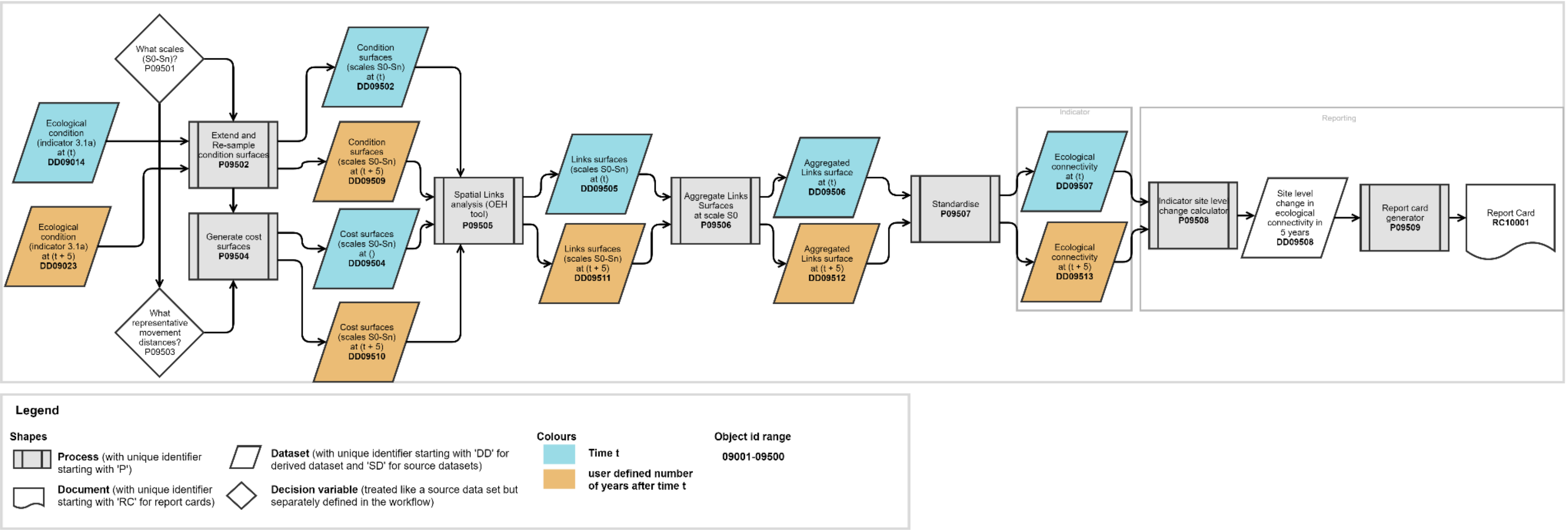
Workflow for indicator: Ecological condition of terrestrial vegetation

Products shown represent the initial period as the condition model is expected to undergo significant change prior to future measures of the indicator being undertaken and then hindcast to measure indicator change. (See larger view.)



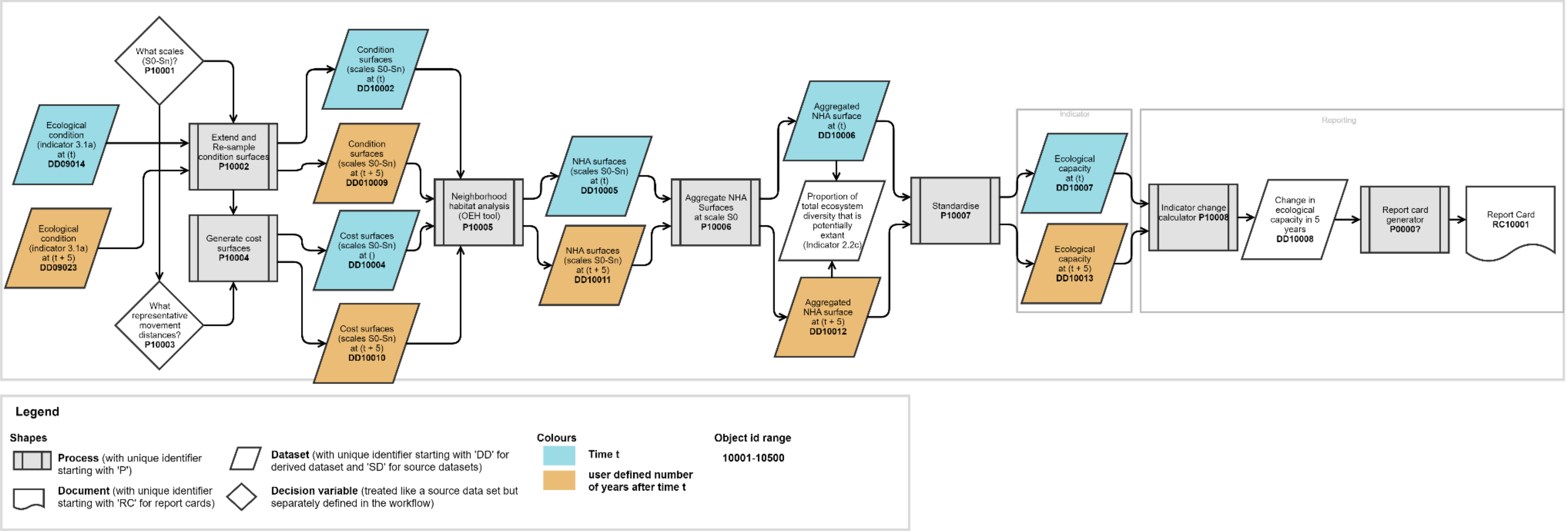
Workflow for indicator: Ecological connectivity of terrestrial vegetation

Only data products for this initial assessment (shown in blue) have been developed. Those in orange represent equivalent data products to be produced in five years to allow a measure of change in the indicator. (See larger view.)



Workflow for indicator: Ecological carrying capacity of terrestrial vegetation

Only data products for this initial assessment (shown in blue) have been developed. Those in orange represent equivalent data products to be produced in five years to allow a measure of change in the indicator. (See larger view.)



Appendix B Ecological condition model data processing

In this appendix, ‘OEH Corporate’ and ‘OEH Science’ refers to the former Office of Environment and Heritage’s corporate and Science Division databases.

1.1 GDM of NSW Keith class probability grids (Uncon3)

Unique IDs: SD09003, P09010, DD09010

Relative foliage projective cover (FPC) and natural woodiness inputs rely on a model of the pre-industrial distribution of vegetation. This was modelled using a stack of raster grids estimating the probabilities of each vegetation class (Keith 2004) occurring at each location in New South Wales (NSW) prior to any clearing or disturbance. Vegetation class probability grids were derived using a generalised dissimilarity model (GDM) (Ferrier et al. 2007) of floristic composition for NSW. This model is described in the *NSW Native Vegetation Management Benefits Analyses: Technical Report* (Drielsma et al. 2012). The GDM was classified using training data derived from high-certainty points in the map of native vegetation for NSW (Keith 2002) and probability grids for each of the 103 classes found in NSW were generated through a kernel regression (Ferrier et al. 2007). Classes not found in NSW are allocated zero probability across the state. For ecological condition, probability grids were bilinearly resampled to 90 metres from their original 250-metre resolution, then values were normalised so that probabilities sum to one at each cell.

1.2 SPOT woody FPC 2011 and woody change data (5–10 m) 2011–2013

Unique IDs: SD09004, SD09006, P09011, DD09011

The most current woody FPC data available for NSW at the time of analysis was for the year 2011. To update the 2011 SPOT woody FPC data to reflect change observed between 2011 and 2013, the factors listed in Table 4 were applied to those areas where change had been detected by the SPOT woody change detection program (OEH 2014). Selective desktop assessment of detected change using satellite imagery for reference confirmed these factors suitably accounted for the varied impacts of the different change events, and the response of native vegetation, in lieu of further information. In future, this may be informed by the observed response of vegetation to such events through the application of consistent time series vegetation cover mapping and field data collection.

Table 4 Foliage projective cover (FPC) factors applied to 2011 FPC data to account for change between 2011 and 2013

2011–2014 clearing category	FPC factor
Infrastructure and agriculture	0.00
Forestry	0.25
Fire and natural	0.50

1.3 Biometric vegetation cover benchmarks

Unique ID: SD09007

Benchmarks representing the amount of vegetation cover expected at each location if vegetation remained intact are needed to estimate how much vegetation cover has changed since the pre-industrial era (c. 1750). 'Lower bound' biometric overstorey, mid-storey, ground and shrub cover benchmarks are reported for the vegetation classes (Keith 2002) that occur in each Catchment Management Authority region (Ayers et al. 2005). The 'lower bound' thresholds represents an estimate of the lowest FPC value expected to be observed by remotely sensed FPC if vegetation in each class remains intact. These were averaged across regions then summed across strata to provide a single lower bound FPC threshold for each vegetation class (Appendix D). Future applications will likely be informed by new vegetation cover benchmarks currently being developed as part of the *Biodiversity Assessment Methodology* (OEH 2017a).

1.4 National parks and public conservation tenure

Unique IDs: P09001, DD09001

Input name: $tenureNP$

Description: National parks and other public conservation areas

Source(s)

NPWS Estate (SD09009)	Vector	OEH Corporate: P:\Corporate\Layers\Tenure\CrownEstate\NPWS_Estate_P	Retrieved 08/11/2017	(OEH 2017g)

Rationale:

National parks and other public conservation areas are primarily managed for conservation purposes. This input contains the same areas as NPW reserves used later for reporting. While their management, history and condition vary, they typically represent the best remaining examples of different vegetation types and provide benchmarks of the condition that can be attained through managing habitat primarily for conservation purposes. They are often selected for acquisition because they encompass habitats which are outstanding examples of their type. For these reasons, it is estimated that national parks and other public conservation areas are generally of higher condition than areas of similar vegetation under different management regimes; however, examples of high condition vegetation are known to occur outside of the reserve system. Where this is expressed in woody vegetation, the method will detect it. In the case of non-woody vegetation, we largely rely on knowledge of management practices, which can only be inferred at this time. Therefore, national parks and public conservation areas are only used to moderate the influence of other tenure outside of reserves (as specified in Ecological condition model).

Process:

The OEH corporate NPWS estate vector data ('NPWS Estate') was raster-converted at a 90-metre resolution using the source attribute table's TYPE field to allocate cell values. The TYPE values were grouped into one of the five classes, and were assigned the specified categorical value as shown in Table 5. Both other tenure types and 'No Data' (i.e. areas outside of NSW but in the analysis extent) were assigned to the 'Outside' class with a value of 0. The VALUE field of the output raster dataset was used to moderate the weighting of other tenure when deriving condition model components.

Table 5 ‘*tenureNP*’ values used as an input to condition component models

Categorical value	Type value classes	Area (ha)
0	Outside	148,825,617
1	National park, nature reserve, karst conservation reserve	6,398,197
4	State conservation area	721,303
6	Aboriginal area	36,145
8	Regional park	20,952
10	Historic site	3,191

1.5 TSR proportion

Unique IDs: P09002, DD09002

Input name: $propTSR$

Description: Proportion of each 90-metre grid cell that is travelling stock reserve (TSR)

Source(s):

Travelling stock routes (SD09010)	Vector	OEH Corporate: P:\Corporate\Layers\Tenure\CrownEstate\TravelingStockRoutes_P	Retrieved 16/10/2017	(DECCW 2009)

Rationale:

In landscapes dominated by agricultural productivity, TSRs represent important areas of relatively less-degraded habitat. TSRs are parcels of Crown land that are reserved under legislation for use by travelling stock, and their management often strikes a balance between the needs of travelling or grazing stock and the conservation of native species. They provide remnant supporting habitat for establishment and dispersal of many native species. By nature, their maintenance results in less pressure when compared with more intensive uses of surrounding land and, while often not in reference condition, TSRs tend to represent the best remaining examples of their type, particuarly in heavily cleared landscapes.

Process:

As TSRs are often narrow, linear features in the landscape, they can have sub-pixel widths that are missed during grid cell conversion. To reduce the occurrence of this, the polygon layer of TSRs was first converted to a 30-metre raster more closely representing its vector resolution and then aggregated up to 90 metre using the sum of 30-metre cells where TSRs are present. These summed grid cell values were then rescaled by dividing by nine (the number of 30-metre cells in each 90-metre cell). The resulting 90-metre raster contains values representing the proportion of 30-metre cells that are TSR in each 90-metre cell ranging from 0 (no TSR present) to 1 (completely consists of TSR). The contribution of this input is weighted as specified in the ecological condition model where it is applied to areas outside national parks and other public conservation areas.

1.6 Terrain ruggedness

Unique IDs: P09003, DD09003

Input name: $ruggedness$

Description: Local variation in elevation

Source(s):

NSW SRTM Level 2, 1 second (30 m) DEM v1.0 (SD09001)	30-m raster	OEH Corporate: P:\Corporate\Grids\Land\Elevation\LCC\DEM30m_SRTM\dem30m	V1.0 Retrieved 27/03/17	Geoscience Australia and CSIRO Land & Water (2010)

Rationale:

Rugged terrain can present a barrier to the types of anthropogenic uses that are often responsible for the loss or degradation of habitat. More rugged areas are less accessible and less suited to cultivation, production, or other land uses that are less sympathetic towards the habitat requirements of native plants and animals. They are typically subject to less disturbance than adjacent flatter, more accessible land under the same ownership, land use or management. The ruggedness of terrain was therefore considered a suitable predictor of a location's habitat quality.

Process:

Ruggedness was calculated using a standard deviation method applied to the 1 second (~30 metre) shuttle radar topographic mission (SRTM) derived digital elevation model (DEM) for New South Wales (Geoscience Australia & CSIRO Land and Water 2010) using a neighbourhood radius of 41 cells (approx. 1.2 km). The resulting product was resampled to 90 metres using mean cell value aggregation and rescaled so that values range between 0 (lowest ruggedness) and 1 (highest ruggedness). Its contribution is weighted as specified in the condition component models where its influence is applied in the non-woody condition component equally to all tenures and irrespective of naturalness.

1.7 Weighted distance to water

Unique IDs: P09004, DD09004

Input name: $distWater$

Description: The distance to water weighted by the order of the nearest waterway

Source(s):

GEODATA TOPO 250K series 3 rivers (stream ordered)	Vector	OEH Science: LMDS_Data_Store\Study_Area_NSW\Data\Rivers\stream_order\river_250topo_ordered.shp	Retrieved 02/08/2017	Geoscience Australia (2006)

Rationale:

Access to water is generally considered an important resource for native species. Habitat that allows access to reliable sources of water through its proximity and connectivity is expected to have a greater capacity to support a range of native species, especially those with limited movement abilities or higher dependence on reliable water sources. Areas providing more reliable sources of water are likely to act as refugia for a range of species during dryer seasons or prolonged drought, and riparian areas provide habitat corridors in drier or heavily modified landscapes (Catterall, Lynch & Jansen 2007; Crome, Isaacs & Moore 1994). This approach was applied to natural watercourses, however, artificial (and many natural) watering points are also places where stock congregate and grazing pressure is higher, therefore, their habitat (especially ground cover) may be further degraded (Amy & Robertson 2001). More work is needed to assess grazing pressure and its correlation with access to water across the state, and future improvements may result from the analysis of consistent vegetation cover time series data, climate variables and water observations from space (Mueller et al. 2016).

Process:

Weighted distance to water was calculated by first generating individual polyline shapefiles for each stream order class (1 to 9) mapped in the OEH Science’s ‘250km Topo Rivers’ shapefile (Mueller et al. 2016). 90-metre resolution grids containing the Euclidian distance of every cell to the nearest polyline of each stream order class were derived. Using equation 5, weightings were applied for each stream order by dividing grids of the stream order value (s) raised to the power of 1.5 by the respective stream order distance (d) grid. An epsilon of 45 metres (1/2 the analysis cell size) was first added to distance grids to avoid divide-by-zero errors. The weighted distance grids for all stream order classes (i) were summed at each cell to produce a single layer with values approaching 0 (furthest from water) to 1 (adjacent to water). The contribution of this input to ecological condition is then weighted as specified in the condition component models.

$$distWater = \sum_i \frac{s_i^{1.5}}{d_i+45} \qquad \text{equation 5}$$

1.8 Relative foliage projective cover

Unique ID: P09005, DD09005

Input name: $relFPC$

Description: Foliage projective cover (FPC) scaled relative to thresholds for intact vegetation types

Source(s):

GDM of NSW Keith class probability grids (Uncon3)	250-m raster	OEH Science: NSW NVM Benefits Project	V3.0 Retrieved 18/10/2017	Drielsma et al. (2012)
SPOT woody FPC 2011 (Metric1)	30-m raster	Supplied by CSIRO: WoodyFPC_2011_Metric1.rst	Retrieved 22/05/2017	OEH (2014)
SPOT woody change data (5–10m) 2011–2014	Vector	OEH Corporate: SLATS_Change2008_2014.gdb	Retrieved 21/08/2017	OEH (2014)
Interim cover benchmarks for the BioMetric Tool	Table	OEH Science: NSW NVM Benefits Project	Retrieved 01/03/2017	Ayers et al. (2005)

Rationale:

Remotely sensed vegetation cover provides a useful indicator of habitat condition by allowing the identification of locations where cover has been lost or degraded over an observed period or from an estimated previous state. However, vegetation cover varies naturally in and between different vegetation types. Without using estimates of the amount of cover expected to occur if vegetation remained intact, loss of cover cannot be inferred from the amount of cover observed. SPOT-derived woody FPC for New South Wales maps the percentage of ground area occupied by the vertical projection of foliage masked to the mapped extent of woody vegetation (OEH 2014). Lower bound cover thresholds (Appendix B, 1.3) and GDM-modelled vegetation class probability grids (Appendix B, 1.1) are used to scale FPC relative to what would be expected if the original vegetation remained intact. This allows estimates of the loss of original cover to be made and ensures ecological condition for locations with naturally sparse vegetation cover, such as grassland or open woodland, are not reduced by having a lower FPC in the same way that a naturally occurring forest would be. Relative FPC for ecological condition improves on that used in the original NVM model by applying benchmarks at the vegetation class rather than broader formation level. Further work is under way to improve vegetation cover benchmarks as part of the *Biodiversity Assessment Methodology* (OEH 2017a).

Process:

To account for the continuous nature of vegetation cover, logistic functions were used to transform FPC values relative to lower bound thresholds for each vegetation class. The transformation function (equation 6) applied to FPC values averaged at a 90-metre resolution uses half the lower bound FPC threshold (t_c) (Appendix D) as a midpoint and a constant (k) of 0.2 defining the slope of the curve. Transformed FPC values for each class are then multiplied by the class's probability (p_c) of occurrence (Appendix B, 1.1) at each cell and the results summed across classes to derive a measure ranging from 0 to 1, relative to the lower bound thresholds for the vegetation type or types estimated to have originally occurred. The contribution of relative FPC is weighted as specified in the condition component models.

$$relFPC = \sum_c p_c \left(1 - \frac{1}{1+e^{-k(FPC - t_c/2)}}\right) \qquad \text{equation 6}$$

1.9 Soil resilience index

Unique ID: P09006, DD09006

Input name: $nswSRI$

Description: Soil resilience derived from land systems and key soil properties

Source(s):

NSW digital soil mapping	100-m raster	OEH Corporate: https://iar.environment.nsw.gov.au/dataset/digital-soil-maps-for-key-soil-properties-over-nsw	Retrieved 03/08/2017	OEH (2017b)
Attribution of Western Land Systems/Mitchell landscapes	Vector	OEH Science: NSW NVM Benefits Project	Retrieved 16/11/2017	D Robson & M Drielsma 2011, pers. comm.

Rationale:

The original NVM condition model relied on an expert-derived estimate of soil resilience, its ability to recover to a healthy state post-disturbance, using a classification of Western Land Systems (D Robson & M Drielsma 2011, pers. comm.) and Mitchell landscapes (Drielsma & Ferrier 2009; Mitchell 2002; OEH 2017e). This classification allocates high, medium or low soil resilience classes to relatively large contiguous areas. For ecological condition, this has been supplemented by a measure of soil resilience developed by adapting an existing index of soil quality in forests (Amacher, O'Neil & Perry 2007) to use digital mapping of soil properties over New South Wales (OEH 2017a). The approach integrates individual soil properties into a single index that is used as a surrogate for soil resilience. Employing soil resilience addresses some of the challenges associated with using remotely sensed vegetation cover to model ecological condition in less woody or more arid landscapes, such as those found in western New South Wales where persistent and stable cover is less indicative of good condition (i.e. places that are naturally or predominantly grassland or bare). Soil resilience may be refined as more explicit knowledge of the relationship between soil properties and habitat quality develops.

Process:

The soil quality index developed by Amacher et al. (2007) was adapted to develop a NSW soil resilience index (*nswSRI*) using data available from the digital soil mapping over New South Wales (OEH 2017b). Values from the total range of each soil property mapped across New South Wales are allocated to scores based on an understanding of the property's influence on native vegetation (Table 6). Scores are summed at each location and the result scaled between 0 (low resilience) and 1 (high resilience) by dividing by the maximum possible score. As knowledge of the relationship between soil and habitat quality is still developing, the index has only been applied to those landscapes allocated medium or low soil resilience in the original NVM model (see Figure 30) and its contribution to the non-woody condition component weighted to appropriately account for uncertainty (see section 2.4: Ecological condition model). As per the NVM model, landscapes originally allocated high resilience (i.e. landscapes with codes Baf, Bap, Bop, Clc, Byc, Gyp, Nac, Tef, Tep and the Eastern Division of NSW) are allocated a value of 1.

Table 6 Soil properties (OEH 2017a) and their ranges allocated to scores used to develop the simplified *nswSRI*

Property	Units	Range	Score
Soil pH	pH units	<=3	-1
		3.1 to 4	0
		4.1 to 5.5	1
		5.6 to 7.2	2
		7.3 to 8.5	1
		> 8.5	0
Soil organic carbon	%, kg/m3	<1	0
		1 to 5	1
		>5	2
Sum of bases	cmolc/kg	<10	0
		10 to 20	1
		>20	2
Cation exchange capacity	cmolc/kg	<45.6	0
		45.6 to 82.5	1
		>82.5	2
ESP (exchangeable sodium %)	%	<=10	1
		>10	0
P Total	mg/kg (ppm)	<298	0
		>298	1

1.10 Natural woodiness

Unique ID: DD09007

Input name: $woodiness$

Description: Predicted original woody cover expected to have occurred at each grid cell location

Source(s):

GDM of NSW Keith class probability grids (Uncon3)	250-m raster	OEH Science: NSW NVM Benefits Project	V3.0 Retrieved 18/10/2017	Drielsma et al. (2012)
Interim cover benchmarks for the BioMetric Tool	Tabular	OEH Science: NSW NVM Benefits Project	Retrieved 01/03/2017	Ayers et al. (2005)

Rationale:

The ecological condition modelling approach relies on an estimate of the original woodiness of vegetation at each location based on the type of vegetation that naturally occurs, or is estimated to have originally occurred if now substantially modified or removed. The natural woodiness at each location weights the proportional contribution that woody and non-woody condition components have on ecological condition. Ecological condition in areas that were originally grassland or open woodland will have a greater proportional contribution from the non-woody model component than areas that were originally forest and where a greater contribution to ecological condition is from the woody model component.

Process:

Vegetation class probability grids (p_c) (Appendix B, 1.1) were multiplied by their respective lower bound cover threshold (b_c) (Appendix B, 1.3) at a 9-metre resolution, then the results summed across classes at each location providing an estimate of the original vegetation's minimum woodiness (equation 7) at each location. The resulting layer was rescaled so that values ranged from 0 (not woody at all) to 1 (completely woody). A complimentary non-woodiness layer was also generated as $1 - woodiness$ to facilitate analysis. Woodiness is used to multiplicatively weight the contribution that both woody and non-woody condition components have on ecological condition at each location. The weighted components are then added at each location to derive its ecological condition (see section 2.4: Ecological condition model).

$$woodiness = \sum_c p_c b_c \quad \text{equation 7}$$

1.11 Stable green vegetation

Unique ID: DD09008

Input name: $stblGrnVeg$

Description: The amount and stability of green fractional cover over a 10-year period

Source(s):

LandSat fractional cover 2007–2016 metrics	30-m raster	Supplied by CSIRO: FracCover_bare_2007-2016_Metric (1-3).rst	Retrieved 22/05/2017	Danaher et al. (2010), Donohue et al. (2017)

Rationale:

The stable green vegetation index was derived from a 10-year time series of remotely sensed fractional cover measures. This index is a combined measure of the amount of green vegetation cover and its stability over time. In predominantly modified and non-woody environments, at the lower range of the index, the initial assessment demonstrated good differentiation between frequently cropped land, land which may be less utilised and occasionally cropped, and land that is grazed or where green vegetation is more stable. At the higher range of the index, it highlights areas of woody vegetation where recent change events have occurred resulting in a significant reduction in green vegetation cover over the 10-year period. Similar indices were developed for both brown vegetation cover and all vegetation cover as shown in Figure 20, however the stable green vegetation product was considered to provide information most relevant to modelling habitat condition.

Process:

Donohue et al. (2017) conducted a review of the most appropriate remote-sensing variables for habitat condition assessment. This review identified five products that were relatively mature and could be provided with little additional effort. Of these five products, three were metrics-based on a time series of each fractional component of LandSat fractional cover measures (Table 7) from 2007 to 2016 (Danaher et al. 2010) provided at a 90-metre resolution. Metrics 1 and 3 of green fractional cover were used to derive the measure of stable green vegetation. The metrics were first standardised from 0 to 1, then the annual average multiplied by the compliment of the mean intra-annual range such that: $stblGrnVeg = \widehat{M_1}(1 - \widehat{M_3})$.

Table 7 Fractional cover time series metrics

Temporal period	2007–2016
Metric 1	Annual average of the period
Metric 2	Mean intra-annual maximum of the period
Metric 3	Mean intra-annual range of the period

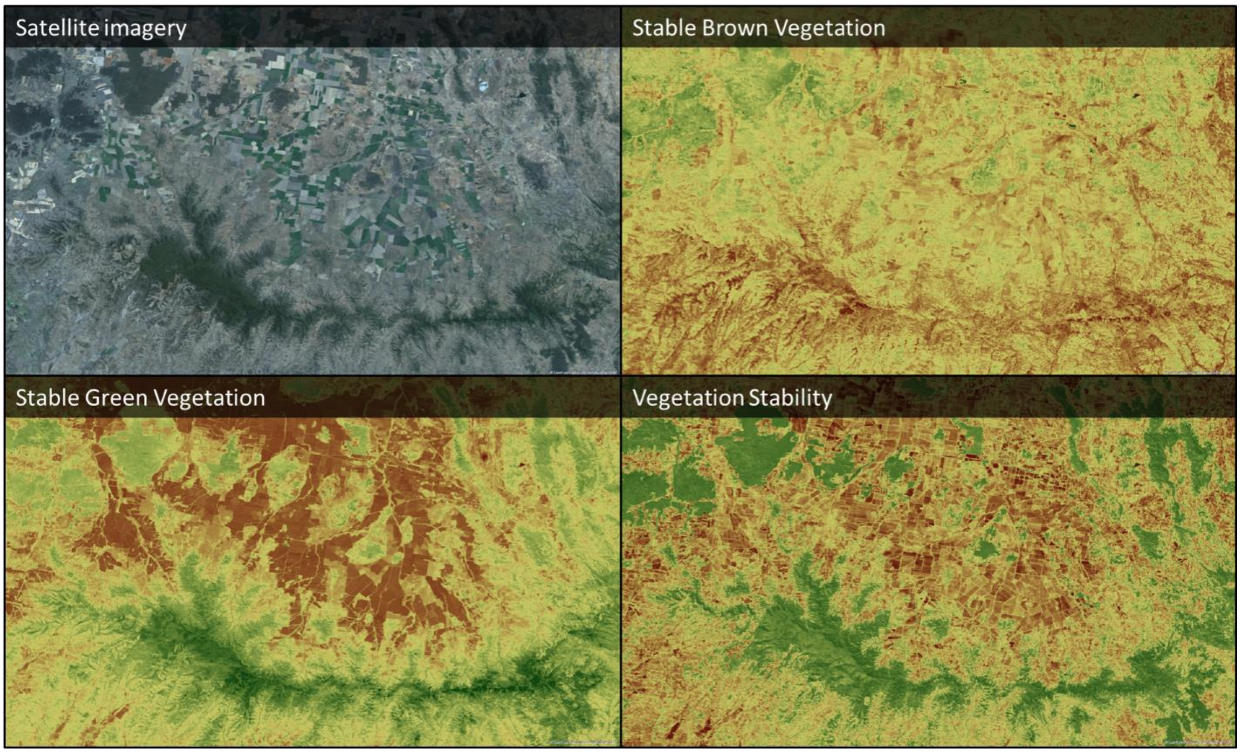


Figure 21 **Vegetation stability indices calculated from fractional cover time series data (2007–2016) shown for the Liverpool Plains area in New South Wales with satellite imagery included for reference (top left).**

Stable green vegetation (bottom left) as used in ecological condition, showing lowest (brown) to highest (green) stable green cover. Stable brown vegetation (top right) and vegetation stability (green and brown vegetation, bottom right) also shown were derived as potential inputs but not included in the ecological condition model.

1.12 Nativeness

Unique ID: DD09009

Input: $nativeness$

Description: An estimate of the ‘nativeness’ of vegetation based on land-use mapping

Source(s)

2017 NSW land use	Vector	OEH Corporate: Final_Landuse_2013.gdb	Retrieved 12/09/2017	(OEH 2017f)

Rationale:

The way in which land is managed has a significant bearing on the quality and extent of habitat that occurs there, and the likelihood of future removal or replacement of native vegetation. At this stage, the management of land can only be inferred from available information. As a surrogate for how habitat has been managed, land-use mapping is used to determine if vegetation present at each location is likely to be exotic, probably contain exotics, or is mostly native. Urban and intensive land uses are also considered.

Process:

The most current (Figure 21) OEH land-use mapping (OEH 2017f) was provided as a polygon dataset in a file geodatabase attributed with the *Australian Land Use and Management* (ALUM) Classification (Australian Government 2006). The polygon data was converted to a 90m grid using the ALUM tertiary classes. Tertiary ALUM classes were then allocated to one of the nativeness classes (summarised in Table 8) as used in the original NVM model (see Appendix E for the assignment details). The *nativeness* input is used as a conditional operator in each condition component model. Separate weights were assigned for each condition component (woody and non-woody) (Table 8), and for areas mapped as exotic or probably exotic, the stable green vegetation input rather than a constant weight is used to inform the non-woody condition component.

Table 8 Condition weights applied to classes of *nativeness* for woody and non-woody condition components and where the *nativeness* input is used to constrain stable green vegetation's contribution to the non-woody component

Nativeness	Woody	Non-woody
Urban/Intensive	0.10	0.05
Exotics	0.50	*stblGrnVeg*
Probable exotics	0.75	*stblGrnVeg*
Mostly native	1.00	1.00

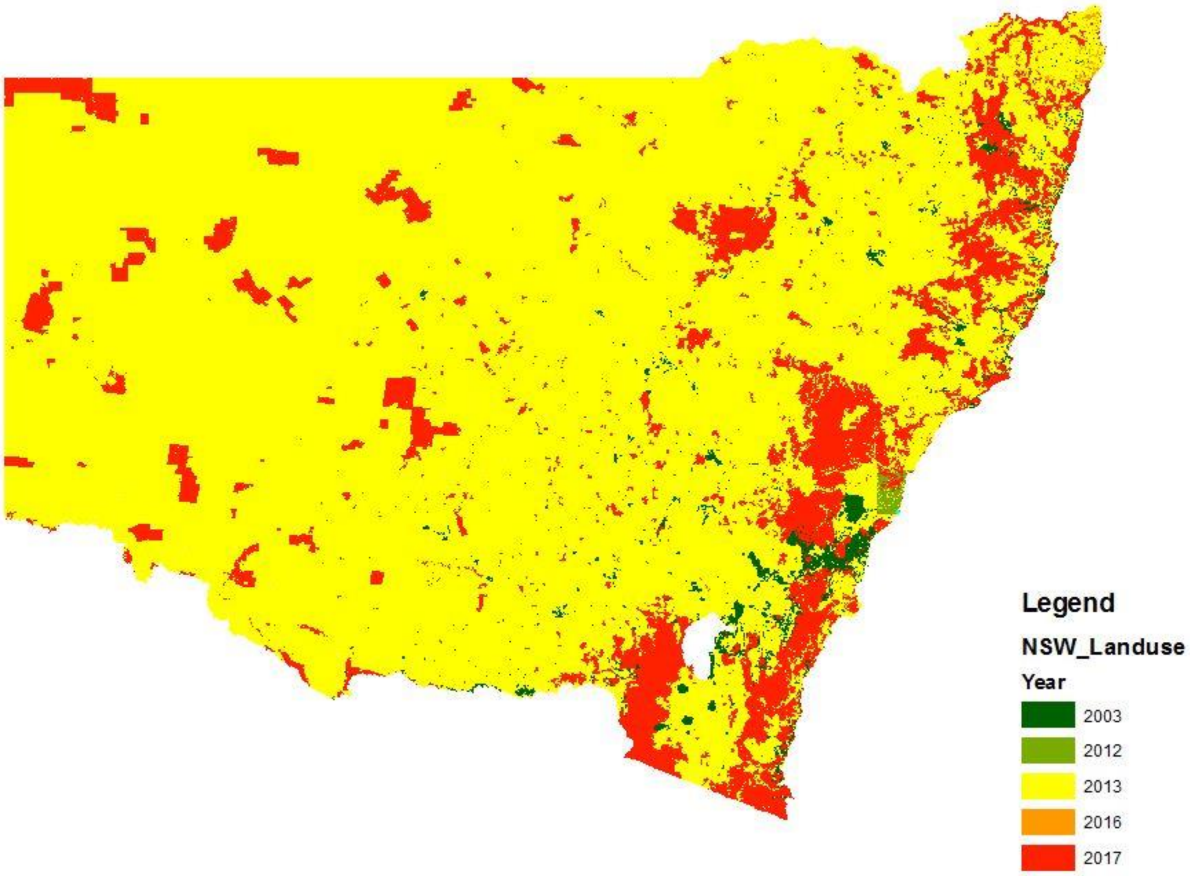
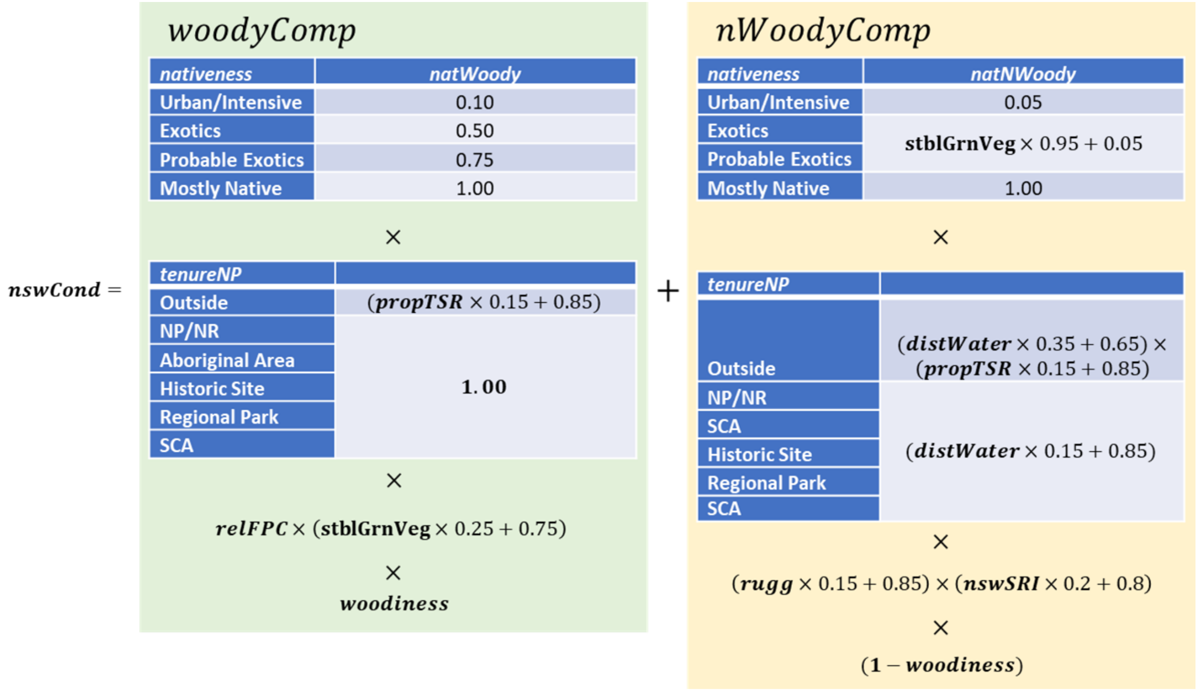


Figure 22 **Currency of land-use data (from 2003 to 2017) in New South Wales used to derive ecological condition's *nativeness* input.**

1.13 Ecological condition model raster calculations



$nswCond =$ *woodyComp* $+$ *nWoodyComp*

woodyComp

nativeness	*natWoody*
Urban/Intensive	0.10
Exotics	0.50
Probable Exotics	0.75
Mostly Native	1.00

$\times$

tenureNP	
Outside	$(propTSR \times 0.15 + 0.85)$
NP/NR	1.00
Aboriginal Area	
Historic Site	
Regional Park	
SCA	

$\times$

$relFPC \times (\mathbf{stblGrnVeg} \times 0.25 + 0.75)$

$\times$

$woodiness$

nWoodyComp

nativeness	*natNWoody*
Urban/Intensive	0.05
Exotics	$\mathbf{stblGrnVeg} \times 0.95 + 0.05$
Probable Exotics	
Mostly Native	1.00

$\times$

tenureNP	
Outside	$(distWater \times 0.35 + 0.65) \times$ $(propTSR \times 0.15 + 0.85)$
NP/NR	$(distWater \times 0.15 + 0.85)$
SCA	
Historic Site	
Regional Park	
SCA	

$\times$

$(rugg \times 0.15 + 0.85) \times (nswSRI \times 0.2 + 0.8)$

$\times$

$(\mathbf{1} - woodiness)$

Figure 23 Ecological condition model showing woody and non-woody components, their inputs and weights.

Calculation 1 ArcMap raster calculation for the condition model's woody component formatted for legibility and colour coded to align with the ecological condition model in Figure 23.

```
"natWoody"
*
("stblGrnVeg" * 0.25 + 0.75)
*
"relFPC"
*
Con("tenureNP" == 0,
        “propTSR" * 0.15 + 0.85,
        1.0)
*
woodiness
```

Calculation 2 ArcMap raster calculation for the condition model's non-woody component formatted for legibility and colour coded to align with the ecological condition model in Figure 23.

```
Con(("natNWoody" > 0.05) & ("natNWoody" < 1.0),
       "stblGrnVeg" * 0.95 + 0.05,
       "natNWoody")
*
("ruggedness" * 0.15 + 0.85)
*
Con("tenureNP"== 0,
      ("propTSR" * 0.15 + 0.85) * ("distWater" * 0.35 + 0.65),
      "distWater" * 0.15 + 0.85)
*
"nswSRI"
*
(1.0 - woodiness)
```

Appendix C Maps of ecological condition inputs for New South Wales

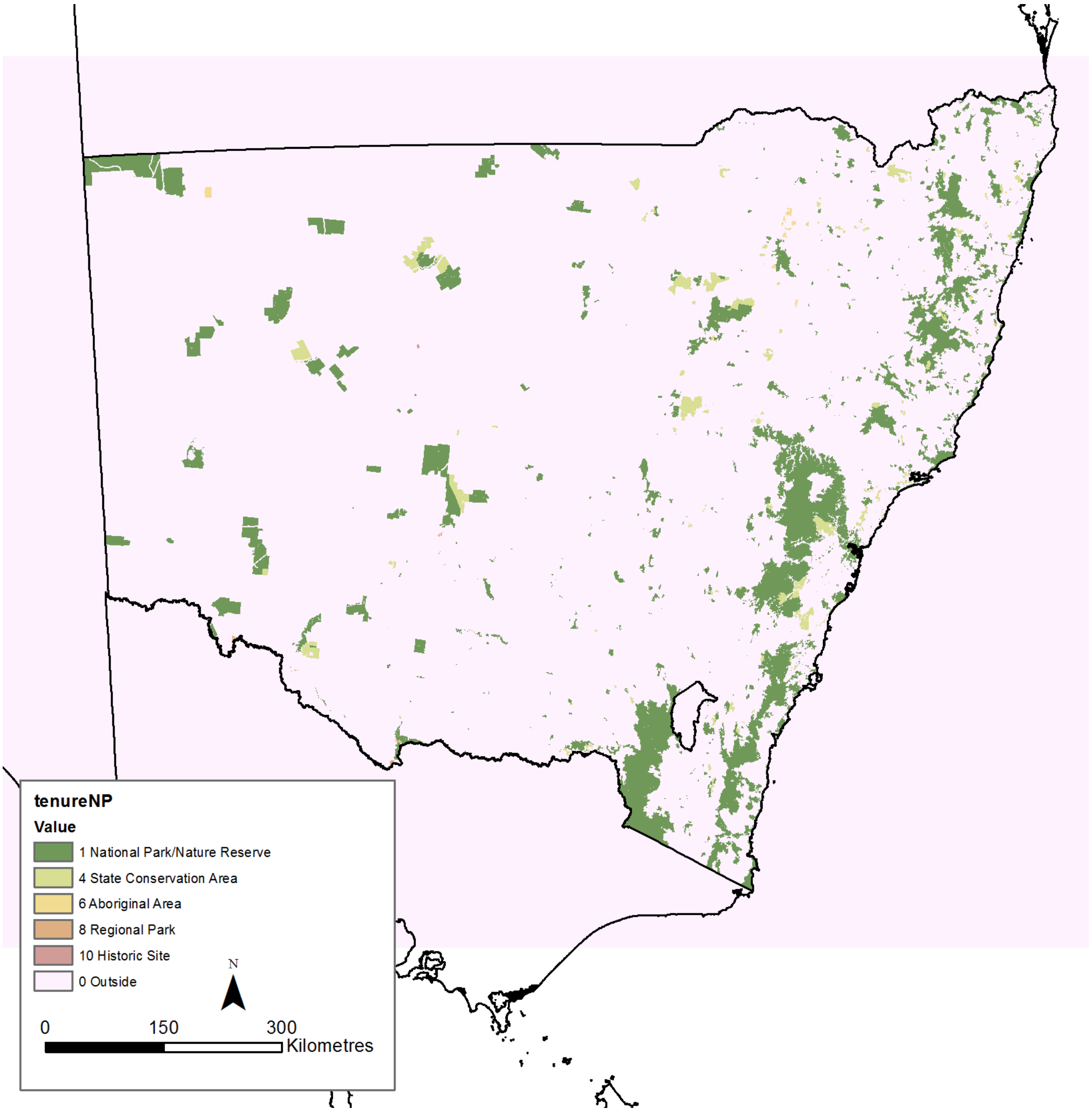


Figure 24 ***tenureNP*** **input layer identifying national parks and other public conservation areas (as used to report on NPW reserves).**

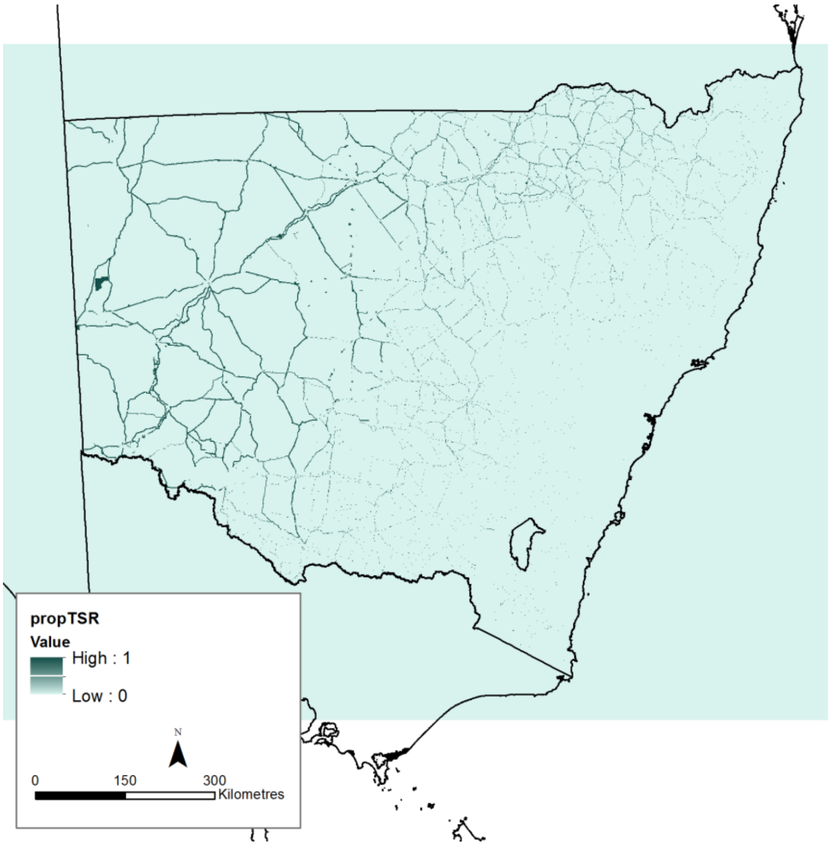


Figure 25 ***propTSR* input layer with the proportion of each 90-metre grid cell that is travelling stock reserve (TSR).**

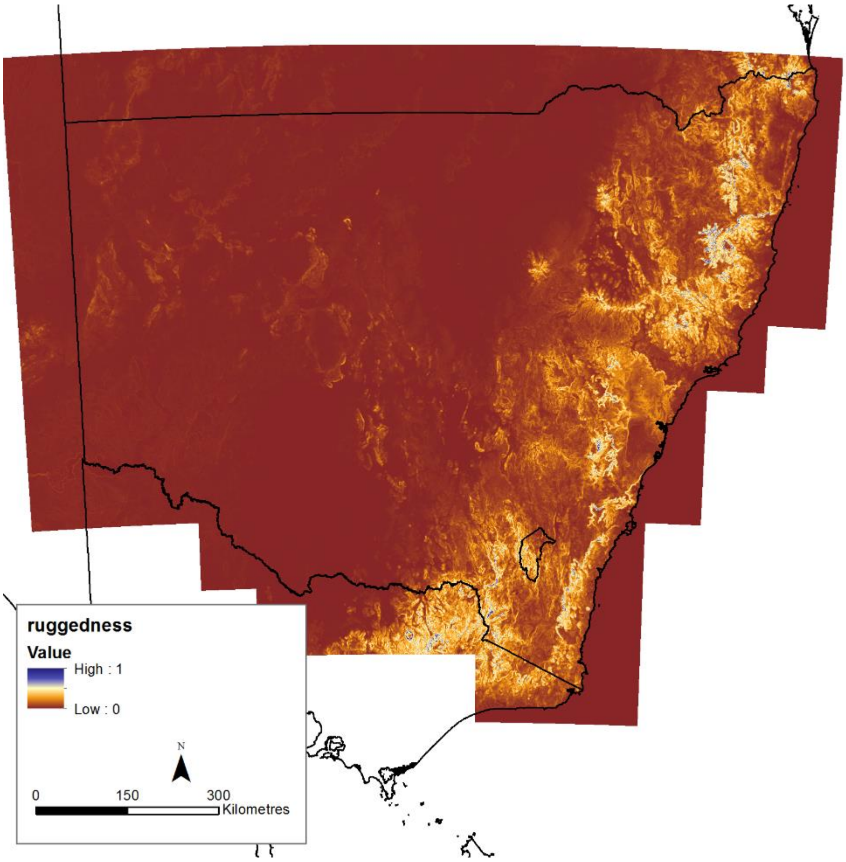


Figure 26 ***ruggedness* input layer showing local variation in elevation.**

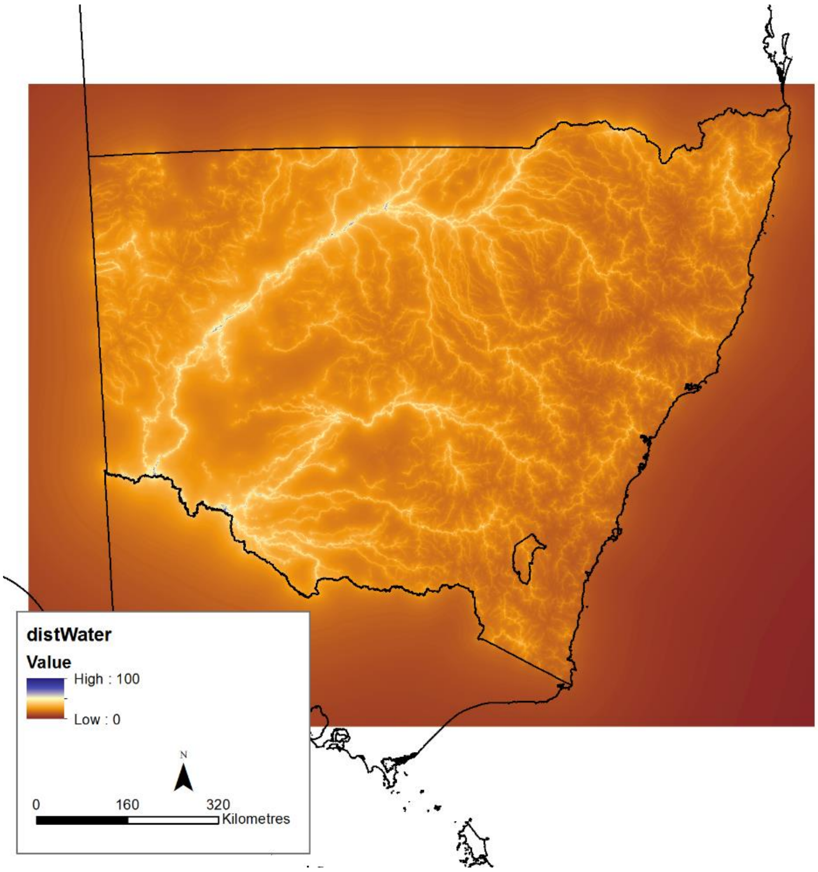


Figure 27 ***distWater*** **input layer showing the distance to water weighted by stream order.**

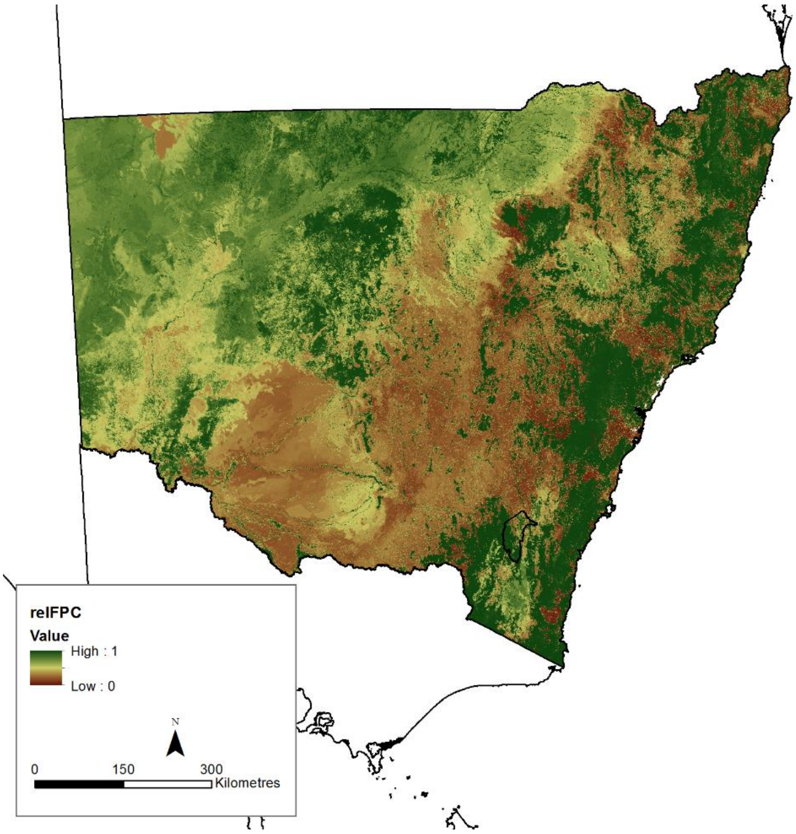


Figure 28 ***relFPC*** **input layer showing foliage projective cover (FPC) scaled relative to thresholds for intact vegetation types.**

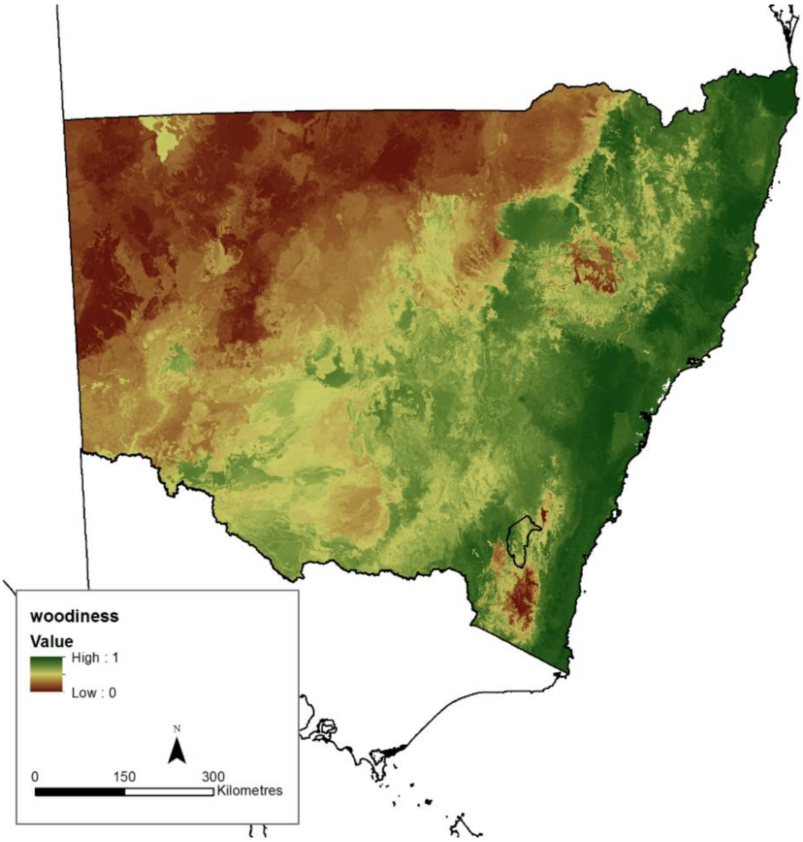


Figure 29 ***woodiness* input layer showing the amount of natural woody cover predicted to have originally occurred prior to the industrial era.**

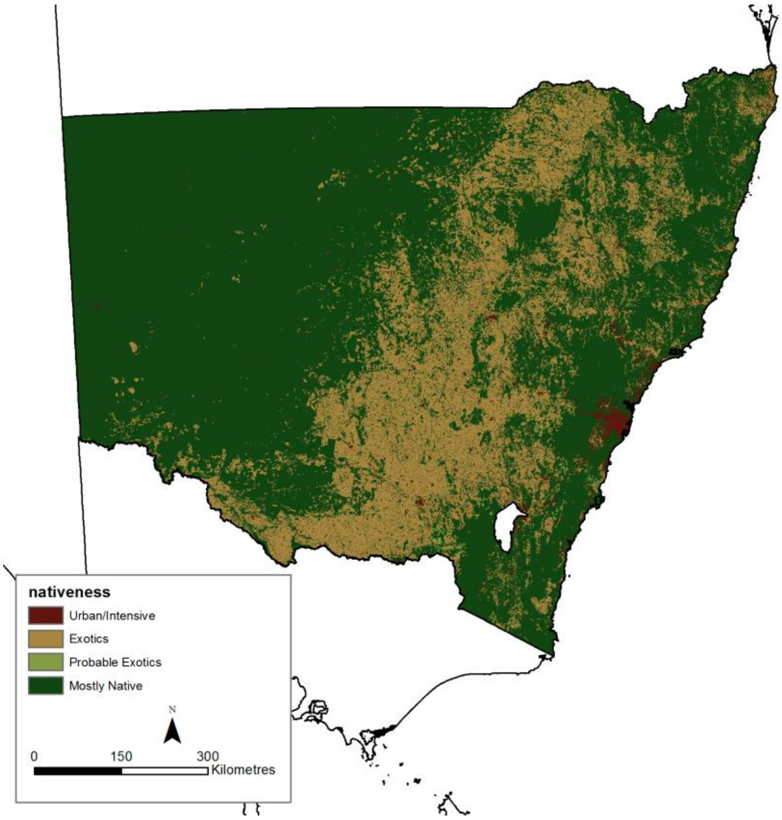


Figure 30 ***nativeness* input layer providing an estimate of the nativeness of vegetation based on land use.**

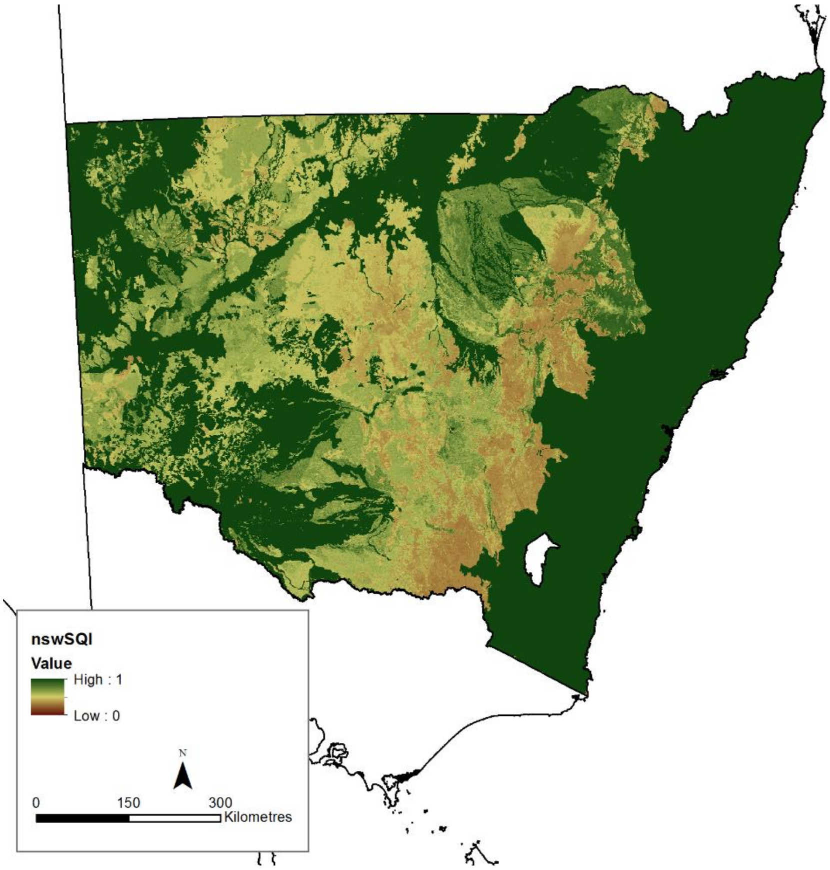


Figure 31 ***nswSRI*** **input layer showing soil resilience derived from land systems and key soil properties.**

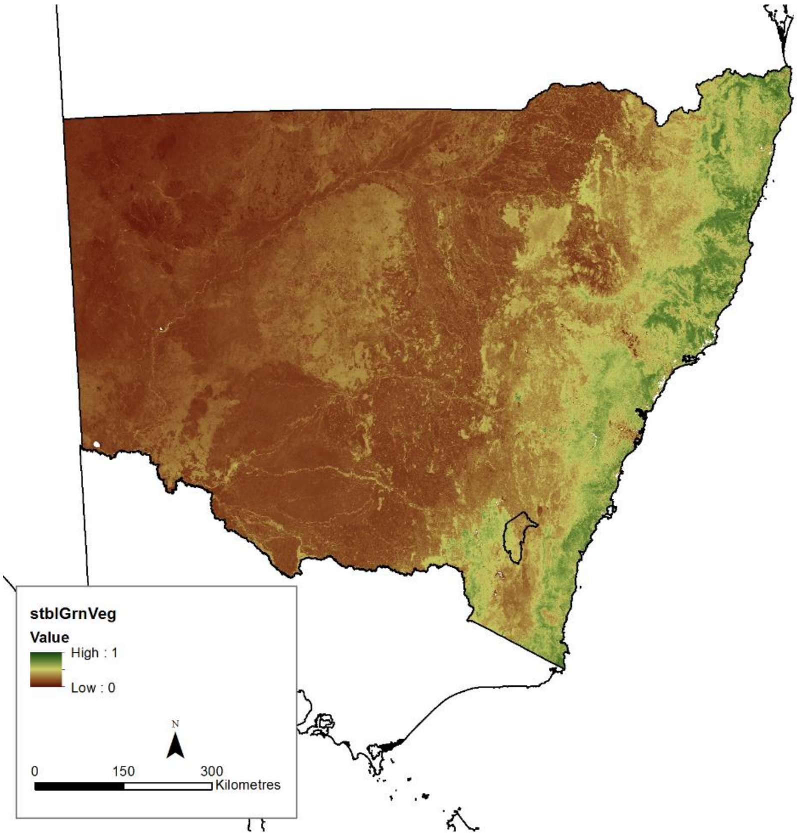


Figure 32 ***stblGrnVeg*** **input layer showing the amount and stability of green vegetation.**

Appendix D Lower bound FPC thresholds

Lower bound cover thresholds at which the canopy of different vegetation types appear intact were required to derive relative foliage projective cover (FPC) and natural woodiness inputs. Lower bound biometric overstorey, mid-storey and shrub cover benchmarks (b) for each vegetation class (Keith 2002, 2004) were averaged across Catchment Management Authority regions where recorded (b_c), then combined across strata using equation 8 to provide a single lower bound FPC threshold for each class (t_c). This threshold represents the lowest FPC value expected to be observed by remote sensing for each vegetation type when remining intact. In the relative FPC model, this is treated as a soft threshold when logistically scaling FPC relative to the vegetation type expected to occur (Figure 33).

$$ {}^{t_c}/_{100} = 1 - \left(\prod\nolimits_b 1 - {}^{b_c}/_{100}\right) \qquad \text{equation 8} $$

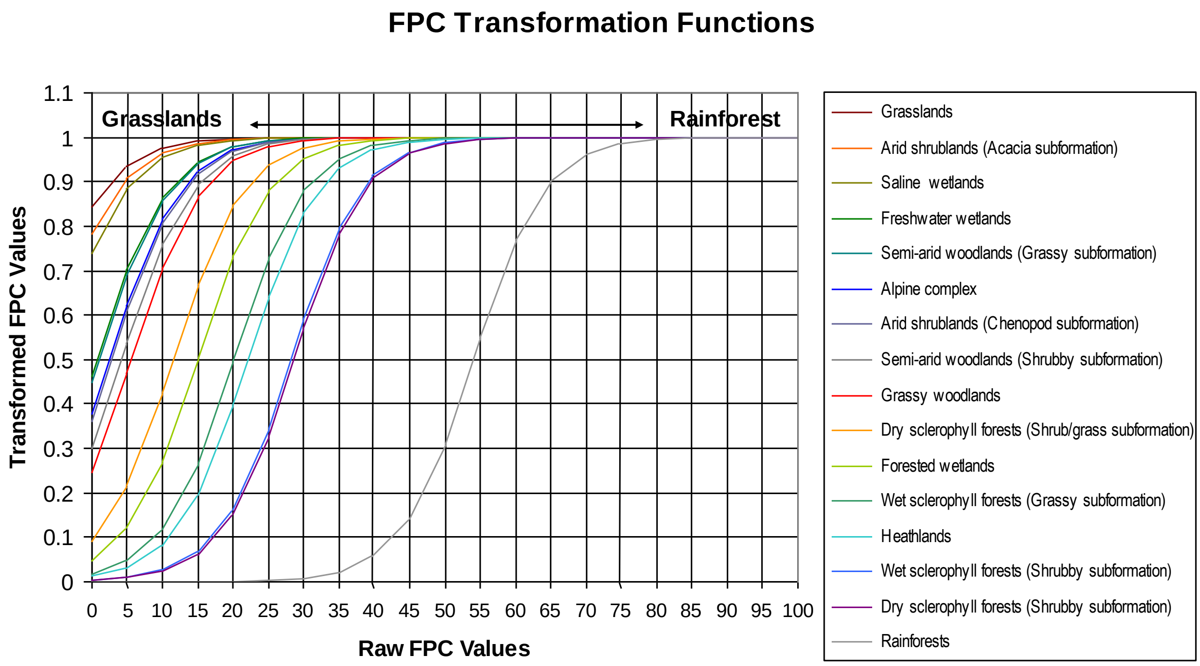


Figure 33 **Example of FPC transformations (equation 8) shown for vegetation formations.**

(Sorted by Lower FPC threshold)

Vegetation class	Native over-storey cover	Native mid-storey cover	Native ground cover (shrubs)	Lower FPC threshold *tc*
Seagrass Meadows	No benchmarks, estimated			0.00
Semi-arid woodland (grassy) - Wadi Woodlands	No benchmarks, estimated using semi-arid woodlands average			5.85
Temperate Montane Grasslands	0.00	0.00	0.00	0.00
Semi-arid Floodplain Grasslands	0.00	0.00	0.00	0.00
Montane Lakes	0.00	0.00	0.00	0.00
Alpine Herbfields	0.00	0.00	0.00	0.00
Western Slopes Grasslands	0.59	0.00	0.00	0.59

Vegetation class	Native over-storey cover	Native mid-storey cover	Native ground cover (shrubs)	Lower FPC threshold *tc*
Gibber Chenopod Shrublands	0.00	0.00	0.92	0.92
Inland Saline Lakes	0.00	0.00	1.00	1.00
Gibber Transition Shrublands	1.00	0.00	0.00	1.00
Stony Desert Mulga Shrublands	0.00	1.00	1.00	1.99
Desert Woodlands	0.00	1.00	2.00	2.98
Maritime Grasslands	1.25	1.25	0.75	3.22
Alpine Bogs and Fens	0.00	0.00	3.33	3.33
Sand Plain Mulga Shrublands	1.16	0.96	1.68	3.75
Subtropical Semi-arid Woodlands	4.20	0.60	0.00	4.77
Montane Bogs and Fens	0.22	1.56	3.40	5.11
North-west Floodplain Woodlands	3.77	0.14	1.41	5.26
North-west Plain Shrublands	2.82	1.36	1.91	5.97
Northern Montane Heaths	1.67	0.06	4.48	6.12
Inland Floodplain Swamps	2.31	4.00	1.26	7.41
Dune Mallee Woodlands	5.71	1.86	0.29	7.73
Semi-arid Sand Plain Woodlands	4.08	0.17	4.00	8.07
Saltmarshes	0.30	0.00	8.00	8.28
Riverine Plain Grasslands	5.60	2.13	1.60	9.09
Riverine Plain Grasslands	5.60	2.13	1.60	9.09
New England Grassy Woodlands	7.38	0.03	1.90	9.17
Coastal Freshwater Lagoons	1.29	2.86	6.00	9.86
Western Peneplain Woodlands	5.57	2.96	1.70	9.91
Alpine Fjaeldmarks	0.00	0.00	10.00	10.00
Northern Gorge Dry Sclerophyll Forests	10.24	0.29	0.14	10.62
Western Slopes Grassy Woodlands	8.72	1.18	1.28	10.95
Aeolian Chenopod Shrublands	7.27	0.00	4.36	11.32
Mangrove Swamps	11.89	0.00	0.00	11.89
Brigalow Clay Plain Woodlands	7.14	3.14	2.29	12.12
Inland Rocky Hill Woodlands	6.08	3.00	3.63	12.20
Tableland Clay Grassy Woodlands	11.57	0.90	0.00	12.37
Riverine Plain Woodlands	6.80	4.10	3.00	13.30
North-west Alluvial Sand Woodlands	6.86	5.36	2.36	13.92
Inland Floodplain Woodlands	6.70	3.13	5.05	14.18
Subalpine Woodlands	14.52	0.00	0.00	14.52
Riverine Chenopod Shrublands	5.93	0.56	9.00	14.88

Vegetation class	Native over-storey cover	Native mid-storey cover	Native ground cover (shrubs)	Lower FPC threshold *tc*
Northern Tableland Wet Sclerophyll Forests	11.82	4.09	0.00	15.43
North-west Slopes Dry Sclerophyll Woodlands	8.48	5.68	3.64	16.82
Upper Riverina Dry Sclerophyll Forests	13.52	4.62	0.01	17.53
Inland Floodplain Shrublands	3.00	0.00	15.00	17.55
Riverine Sandhill Woodlands	9.21	4.64	5.80	18.45
Southern Tableland Grassy Woodlands	15.85	3.84	0.90	19.81
Forested Wetlands Class	15.00	5.00	2.00	20.87
Floodplain Transition Woodlands	9.42	11.71	1.84	21.50
Hunter-Macleay Dry Sclerophyll Forests	15.00	4.30	3.60	21.58
Western Slopes Dry Sclerophyll Forests	14.72	6.05	2.20	21.64
Coastal Valley Grassy Woodlands	12.97	9.02	1.07	21.67
Coastal Floodplain Wetlands	16.68	5.82	0.29	21.76
Eastern Riverine Forests	16.27	5.97	1.07	22.11
Inland Riverine Forests	12.63	5.30	6.30	22.47
Northern Escarpment Dry Sclerophyll Forests	14.62	5.31	4.38	22.69
North Coast Dry Sclerophyll Forests	10.00	5.00	10.00	23.05
Coastal Dune Dry Sclerophyll Forests	18.89	1.78	3.67	23.25
Sand Plain Mallee Woodlands	8.25	13.90	3.20	23.53
Southern Tableland Dry Sclerophyll Forests	15.46	5.94	4.27	23.88
Sydney Sand Flats Dry Sclerophyll Forests	11.69	14.44	2.50	26.33
Pilliga Outwash Dry Sclerophyll Forests	18.82	4.91	5.55	27.08
South East Dry Sclerophyll Forests	16.26	8.38	5.26	27.31
New England Dry Sclerophyll Forests	20.35	5.53	3.93	27.71
Cumberland Dry Sclerophyll Forests	15.34	14.65	0.00	27.74
South Coast Wet Sclerophyll Forests	20.00	5.00	5.00	27.80
Southern Lowland Wet Sclerophyll Forests	20.00	5.00	5.00	27.80
Clarence Dry Sclerophyll Forests	20.00	5.00	5.00	27.80
Coastal Heath Swamps	5.64	8.91	16.23	27.99
Sydney Montane Heaths	2.86	17.43	11.64	29.13
Coastal Headland Heaths	15.00	11.67	5.83	29.30
Northern Hinterland Wet Sclerophyll Forests	21.00	7.59	4.12	30.00

Vegetation class	Native over-storey cover	Native mid-storey cover	Native ground cover (shrubs)	Lower FPC threshold *tc*
Sydney Coastal Heaths	12.23	9.77	11.72	30.09
Coastal Swamp Forests	17.53	14.50	1.33	30.43
Southern Escarpment Wet Sclerophyll Forests	23.74	8.87	0.00	30.50
Northern Tableland Dry Sclerophyll Forests	24.42	5.96	3.27	31.25
Yetman Dry Sclerophyll Forests	25.00	6.00	3.00	31.62
Northern Escarpment Wet Sclerophyll Forests	13.21	21.94	0.00	32.25
Central Gorge Dry Sclerophyll Forests	21.83	13.46	1.67	33.48
Montane Wet Sclerophyll Forests	23.33	8.33	7.33	34.88
Southern Tableland Wet Sclerophyll Forests	19.93	11.69	8.57	35.35
Southern Hinterland Dry Sclerophyll Forests	30.00	5.00	5.00	36.83
Southern Wattle Dry Sclerophyll Forests	30.00	5.00	5.00	36.83
Dry Rainforests	19.41	20.70	3.63	38.41
Southern Montane Heaths	0.00	36.36	3.64	38.68
Sydney Montane Dry Sclerophyll Forests	20.17	20.83	3.83	39.22
North Coast Wet Sclerophyll Forests	24.44	20.06	0.35	39.81
Alpine Heaths	0.00	0.00	40.00	40.00
Sydney Coastal Dry Sclerophyll Forests	16.72	24.78	5.18	40.60
South Coast Sands Dry Sclerophyll Forests	25.58	8.79	12.92	40.89
Wallum Sand Heaths	11.43	22.86	14.71	41.73
Sydney Hinterland Dry Sclerophyll Forests	18.96	24.39	6.07	42.45
South Coast Heaths	0.00	25.00	25.00	43.75
Western Vine Thickets	40.00	10.00	5.00	48.70
Littoral Rainforests	43.36	12.29	1.71	51.17
Cool Temperate Rainforests	58.00	10.80	0.00	62.54
Subtropical Rainforests	55.14	27.53	0.45	67.63
Southern Warm Temperate Rainforests	58.67	24.81	0.00	68.92
Northern Warm Temperate Rainforests	56.38	29.70	0.67	69.54

Appendix E Nativeness land-use classification

The following table lists the classes applied to the nativeness input and the allocation of tertiary ALUM 7 land-use classes to each. The weights assigned for the three condition components are also listed, however, as the soil component was removed from the final model, the values in the soil column were not used but are left here for completeness.

Nativeness	ALUM 7 code and description	Woody	Non-woody	Soil
1 Urban/Intensive	5.1.0 Intensive horticulture	0.10	0.05	0.10
1 Urban/Intensive	5.1.1 Shadehouses	0.10	0.05	0.10
1 Urban/Intensive	5.1.2 Glasshouses	0.10	0.05	0.10
1 Urban/Intensive	5.1.3 Glasshouses (hydroponic)	0.10	0.05	0.10
1 Urban/Intensive	5.1.4 Abandoned intensive horticulture	0.10	0.05	0.10
1 Urban/Intensive	5.2.0 Intensive animal husbandry	0.10	0.05	0.10
1 Urban/Intensive	5.2.1 Dairy sheds and yards	0.10	0.05	0.10
1 Urban/Intensive	5.2.2 Cattle feedlots	0.10	0.05	0.10
1 Urban/Intensive	5.2.3 Sheep feedlots	0.10	0.05	0.10
1 Urban/Intensive	5.2.4 Poultry farms	0.10	0.05	0.10
1 Urban/Intensive	5.2.5 Piggeries	0.10	0.05	0.10
1 Urban/Intensive	5.2.6 Aquaculture	0.10	0.05	0.10
1 Urban/Intensive	5.2.7 Horse studs	0.10	0.05	0.10
1 Urban/Intensive	5.2.8 Stockyards/saleyards	0.10	0.05	0.10
1 Urban/Intensive	5.2.9 Abandoned intensive animal husbandry	0.10	0.05	0.10
1 Urban/Intensive	5.3.0 Manufacturing and industrial	0.10	0.05	0.10
1 Urban/Intensive	5.3.1 General purpose factory	0.10	0.05	0.10
1 Urban/Intensive	5.3.2 Food processing factory	0.10	0.05	0.10
1 Urban/Intensive	5.3.5 Abattoirs	0.10	0.05	0.10
1 Urban/Intensive	5.3.7 Sawmill	0.10	0.05	0.10
1 Urban/Intensive	5.4.0 Residential and farm infrastructure	0.10	0.05	0.10
1 Urban/Intensive	5.4.1 Urban residential	0.10	0.05	0.10
1 Urban/Intensive	5.4.4 Remote communities	0.10	0.05	0.10
1 Urban/Intensive	5.4.5 Farm buildings/infrastructure	0.10	0.05	0.10
1 Urban/Intensive	5.5.0 Services	0.10	0.05	0.10
1 Urban/Intensive	5.5.1 Commercial services	0.10	0.05	0.10
1 Urban/Intensive	5.5.2 Public services	0.10	0.05	0.10
1 Urban/Intensive	5.5.3 Recreation and culture	0.10	0.05	0.10
1 Urban/Intensive	5.5.5 Research facilities	0.10	0.05	0.10

Nativeness	ALUM 7 code and description	Woody	Non-woody	Soil
1 Urban/Intensive	5.6.0 Utilities	0.10	0.05	0.10
1 Urban/Intensive	5.6.1 Fuel powered electricity generation	0.10	0.05	0.10
1 Urban/Intensive	5.6.3 Wind farm electricity generation	0.10	0.05	0.10
1 Urban/Intensive	5.6.4 Electricity substations and transmission	0.10	0.05	0.10
1 Urban/Intensive	5.6.5 Gas treatment, storage and transmission	0.10	0.05	0.10
1 Urban/Intensive	5.6.6 Water extraction and transmission	0.10	0.05	0.10
1 Urban/Intensive	5.7.0 Transport and communication	0.10	0.05	0.10
1 Urban/Intensive	5.7.1 Airports/aerodromes	0.10	0.05	0.10
1 Urban/Intensive	5.7.2 Roads	0.10	0.05	0.10
1 Urban/Intensive	5.7.3 Railways	0.10	0.05	0.10
1 Urban/Intensive	5.7.4 Ports and water transport	0.10	0.05	0.10
1 Urban/Intensive	5.7.5 Navigation and communication	0.10	0.05	0.10
1 Urban/Intensive	5.8.0 Mining	0.10	0.05	0.10
1 Urban/Intensive	5.8.1 Mines	0.10	0.05	0.10
1 Urban/Intensive	5.8.2 Quarries	0.10	0.05	0.10
1 Urban/Intensive	5.8.3 Tailings	0.10	0.05	0.10
1 Urban/Intensive	5.8.4 Extractive industry not in use	0.10	0.05	0.10
1 Urban/Intensive	5.9.0 Waste treatment and disposal	0.10	0.05	0.10
1 Urban/Intensive	5.9.1 Effluent pond	0.10	0.05	0.10
1 Urban/Intensive	5.9.2 Landfill	0.10	0.05	0.10
1 Urban/Intensive	5.9.5 Sewage/sewerage	0.10	0.05	0.10
2 Exotics	3.2.0 Grazing modified pastures	0.50	0.25	0.50
2 Exotics	3.2.2 Woody fodder plants	0.50	0.25	0.50
2 Exotics	3.2.3 Pasture legumes	0.50	0.25	0.50
2 Exotics	3.2.5 Sown grasses	0.50	0.25	0.50
2 Exotics	3.3.0 Cropping	0.50	0.25	0.50
2 Exotics	3.3.2 Beverage & spice crops	0.50	0.25	0.50
2 Exotics	3.3.3 Hay & silage	0.50	0.25	0.50
2 Exotics	3.3.5 Sugar	0.50	0.25	0.50
2 Exotics	3.3.8 Pulses	0.50	0.25	0.50
2 Exotics	3.4.0 Perennial horticulture	0.50	0.25	0.50
2 Exotics	3.4.1 Tree fruits	0.50	0.25	0.50
2 Exotics	3.4.2 Oleaginous fruits	0.50	0.25	0.50
2 Exotics	3.4.3 Tree nuts	0.50	0.25	0.50

Nativeness	ALUM 7 code and description	Woody	Non-woody	Soil
2 Exotics	3.4.4 Vine fruits	0.50	0.25	0.50
2 Exotics	3.4.5 Shrub nuts, fruits & berries	0.50	0.25	0.50
2 Exotics	3.4.6 Perennial flowers & bulbs	0.50	0.25	0.50
2 Exotics	3.4.7 Perennial vegetables & herbs	0.50	0.25	0.50
2 Exotics	3.4.8 Citrus	0.50	0.25	0.50
2 Exotics	3.4.9 Grapes	0.50	0.25	0.50
2 Exotics	3.5.0 Seasonal horticulture	0.50	0.25	0.50
2 Exotics	3.5.2 Seasonal nuts	0.50	0.25	0.50
2 Exotics	3.5.3 Seasonal flowers & bulbs	0.50	0.25	0.50
2 Exotics	3.5.4 Seasonal vegetables & herbs	0.50	0.25	0.50
2 Exotics	3.6.5 Abandoned perennial horticulture	0.50	0.25	0.50
2 Exotics	4.2.0 Grazing irrigated modified pastures	0.50	0.25	0.50
2 Exotics	4.2.1 Irrigated woody fodder plants	0.50	0.25	0.50
2 Exotics	4.2.4 Irrigated sown grasses	0.50	0.25	0.50
2 Exotics	4.3.0 Irrigated cropping	0.50	0.25	0.50
2 Exotics	4.3.1 Irrigated cereals	0.50	0.25	0.50
2 Exotics	4.3.3 Irrigated hay & silage	0.50	0.25	0.50
2 Exotics	4.3.6 Irrigated cotton	0.50	0.25	0.50
2 Exotics	4.3.8 Irrigated pulses	0.50	0.25	0.50
2 Exotics	4.4.0 Irrigated perennial horticulture	0.50	0.25	0.50
2 Exotics	4.4.1 Irrigated tree fruits	0.50	0.25	0.50
2 Exotics	4.4.2 Irrigated oleaginous fruits	0.50	0.25	0.50
2 Exotics	4.4.3 Irrigated tree nuts	0.50	0.25	0.50
2 Exotics	4.4.4 Irrigated vine fruits	0.50	0.25	0.50
2 Exotics	4.4.7 Irrigated perennial vegetables & herbs	0.50	0.25	0.50
2 Exotics	4.5.0 Irrigated seasonal horticulture	0.50	0.25	0.50
2 Exotics	4.5.3 Irrigated seasonal flowers & bulbs	0.50	0.25	0.50
2 Exotics	4.5.4 Irrigated seasonal vegetables & herbs	0.50	0.25	0.50
2 Exotics	4.5.5 Irrigated turf farming	0.50	0.25	0.50
2 Exotics	4.6.2 Abandoned irrigated land	0.50	0.25	0.50
3 Probable exotics	3.1.0 Plantation forestry	0.75	0.35	0.80
3 Probable exotics	3.1.2 Softwood plantation	0.75	0.35	0.80
3 Probable exotics	3.2.1 Native/exotic pasture mosaic	0.75	0.35	0.80
3 Probable exotics	4.1.0 Irrigated plantation forestry	0.75	0.35	0.80

Nativeness	ALUM 7 code and description	Woody	Non-woody	Soil
3 Probable exotics	4.1.2 Irrigated softwood plantation	0.75	0.35	0.80
3 Probable exotics	5.4.2 Rural residential with agriculture	0.75	0.35	0.80
3 Probable exotics	5.4.3 Rural residential without agriculture	0.75	0.35	0.80
4 Mostly native	1.1.0 Nature conservation	1.00	1.00	1.00
4 Mostly native	1.1.1 Strict nature reserve	1.00	1.00	1.00
4 Mostly native	1.1.3 Nature Park	1.00	1.00	1.00
4 Mostly native	1.1.7 Other conserved area	1.00	1.00	1.00
4 Mostly native	1.2.0 Managed resource protection	1.00	1.00	1.00
4 Mostly native	1.2.2 Surface water supply	1.00	1.00	1.00
4 Mostly native	1.2.4 Landscape	1.00	1.00	1.00
4 Mostly native	1.3.0 Other minimal use	1.00	1.00	1.00
4 Mostly native	1.3.2 Stock route	1.00	1.00	1.00
4 Mostly native	1.3.3 Residual native cover	1.00	1.00	1.00
4 Mostly native	1.3.4 Rehabilitation	1.00	1.00	1.00
4 Mostly native	2.1.0 Grazing native vegetation	1.00	1.00	1.00
4 Mostly native	2.2.0 Production forestry	1.00	1.00	1.00
4 Mostly native	3.1.1 Hardwood plantation	1.00	1.00	1.00
4 Mostly native	3.1.3 Other forest plantation	1.00	1.00	1.00
4 Mostly native	4.1.1 Irrigated environmental forest plantation	1.00	1.00	1.00
4 Mostly native	4.1.3 Irrigated other forest plantation	1.00	1.00	1.00
4 Mostly native	5.5.4 Defence facilities - urban	1.00	1.00	1.00
4 Mostly native	6.1.0 Lake	1.00	1.00	1.00
4 Mostly native	6.1.1 Lake - conservation	1.00	1.00	1.00
4 Mostly native	6.2.0 Reservoir or dam	1.00	1.00	1.00
4 Mostly native	6.2.1 Water storage - intensive use/farm dams	1.00	1.00	1.00
4 Mostly native	6.2.2 Reservoir - intensive use	1.00	1.00	1.00
4 Mostly native	6.2.3 Evaporation basin	1.00	1.00	1.00
4 Mostly native	6.3.0 River	1.00	1.00	1.00
4 Mostly native	6.3.3 River - intensive use	1.00	1.00	1.00
4 Mostly native	6.4.0 Channel/aqueduct	1.00	1.00	1.00
4 Mostly native	6.4.1 Supply channel/aqueduct	1.00	1.00	1.00
4 Mostly native	6.4.2 Drainage channel/aqueduct	1.00	1.00	1.00
4 Mostly native	6.5.0 Marsh/wetland	1.00	1.00	1.00
4 Mostly native	6.5.1 Marsh/wetland - conservation	1.00	1.00	1.00
4 Mostly native	6.5.3 Marsh/wetland - intensive use	1.00	1.00	1.00

Nativeness	ALUM 7 code and description	Woody	Non-woody	Soil
4 Mostly native	6.5.4 Marsh/wetland - saline	1.00	1.00	1.00
4 Mostly native	6.6.0 Estuary/coastal waters	1.00	1.00	1.00
4 Mostly native	6.6.1 Estuary/coastal waters - conservation	1.00	1.00	1.00
4 Mostly native	6.6.3 Estuary/coastal waters - intensive use	1.00	1.00	1.00

Glossary

Abiotic variables: environmental variables that characterise non-living predictors of biodiversity, such as those describing climate, topography, water and soils.

Adaptation: responses that decrease the negative effects of change and capitalise on positive opportunities associated with impacts. In relation to biodiversity responses, whether natural or assisted by humans, enable species and ecological processes to adjust and evolve in response to a changed environment.

Animal: any animal, whether vertebrate or invertebrate and in any stage of biological development, but does not include: (a) humans, or (b) fish within the meaning of the *Fisheries Management Act 1994*. Note: some types of fish may be included in the definition of animal and some types of animal may be included in the definition of fish. See s. 14.6 of the BC Act.

Anthropogenic: produced or caused by human activity.

Assessment: using biophysical data collected through monitoring, combined with other inputs such as benchmarks, to make judgements about environmental condition and trends.

Benchmark: the quantitative measures that represent the ‘best-attainable’ condition, which acknowledges that native vegetation within the contemporary landscape has been subject to both natural and human-induced disturbance. Benchmarks are defined for specified variables for each Plant Community Type. Vegetation with relatively little evidence of modification generally has minimal timber harvesting (few stumps, coppicing, cut logs), minimal firewood collection, minimal exotic weed cover, minimal grazing and trampling by introduced or overabundant native herbivores, minimal soil disturbance, minimal canopy dieback, no evidence of recent fire or flood, is not subject to high frequency burning and has evidence of recruitment of native species.

Biodiversity (biological diversity): variability among living organisms from all sources (including terrestrial, freshwater, coastal, marine and other ecosystems and ecological complexes of which they are part), which includes genetic diversity, species diversity and ecosystem diversity.

Biodiversity Assessment Method (BAM): this method was established under section 6.7 of the BC Act for the purpose of assessing certain impacts on threatened species and threatened ecological communities, and their habitats, and the impact on biodiversity values, where required under the BC Act, *Local Land Services Act 2013* (LLS Act) or the *State Environmental Planning Policy (Vegetation in Non-Rural Areas) 2017*).

Biodiversity conservation: protect the variety of all life forms including genetic, species and ecosystem diversity from harm or destruction to safeguarding the biological support systems on earth.

Biodiversity Information Program: program/s that can be established by the Environment Agency Head for the collection, monitoring and assessment of information on biodiversity under the BC Act.

Biodiversity values: include the composition, structure and function of ecosystems, and (but not limited to) threatened species, populations and ecological communities, and their habitats.

Bioregion: relatively large land areas characterised by broad, landscape-scale natural features and environmental processes that influence the functions of entire ecosystems and capture large-scale biophysical patterns. These patterns in the landscape are linked to fauna and flora assemblages and processes at the ecosystem scale. There are 18 bioregions represented in New South Wales.

Categorical data: data consisting of attributes classified into discrete classes.

Class probability stack: A set of continuous value raster surfaces, one for each ecosystem class where each cell equals the probability of the class occupying the cell; or the proportion of the cell that is occupied by the class.

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 to persistent anthropogenic changes in the composition of the atmosphere or in land use.

Climate variability: long-term changes in the patterns of average weather of a region or the Earth as a whole.

Community composition: an assemblage or association of populations of two or more different species occupying the same geographical area and in a particular time.

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

Conservation: in relation to biodiversity, conservation is the protection, maintenance, management, sustainable use, restoration and improvement of the natural environment. In relation to natural and cultural heritage, conservation generally refers to the safekeeping or preservation of the existing state of a heritage resource from destruction or change.

Continuous data: data consisting of a range of real number values generally represented by 32-bit floating point values.

Cost benefit approach. A technique for predicting colonisation potential of locations across a region using measures of habitat condition and connectivity applied to rasterised spatial data (See Drielsma, Ferrier & Manion 2007).

Crown land: Crown land within the meaning of the *Crown Lands Act 1989*, including Crown land dedicated for a public purpose under that Act.

Dispersal: the spread of animals and plants into new areas.

Disturbance: (Ecology) any process or event which disrupts ecosystem structure and resource availability.

Ecological carrying capacity: the ability of an area to maintain self-sustaining and interacting populations of all species naturally expected to occur there, given the habitat resources, such as food and water, and connections to other habitat, needed for persistence.

Ecological community: an assemblage of species occupying a particular area at a particular time.

Ecological condition: the intactness and naturalness of habitat to support biodiversity, without considering the indirect effects of fragmentation or connections with surrounding suitable habitat.

Ecological connectivity: accounts for the generalised quality of habitats supporting biodiversity at each location, the fragmentation of habitat within its neighbourhood and its position in the landscape (e.g. as part of a habitat corridor, or a stepping stone).

Ecological integrity: is about maintaining the diversity and quality of ecosystems and enhancing their capacity to adapt to change and provide for the needs of future generations.

Ecosystem: a dynamic complex of plant, animal and microorganism communities and their nonliving environment that interact as a functional unit. Ecosystems may be small and simple, like an isolated pond, or large and complex, like a specific tropical rainforest or a coral reef.

Ecosystem function: a general term that includes stocks of materials and rates of processes, for example, photosynthesis, respiration, carbon and nutrient cycles.

Ecosystem integrity: supporting and maintaining a balanced, integrated adaptive community of organisms having a species composition, diversity and functional organisation comparable to that of a natural habitat of the region.

Effective habitat area: the proportion of residual habitat quality at a site following the impacts of clearing, degradation and fragmentation at the site and in its neighbourhood.

Extant: currently existing.

Extent: the area covered by something.

Fragmentation: the division of continuous habitat by vegetation clearance for human land-use activities, which isolates the remnant patches of vegetation and the species within them, and limits genetic flow between populations.

Generalised dissimilarity modelling (GDM): a statistical technique for analysing and predicting spatial patterns of change in community composition across large regions. See section 1.5.1.

Geographic scale: the ratio of a distance on a map to the corresponding distance on the ground. Here, used to indicate how much area we are looking at, such as locally (based on a small site or area, able to be defined as a unit, such as a town or a forest), regionally (for example, the Murray Darling Basin) or nationally (across Australia).

Grid: a georeferenced spatial raster dataset consisting of a two-dimensional array of pixels (grid cells) containing categorical or continuous numerical values representing some measure or characteristic of each location with additional attributes optionally stored in an associated raster attribute table.

Grid cell: a single location of a specified size represented by an individual pixel in a raster dataset with a categorical or continuous value representing some measure or characteristic of that location.

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 condition: the capacity of an area to provide the structures and functions necessary for the persistence of all species naturally expected to occur there in an intact state.

Habitat corridor: an area of habitat connecting wildlife populations separated by human activities or structures (such as roads, development, or logging).

Habitat fragmentation: the emergence of discontinuities (fragmentation) in an organism's preferred environment (habitat), causing population fragmentation and ecosystem decay.

HCAS: the habitat condition assessment system method (Harwood et al., 2016), a novel approach to environmental modelling designed to work with sparse site data to calibrate remote sensing applied across large areas.

Hindcasting: is a process that involves the re-running of mathematical models when new data become available, about a period of time in the past.

Index (plural indices): a metric used to quantify the information represented by an indicator.

Indicator: something that shows what a situation is like, or measures the status or level of something. See section 1.2.1.

Inferential modelling. A technique where properties or relationships are inferred from available information and expert knowledge rather than statistically modelled from predictive variables.

Invasive species: a plant or animal that has been introduced into a region in which it does not naturally occur and that becomes established and spreads, displacing naturally occurring species.

Kernel regression: a non-parametric technique in statistics to estimate the conditional expectation of a random variable. The objective is to find a non-linear relation between a pair of random variables X and Y.

Key threatening process: a threatening process listed in Schedule 4 of the BC Act. Processes are listed by the NSW Scientific Committee if they adversely affect threatened species or ecological communities, or could cause species or ecological communities that are not threatened to become threatened.

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.

Least cost path: From graph theory, the shortest set of connected edges traversing a graph between two nodes.

Location: refers to an individual position in a region or landscape represented in the analysis by a single grid cell of a specified size.

Mitchell landscapes: landscape with relatively homogeneous geomorphology, soils and broad vegetation types, mapped at a scale of 1:250,000.

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. See section 3.2.1.

Monitoring: in this context, activities to collect new biophysical data.

NARCliM: NSW and ACT Regional Climate Modelling project. See https://climatechange.environment.nsw.gov.au/Climate-projections-for-NSW/About-NARCliM

Native Vegetation Management Benefits. Spatial outputs of a NSW Government project that identify benefits to the state’s biodiversity that would result from different management interventions.

Non-woody vegetation: for vegetation monitoring using Landsat MSS satellite sensors, vegetation formations that are less than two metres high or with less than 20% canopy cover (mainly grasslands, arid shrublands and woodlands).

Permeability: a measure of the extent to which habitat enables biological entities to move in different directions inversely proportional to resistance against movement.

Plant: any plant, whether vascular or non-vascular and in any stage of biological development in the taxonomic kingdom of Plantae. Note that under the New South Wales biodiversity legislation, ‘plant’ includes fungi and lichens (but not marine vegetation which is under fisheries legislation).

Potential diversity: The maximum diversity likely to be supported at a location or in a region if habitat remained intact. Similar to an estimate of pre-industrial diversity but acknowledging that habitat suitability can change even when habitat condition has remained intact.

Private land conservation agreement: a biodiversity stewardship agreement, a conservation agreement or a wildlife refuge agreement under Part 5 of the BC Act.

Proxy: in this context, a species or group of taxa used as substitutes for other taxa. See also 'representative' and 'surrogate' species.

Reference sites: sites used to establish benchmarks of environmental condition.

Region: refers to a spatially explicit area consisting of multiple locations represented in the analysis by a collection of grid cells of a specified size, grouped together by some common theme or purpose and often, but not necessarily, spatially contiguous.

Remnant: (Ecology) a small, fragmented portion of vegetation that once covered an area before being cleared.

Remote sensing: a means of acquiring information using airborne or satellite equipment and techniques to determine the characteristics of an area; most commonly using imagery from aircraft and images from satellites.

Single-source shortest path tree: a graph representing a tree structure where the root node is the source and branches to leaf nodes represent the shortest path to every possibly destination node in the graph.

Site-level vegetation integrity: site-level observations of vegetation condition.

Spatial Links Tool. Software for performing habitat connectivity modelling using ecological theory to apply least cost path graph search algortihms to rasterised spatial data.

Spatial resilience: an ecological integrity indicator that aims to measure the capacity of terrestrial ecosystems to retain their biological diversity in the face of climate change, as a function of the quality (condition) and spatial-environmental connectedness of these ecosystems, through time.

Species: a taxon comprising one or more populations of individuals capable of interbreeding to produce fertile offspring.

Status: the condition or 'health' of a species, population, community, habitat or ecosystem.

Suitable habitat: suitable habitat is predicted by identifying where each species lived originally and its associated environment.

Surrogate, biodiversity: a species, group of species or ecosystem that can be used as a substitute for wider biological groups, see section 1.5.3.

Threatening process: a process that threatens, or that may threaten, the survival or evolutionary development of species or ecological communities.

Trends: directions of significant change in the environment, as shown by the changing values of measures (like essential variables, indicators or indices).

Vascular plant: plants containing vascular tissue (tissue specialised for the conduction of fluids); the more highly evolved plants above mosses and liverworts.

Vegetation condition: the health of native vegetation communities which reflects the level of naturalness and is commonly assessed against a benchmark, considering factors such as structural integrity, species composition, presence or absence of weeds and diseases and reproduction of species.

Vegetation integrity: being the degree to which the composition, structure and function of vegetation at a particular site and the surrounding landscape has been altered from a near-natural state.

Vegetation structure: the organisation of plants within a plant stand or assemblage consisting of one or more layers or strata.

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

References

Amacher MC, O'Neil KP & Perry CH 2007, Soil vital signs: a new soil quality index (SQI) for assessing forest soil health, Fort Collins, Department of Agriculture, Forest Service, Rocky Mountain Research Station, Colorado, USA.

Amy J & Robertson AI 2001, Relationships between livestock management and the ecological condition of riparian habitats along an Australian floodplain river, *Journal of Applied Ecology*, 38(1), pp.63–75.

Australian Government 2006, *Guidelines for land-use mapping in Australia: Principles, procedures and definitions – a technical handbook supporting the Australian Collaborative Land-use Mapping Program*, 3rd edition, Bureau of Rural Sciences, Canberra, Australia.

Ayers D, Seddon J, Briggs S, Doyle S & Gibbons P 2005, Interim benchmarks for the BioMetric Tool, Department of Environment and Conservation NSW, Hurstville, Australia.

Baguette M, Blanchet S, Legrand D, Stevens VM & Turlure C 2013, Individual dispersal, landscape connectivity and ecological networks, *Biological Reviews*, 88(2), pp.310–326.

Brown JH, Gupta VK, Li B-L, Milne BT, Restrepo C & West GB 2002, The fractal nature of nature: Power laws, ecological complexity and biodiversity, *Philosophical Transactions: Biological Sciences*, 357(1421), pp.619–626.

Catterall CP, Lynch RJ & Jansen A 2007, Riparian wildlife and habitats, in S Lovett and P Price (eds.), *Principles for riparian lands management*, CSIRO, Land and Water Canberra, Australia:.

Cormen TH 2014, *Introduction to algorithms*, 3rd edition, Cambridge MIT Press.

Crome F, Isaacs J & Moore L 1994, The utility to birds and mammals of remnant riparian vegetation and associated windbreaks in the Tropical Queensland Uplands, *Pacific Conservation Biology*, 1(4), pp.328–343.

Danaher T, Scarth P, Armston J, Collet L, Kitchen J & Gillingham S 2010, Remote sensing of tree-grass systems: the eastern Australian woodlands, in MJ Hill & NP Hanan (eds.), *Ecosystem function in savannas: Measurement and modelling at landscape to global scales*, CRC Press, Boca Raton, FL, pp.175–193.

DECCW 2009, Identification of priority travelling stock reserves in NSW, A report prepared for the Commonwealth Department of Environment, Water, Heritage and the Arts, Department of Environment Climate Change and Water NSW, Queanbeyan.

Dickson F, White M, Pirzl R, Williams KJ & Lyon PAW 2016, *A national reference library of expert site condition assessments*, project flier, CSIRO Land and Water, Canberra, Australia.

Dijkstra EW 1959, A note on two problems in connexion with graphs, *Numerische Mathematik*, 1(1), pp.269–271.

Dillon M, McNellie M & Oliver I 2011, *Assessing the extent and condition of native vegetation in NSW: Monitoring, evaluation and reporting program*, technical report series, Office of Environment and Heritage, Sydney, Australia.

Donohue R, Lingtao L & Williams K 2017, Generation of the input BBA remote sensing variables: Methods, specifications and challenges of Phase 1 product delivery, CSIRO, Canberra, Australia.

DPIE 2020, *NSW Biodiversity Outlook Report: Results from the Biodiversity Indicator Program, first assessment*, Department of Planning, Industry and Environment NSW, Sydney, Australia.

Drielsma M & Ferrier S 2006, Landscape scenario modelling of vegetation condition, *Ecological Management & Restoration*, 7, S45-S52.

Drielsma M & Ferrier S 2009, Rapid evaluation of metapopulation persistence in highly variegated landscapes, *Biological Conservation*, 142(3), 529.

Drielsma M, Ferrier S & Manion G 2007, A raster-based technique for analysing habitat configuration: The cost-benefit approach, *Ecological Modelling*, 202(3-4), p.324.

Drielsma M, Howling G & Love J 2012, *NSW native vegetation management benefits analyses: Technical report*, Office of Environment and Heritage, Sydney, Australia.

Drielsma M, Love J, Manion G & Barrett T 2010, Great Eastern Ranges vegetation condition modelling project report, spatial analysis of conservation priorities in the Great Eastern Range, Department of Environment, Climate Change and Water NSW, Armidale, Australia.

Drielsma M, Love J, Williams KJ, White M & Ferrier S 2020, *A model-based indicator of capacity for biodiversity persistence using vascular plant records and habitat condition*, Biodiversity Indicator Program Implementation Report, Department of Planning, Industry and Environment, Sydney, Australia, www.environment.nsw.gov.au/research-and-publications/publications-search/modelbased-indicator-capacity-biodiversity-persistence-using-vascular-plant-record-habitat-condition.

Drielsma M, Manion G & Ferrier S 2007, The spatial links tool: Automated mapping of habitat linkages in variegated landscapes, *Ecological Modelling*, 200(3-4), p.403.

Drielsma M, Manion G, Love J, Williams K, Harwood T & Saremi H 2015, 3C modelling for biodiversity under future climate, Office of Environment and Heritage, Sydney, Australia.

Evans JP, Ji F, Lee C, Smith P, Argueso D & Fita L 2014, Design of a regional climate modelling projection ensemble experiment: NARCliM, *Geoscientific Model Development*, 7(2), p. 621.

Eyre TJ, Kelly AL, Neldner VJ, Wilson BA, Ferguson DJ & Laidlaw MJ 2015*, BioCondition: A condition assessment framework for terrestrial biodiversity in Queensland – assessment manual*, version 2.2, Queensland Herbarium and Department of Science, Information Technology, Innovation and the Arts, Brisbane, Australia.

Ferrier S, Manion G, Elith J & Richardson K 2007, Using generalized dissimilarity modelling to analyse and predict patterns of beta diversity in regional biodiversity assessment, *Diversity and Distributions*, 13(3), pp.252–264.

Foster E, Love J, Rader R, Reid N, Dillon M & Drielsma MJ 2016, Planning for metapopulation persistence using a multiple-component, cross-scale model of connectivity, *Biological Conservation*, 195, p.177.

Geoscience Australia & CSIRO Land & Water 2010, *1 Second SRTM-Derived Digital Elevation Model (DSM, DEM, DEM-S and DEM-H) User Guide*, version 1.0, Geoscience Australia.

Geoscience Australia 2006, *GEODATA TOPO 250K Series 3, bioregional assessment source dataset*, Geoscience Australia.

Hak J & Comer P 2017, Modeling landscape condition for biodiversity assessment: Application in temperate North America, *Ecological Indicators*, 82, pp.206–216.

Harwood TD, Donohue RJ, Williams KJ, Ferrier S, McVicar TR & Newell G 2016, Habitat condition assessment system: A new way to assess the condition of natural habitats for terrestrial biodiversity across whole regions using remote sensing data, *Methods in Ecology and Evolution*, 7(9), pp.1050–1059.

Jarihani AA, McVicar TR, van Niel TG, Emelyanova IV, Callow JN & Johansen K 2014, Blending landsat and MODIS data to generate multispectral indices: a comparison of "index-then-blend" and "Blend-Then-Index" approaches, *Remote Sensing*, 6(10), pp.9213–9238.

Keith D 2002, A compilation map of native vegetation for New South Wales, NSW Biodiversity Strategy, New South Wales Government.

Keith D 2004, *Ocean shores to desert dunes: The native vegetation of New South Wales and the ACT*, Department of Environment and Conservation NSW, Hurstville, Australia.

Lausch A, Erasmi S, King D, Magdon P & Heurich M 2017, Understanding forest health with remote sensing: Part ii – a review of approaches and data models, *Remote Sensing*, (9).

Lawley, V, Lewis, M, Clarke, K, & Ostendorf, B 2016, Site-based and remote sensing methods for monitoring indicators of vegetation condition: An Australian review, *Ecological Indicators*, 60, 1273-1283.

Lentini PE, Gibbons P, Carwardine J, Fischer J, Drielsma M & Martin TG 2013, Effect of planning for connectivity on linear reserve networks, *Conservation Biology*, 27(4), pp.796–807.

Love J, Drielsma M & Welch M (in prep), Efficient GPGPU based parallel processing approach to optimising existing biodiversity evaluation techniques.

Lyon P, Williams K, Dickson F, Ferrier S & Harwood T 2016, *A habitat condition assessment system for Australia: Developing a new approach to mapping change in habitat for biodiversity continentally*, Vol. EP157068, CSIRO, Canberra, Australia.

Mackey B & Hugh S 2010, Spatial analysis of conservation priorities in the Great Eastern Ranges: Project 3 – productivity analysis and drought refuge – final report, Australian National University, Canberra, Australia.

Mackey B, Watson J & Worboys G 2010, Connectivity conservation and the Great Eastern Ranges Corridor: An independent report to the Interstate Agency Working Group (Alps to Atherton Connectivity Conservation Working Group) convened under the Environment Heritage and Protection Council/Natural Resource Management Ministerial Council, Department of Environment, Climate Change and Water NSW, Sydney, Australia.

McNellie M, Oliver I, Ferrier S, Newell G, Manion G & Griffioen P 2014, A solution to modelling vegetation condition for whole-of-landscape conservation planning, presentation to the Spatial Ecology and Conservation (SEC2) conference, Birmingham.

Mitchell P 2002, NSW landscapes mapping: Background and methodology, Department of Environment and Climate Change NSW, Sydney, Australia.

Mueller N, Lewis A, Roberts D, Ring S, Melrose R & Sixsmith J 2016, Water observations from space: Mapping surface water from 25 years of Landsat imagery across Australia, *Remote Sensing of Environment*, 174, p.341.

Newell GR, White MD, Griffioen P & Conroy M 2006, Vegetation condition mapping at a landscape-scale across Victoria, *Ecological Management & Restoration*, 7, S65–S68.

Nipperess D, Faith DP, Williams KJ, King D, Manion G & Ware C 2020, *Using representative sets of known species and habitat condition to inform change in biodiversity status: A case example for vascular plants*, Biodiversity Indicator Program Implementation Report, Department of Planning, Industry and Environment, Sydney, Australia, www.environment.nsw.gov.au/research-and-publications/publications-search/using-representative-sets-known-species-habitat-condition-inform-change-biodiversity-status.

Noss RF 1987, Corridors in real landscapes: A reply to Simberloff and Cox, *Conservation Biology*, 1(2), pp.159–164.

OEH 2014, Technical report: A comparison of woody change mapping based on SPOT 5 and Landsat TM imagery using 2010–2011 imagery,Office of Environment and Heritage NSW, Sydney, Australia.

OEH 2016, Biodiversity impacts and adaptation project (final report) - NSW and ACT Regional Climate Modelling Project, Office of Environment and Heritage NSW, Armidale, Australia.

OEH 2017a, *Biodiversity assessment method*, Office of Environment and Heritage NSW, Sydney, Australia.

OEH 2017b, Digital soil mapping of key soil properties over NSW, Technical Report Sydney, Office of Environment and Heritage NSW, Sydney, Australia.

OEH 2017c, Native vegetation integrity benchmarks: An information sheet, Office of Environment and Heritage NSW, Sydney, Australia.

OEH 2017d, *Native vegetation regulatory map: Method statement*, (OEH 2017/0495), Office of Environment and Heritage NSW, Sydney, Australia.

OEH 2017e, NSW landscapes (Mitchell 2002) release notes, January 2017, Office of Environment and Heritage NSW, Sydney, Australia.

OEH 2017f, NSW landuse 2013 dataset, Office of Environment and Heritage NSW, Sydney, Australia.

OEH 2017g, NSW National Parks and Wildlife Service (NPWS) estate, Office of Environment and Heritage NSW, Sydney, Australia.

OEH & CSIRO 2019, *Measuring biodiversity and ecological integrity in New South Wales: Method for the Biodiversity Indicator Program*, Office of Environment and Heritage NSW and Commonwealth Scientific and Industrial Research Organisation, Sydney, Australia.

Scotts D & Drielsma M 2002, Developing landscape frameworks for regional conservation planning: An approach integrating fauna spatial distributions and ecological principles, *Pacific Conservation Biology*, 8(4), pp.235–254.

Sivertsen D 2009, Native vegetation interim type standard, Department of Environment, Climate Change and Water NSW, Sydney, Australia.

Tehrany MS, Kumar L & Drielsma M 2017, Review of native vegetation condition assessment concepts, methods and future trends, *Journal of Nature Conservation*,. 40, pp.12–23).

Thackway R & Lesslie R 2006, Reporting vegetation condition using the vegetation assets, states and transitions (VAST) framework, *Ecological Management & Restoration*, 7(s1), S53–S62.

Vihervaara P, Auvinen A-P, Mononen L, Törmä M, Ahlroth P & Anttila S 2017, How essential biodiversity variables and remote sensing can help national biodiversity monitoring, 10, pp.43–59.

Wu BY & Chao K 2004, *Spanning trees and optimization problems*, Chapman & Hall/CRC,Boca Raton.