DEPARTMENT OF PLANNING, INDUSTRY & ENVIRONMENT

A model-based indicator of capacity for biodiversity persistence using vascular plant records and habitat condition

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This document should be cited as: Drielsma M, Love J, Williams K, 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 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)
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ISBN 978-1-922318-51-0
EES 2020/0098
February 2020

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Acknowledgments

The authors would like to acknowledge those who have made valuable contributions to this work. This includes the NSW Government for funding. Becky Schmidt and Jodie Pritchard (CSIRO); Hanieh Saremi, Rajesh Thapa and Nick Reid (University of New England); Megan McNellie, Joanne Wilson, Laura Babian, Mark Littleboy, Greg Summerell and Jo White (Department of Planning, Industry and Environment, DPIE) for support and contributions. Special thanks to Josephine Drielsma (undergraduate at University of Newcastle) for help developing the Venn diagram concept and figure. DPIE reviewers, Mark Cameron and Murray Ellis; and external reviewers, Anita Smyth, Simon Ferrier (both CSIRO) and Matt White (Department of Environment, Land, Water and Planning, Victoria). Simon and Matt kindly agreed post-review to join as co-authors. Thanks to Tim Cooney (DPIE) and Darren King (CSIRO) for assisting in workflow and data management. Glenn Manion for programming on the T-BFT and GDM. Thanks to Donella Andersen, Nature Edit, for her work editing and formatting this report.

Acronyms

BC Act	*Biodiversity Conservation Act 2016*
CSIRO	Commonwealth Scientific and Industrial Research Organisation
GDM	Generalised dissimilarity modelling
IBRA	Interim Biogeographic Regionalisation of Australia – see Table 1 for individual NSW bioregion acronyms
IUCN	International Union for the Conservation of Nature
NPW	National Park and Wildlife Act, as in NPW reserves
NSW	New South Wales, Australia
SAC	Species–area curve
SAR	Species–area relationship
T-BFT	Terrestrial Biodiversity Forecasting Toolkit

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 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 / Environment, Energy and Science.

Monitoring of all the plants and animals across New South Wales is a large, complex task requiring novel approaches to data collection and use, including the application of models. The persistence of ecosystems indicator for vascular plants (the indicator), reported here, is therefore one of many ways in which the state of biodiversity and ecological integrity in New South Wales is being monitored and reported.

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.

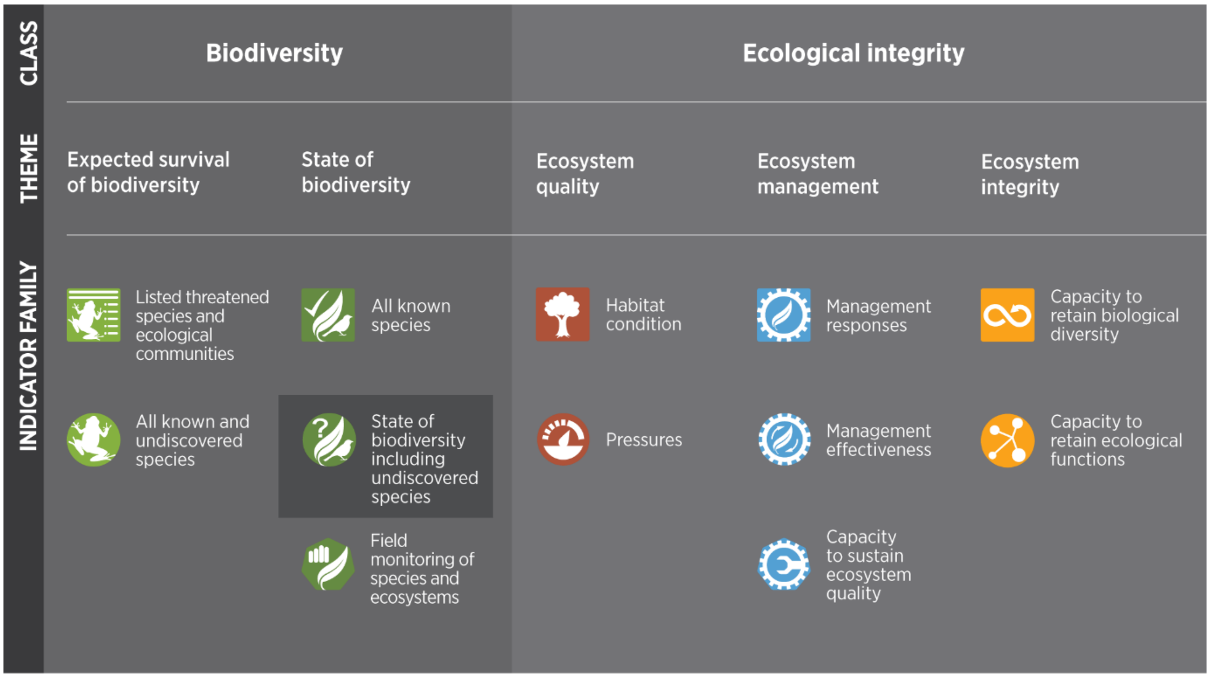

Figure 1 Nested structure used to arrange and link indicators for measuring biodiversity and ecological integrity in New South Wales. This implementation report covers indicators in the state of biodiversity indicator family (shown by the darker grey box).

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 indicator detailed in this report sits within the nested framework as follows:

Class:	**Biodiversity**
Theme:	**2. State of biodiversity**
Indicator family:	2.2 State of biodiversity including undiscovered species
Indicator:	2.2c Persistence of ecosystems (including undiscovered species) *The expected persistence of species diversity as a function of the proportion of habitat remaining in ecosystems, derived from a classification of known and undiscovered species*

The **state of biodiversity** including undiscovered species indicator family aims to report on the overall amount of biodiversity (genes, species and ecosystems), both known and undiscovered, that currently exists and what is expected to persist in the long term. The indicators are measured indirectly through a suite of models that integrate biological records with remote mapping of environment, satellite remote sensing of land condition and land-use information. These are then combined using process understanding of biodiversity persistence. The assessment is undertaken using the best available data at spatial scales of c. 90 metres and 250 metres.

This indicator expresses the expected persistence of species diversity as a function of the proportion of effective habitat remaining in ecosystems. The results presented here are based on vascular plants. Future assessments of this indicator will include results for other taxonomic groups.

This indicator has been developed as part of the first assessment report on the state and outlook of NSW's biodiversity. It reports on the state and outlook of ecosystem diversity in 2013 (based on available data), proximal to the commencement of the BC Act in 2017. Indicators are intended as a reference for comparison into the future, and prior to 2017 where suitable data are available.

Summary

The persistence of ecosystems (including undiscovered species) for vascular plants indicator quantifies diversity at the ecosystem level, along with species- and genetic-level diversity within ecosystems.

The industrial era in Australia commenced around 1750 and followed European settlement patterns, with gradual expansion of intensive uses of the land leading to the clearing of native vegetation for agriculture and urban development, the introduction and establishment of invasive species, disturbance associated with resource exploitation (e.g. timber harvesting and grazing) and bushfire management.

In 2013, only a third of the ecological carrying capacity that existed in the pre-industrial era remained in New South Wales. The timing and severity of impacts varies considerably across different regions and ecosystems. Some parts of the state have been severely altered, while others are still close to their original, pre-industrial state. Most parts of New South Wales lie along a continuum between these extremes.

The indicator reports on changes to the original **ecosystem-level vascular plant diversity** for New South Wales arising from changes in ecological carrying capacity. Results are provided for the whole of New South Wales and for reporting regions within the state, in particular, bioregions, landscapes and reserves. The indicator also maps the corresponding levels of **unique plant diversity** across New South Wales (based on 90-metre grid cells); which are suitable for use in regional conservation priority assessments.

This biodiversity indicator is expressed as a percentage of a modelled estimate of the state of biodiversity in the pre-industrial era. Diversity loss occurs directly because of clearing and disturbance, and continues for some time after these events due to extinction lag. Accurate estimations of the state of diversity at a given time rely on knowing the elapsed time since the disturbance. As this is generally unknown, we define the indicator within a bounded range of values to accommodate this uncertainty.

The indicator is derived by intersecting an ecosystem classification based on a generalised dissimilarity model, which defines the pre-industrial distribution of ecosystems across New South Wales, with a map of ecological carrying capacity from the habitat condition family of indicators. The combination of these two datasets defines the capacity of contemporary patterns of habitat to support natural diversity, in this case for vascular plants.

Change in the indicator is determined by periodically applying updates of the ecological condition and carrying capacity indicators, primarily informed by a series of remotely sensed observations. With successive assessments, we anticipate a time series of indicators will emerge, allowing trends in biodiversity persistence to be identified.

Key findings

- In 2013, a maximum of around 84% of the original diversity of vascular plant ecosystems in New South Wales is estimated as persisting, although this persistence is unevenly spread across the state. It is estimated that 16% of original diversity has already been lost, and a further 4% has either probably been lost, or is destined to be lost over time unless timely improvements are made to the extent and condition of supporting habitat.
- Private land conservation and public reserves are both critical in securing the maximum original diversity of vascular plant ecosystems.
- Over half of the original vascular plant diversity of New South Wales is represented in NPW reserves (i.e. public reserves established in perpetuity under the *National Parks and Wildlife Act 1974*). In 2017, NPW reserves covered about 9% of the state, and those reserves retain increased levels of unique diversity as habitat is lost and further degraded on other land tenures.
- Tenures other than NPW reserves (covering 91% of the state) contain over three times the unique diversity found in NPW reserves, but that diversity is spread over an area that is more than 10 times larger. Over 70% of the original vascular plant diversity is found outside of NPW reserves, and around 29% is unique to those other tenures.
- At a bioregional level, the North Coast, South East Corner, South Eastern Highlands and Sydney Basin bioregions, which have always supported high total and unique diversity, remain biodiversity hotspots in comparison to other NSW regions.
- The state’s central wheat-sheep belt retains the least of its original diversity. Bioregions such as the NSW South Western Slopes once supported high levels of diversity (19% of original NSW diversity), but this capacity has diminished significantly in the industrial era (now estimated to be 13% of original NSW diversity).
- Up to 2013, the rate of loss of vascular plant diversity has been slower than the rate of loss of supporting habitat in New South Wales. However, diversity loss accelerates as the proportion of original habitat remaining declines. Using a simple species–area relationship, we estimate that if the proportion of the original ecological carrying capacity remaining falls below 20%, the rate of diversity loss will exceed that of habitat loss.
- Understanding biodiversity patterns and distributions, for example by using vascular plants to identify places of unique diversity, is important supporting information for prioritising conservation investments on private and public land.

1. Introduction

Consistent with the *Biodiversity Conservation Act 2016* (the BC Act), ‘biodiversity’ is defined here as ‘the variety of living animal and plant life from all sources, and includes diversity within and between species and diversity of ecosystems’. We quantify ecosystem diversity from the proportion of remaining biodiversity for broad taxonomic groups (in this case vascular plants) using a classification of locations (grid cells) into ecosystems according to their similarity in species composition, based on the contemporary extent and condition of remnant habitats.

Ecosystems emerge from complex interactions between their biological and physical components, but the properties of ecosystems are not immediately apparent from individual components (Holland 1998; Noss 1990). An ecosystem perspective of biodiversity is critical because, at this level of organisation, not just the components of biodiversity are considered (e.g. organisms and their environment), but also their complex interactions. It is these interactions that underpin ecosystem stability, integrity and biodiversity persistence. Ecosystems provide a useful conceptual foundation for how we approach the measurement of diversity.

Drielsma et al. (2018) presented a conceptualisation of ecological interactions as fractal in nature, showing how self-similar patterns emerge across spatial scales. Within this framework the ‘condition’ of native vegetation or habitat can be assessed across scales, from the site to whole regions, continents, or even globally. As the spatial scales are traversed, compositional, structural and functional features of ecosystems emerge from, and depend on, species and ecological features at finer spatial scales; and vice versa, coarse-scale properties feedback to influence fine-scale properties. As all spatial scales are relevant to the rich biodiversity story, we measure the status of biodiversity across a range of spatial scales using a variety of technologies appropriate to each.

It is well understood that the state of healthy natural systems fluctuates, sometimes dramatically, through the natural effects of storms, drought, fire, disease and predation (e.g. see Thapa et al. 2015). Species and population requirements vary in terms of the extent of habitat needed, and in how this habitat is arranged or connected. To properly assess the implications for biodiversity of what is observed at a local scale, we need to understand its context within broader spatial and temporal scales. Full complements of NSW’s species and ecosystems are sustained across regions that provide dynamic and diverse environments of sufficient networked extent to enable populations of each species to persist and recover following disturbance.

This persistence of ecosystems (including undiscovered species) for vascular plants indicator (referred to as ‘the indicator’) estimates the proportions of original (i.e. pre-industrial) vascular plant diversity that can be supported by a given configuration of extant habitats resulting from the net effects of habitat removal and alteration in the industrial era.

This first assessment of the indicator estimates NSW plant ecosystem diversity at 2013. With successive assessments (i.e. when habitat condition is updated), a time series of results will emerge, and trends can be identified, providing for a new dimension of the indicator to be reported. Any future assessment using improved methods (e.g. the measure of ecosystem diversity used, or of habitat condition) would involve re-running the previous assessment to allow reliable comparisons through time.

2. Methods

2.1 General approach

The approach taken here uses a process-based biodiversity assessment framework. It infers diversity retention as a function of the proportion of effective habitat remaining, while considering compositional similarities in species-level diversity between ecosystems (Drielsma et al. 2014b; Ferrier & Drielsma 2010). To support this framework, we adopt a modelled classification of ecosystem classes which has been derived from a prediction of spatial turnover (or changes across geographic space) in vascular plant species composition using field survey data correlated with a range of environmental predictor surfaces (Ferrier et al. 2007). Then each class is spatially interpolated across New South Wales to characterise the strength of overlapping relationships with environment predictors and shared species.

These ecosystem classes and their predicted species-level compositional relationships are combined with estimates of habitat condition using the ecological condition and carrying capacity indicators (Love et al. 2020) to derive the measures of persistence of extant ecosystem diversity for reporting. Given the nature of biodiversity distribution, whereby any place or region will generally share a portion of its diversity with one or many others, a '**total and unique diversity** reporting framework' has been developed. In this framework, the status of a range of reporting regions is assessed in terms of both the total diversity they support, as well as the unique diversity they contribute to New South Wales. The framework provides for assessments from which indicators are drawn for monitoring status and trend, and simultaneously produces maps and data layers to inform spatial prioritisation of conservation actions. The link between these two functions of biodiversity assessment should help enable regional approaches to adaptive management (Ferrier & Drielsma 2010).

The general approach to modelling the persistence of ecosystems indicator is outlined in Figure 2, whereby a model of biodiversity pattern and a model of ecological carrying capacity underpin the analysis.

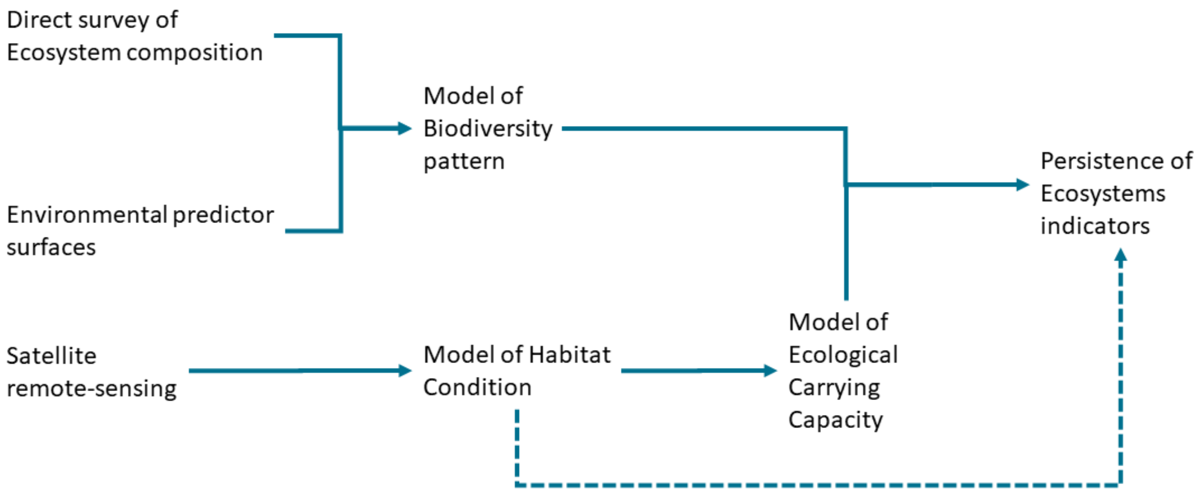

Figure 2 General approach to deriving the persistence of ecosystems indicator

The approach follows the framework provided by Ferrier & Drielsma (2010) that is operationalised within the Terrestrial Biodiversity Forecasting Toolkit (Drielsma et al. 2014b) (see section 2.6 for details). In this application, a model of the pre-industrial biodiversity pattern, derived from field sampling of species compositions within relatively intact ecosystems and associated environmental data, is used as a basis for a classification of ecosystems. Starting with a simple notion that the ‘area of each ecosystem remaining’ approximates ecosystem persistence, additional criteria add layers of model sophistication leading to progressively greater realism in the modelling method used (see Figure 3). The analytical workflow for the indicator is presented in Appendix A and key assumptions of the method are listed in Appendix B.

Notwithstanding compositional overlaps, the method values each classified ecosystem equally, regardless of its intrinsic species richness or original extent. Operationally, this means that all ecosystems potentially contribute equal levels of total diversity in their pre-industrial state. In practice this potential is tempered by known compositional overlap between ecosystems. The individual ‘worth’ of ecosystems is also supported by defining ecosystem classes using an unsupervised classification method in which each ecosystem approximates an equivalent fraction of the environmental space (based on rates of species-level compositional turnover from the model of biodiversity pattern). Thus, the method is focused on the notion of characterising ecosystems as entities unto themselves, as well as representing the diversity (within and between species) those ecosystems inherently support and contribute to the broader region.

The indicator is calculated at a number of different scales:

- all of New South Wales (see section 2.8)
- three reporting regions comprising (see section 2.9):
    - Interim Biogeographic Regionalisation of Australia (IBRA) bioregions (Thackway & Cresswell 1995)
    - NPW reserves (i.e. public reserves established in perpetuity under the *National Parks and Wildlife Act 1974*) and other tenures
    - abiotic Mitchell landscape classes
- site-scale unique diversity mapping based on 90-metre grid cell across New South Wales (see section 2.10).

This current set of reporting regions spans a range of spatial scales. At broader scales (NSW-wide and bioregions), the results are generalised across those regions and do not represent the finer-scale variation within the region that is evident in the finer-scale reporting regions (i.e. Mitchell landscapes) and grid cell–based mapping.

The theoretical maximum value of the indicator across New South Wales equals 100%, that is, the level where each ecosystem has its full (original) complement of diversity. This maximum value is realised (by definition) in the pre-industrial era and has been reduced during the industrial era due to losses in ecological condition and carrying capacity. Potential ecosystem extent is fixed at the pre-industrial state by the modelled patterns predicted from known species occurrence records, and the number of ecosystems recognised in this measure of diversity is arbitrarily defined by the chosen scale of classification (number of classes derived).

Due to species-level compositional overlap between ecosystem classes, the simple sum of the total diversity found within each reporting region exceeds the total diversity for New South Wales because ecosystems naturally share a portion of their diversity with other ecosystems and across multiple reporting regions.

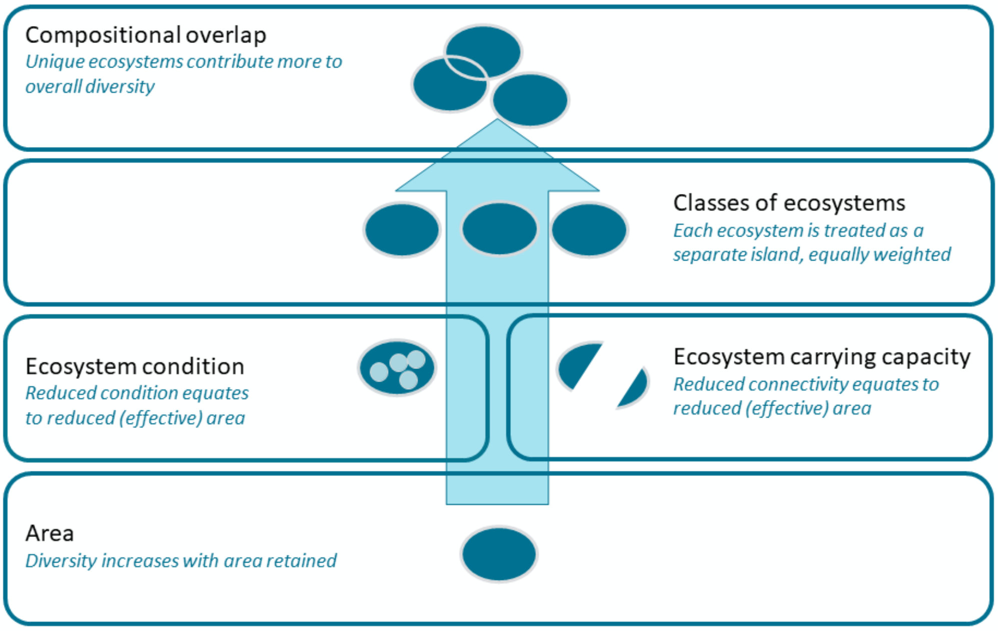

Figure 3 The criteria driving the indicator, showing building level of complexity

The figure illustrates the building of complexity, starting with a simple notion of habitat area at the base, and successively refining it towards the top of the figure by considering condition, connectivity, multiple ecosystems, and finally compositional overlap across the ecosystems.

2.2 The 'total and unique diversity reporting framework'

The ecosystem diversity indicators were developed around two perspectives on reporting and monitoring of biodiversity that we refer to as 'the total and unique diversity reporting framework' (see Figure 4). **Total diversity** is an estimate of the proportion of original NSW diversity supported within a region, with no consideration of how the region shares its diversity with other regions. Total diversity is a 'bottom-up' analysis perspective. Coarser-scale properties emerge from finer-scale properties within the reporting region, but are not merely a sum of those properties at the finer scale. Viewed this way, reporting regions are treated as 'closed systems' which provide a snapshot for comparison over space and time relative to a pre-industrial reference state – assumed to be a state of maximum habitat condition across New South Wales. Total diversity reporting assumes that the individual components of diversity do not interact with, and are in no way contingent on, neighbouring or nearby regions/jurisdictions.

To supplement total diversity, **unique diversity** adopts a 'top-down' perspective for sets of reporting regions by considering each region's unique contribution to biodiversity across New South Wales. Unique diversity is based on that part of NSW's pre-industrial diversity that is represented within a reporting region and nowhere else. In set theory, unique diversity corresponds to the relative complement[1] of each element. Regions with high levels of unique diversity support ecosystems that are either so degraded elsewhere that few examples of their type remain, or these ecosystems were not found elsewhere in pre-industrial times. In

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[1] See https://en.wikipedia.org/wiki/Complement_(set_theory)

practice, unique diversity is more subtlety influenced by the compositional dissimilarity between each ecosystem and the others persisting in other regions (see section 2.5).

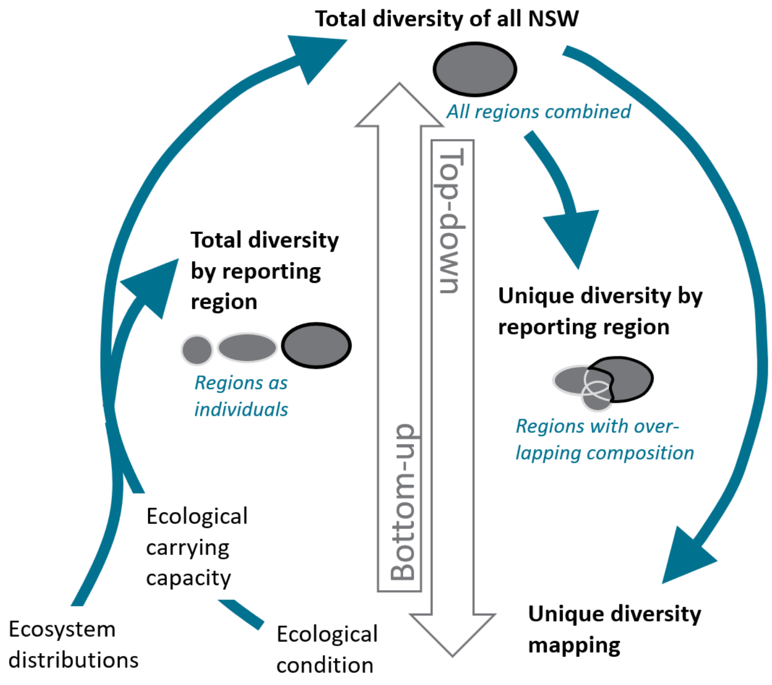


Figure 4 The total and unique diversity reporting framework

Total diversity (left), whereby the indicators are developed from the bottom-up analytical process, based on finer-scale data, including the status of habitats using ecological condition and carrying capacity, and pre-industrial ecosystem distributions. Unique diversity (right), whereby the indicators are a top-down analysis where unique diversity is the difference it makes to total diversity if the habitat condition across the entire region were at a minimum (= 0). The unique diversity is diversity that is not shared with any other region.

Unique diversity can be thought of as a measure of irreplaceability, with some important distinctions. Irreplaceability is defined by Ferrier et al. (2000) as 'the likelihood that a given site will need to be protected to ensure achievement of a set of regional conservation targets'. We replace 'sites' with reporting regions and, rather than using targets, we measure outcome on a continuous scale. Therefore, each region is at once never fully irreplaceable; but each contributes some level of unique diversity and is to some lesser or greater degree irreplaceable.

Unique diversity indicators are calculated like a sensitivity analysis. Each region is assessed for the difference it makes to the 2013 NSW-wide ecosystem diversity persistence indicator (the proportion of original biodiversity that persists across New South Wales at (t) [analytical work flow unit DD07507, Appendix A]) when all its suitable habitat is hypothetically removed (see section 2.9, Figure 9).

In the future, if the indicator is reassessed using an updated estimate of habitat condition, the unique diversity is likely to change. For example, unique diversity will be greater in regions where habitat has been restored, and particularly where that type of habitat and the biodiversity it supports are of limited and declining extent elsewhere in the state. As certain types of biodiversity become increasingly rare, regions that continue to maintain them become increasingly unique, even if that region is experiencing no change in habitat condition. For this reason, a detected change in unique diversity also reflects a change in conservation importance, highlighting areas where retaining high quality habitat will most effectively avert further biodiversity loss.

Unique diversity reporting of the ecosystem diversity indicator fully implements the complementarity principle in conservation planning (Faith et al. 2003; Margules & Pressey 2000), both within and between reporting regions; whereas total diversity reporting only applies complementarity within each region (i.e. between ecosystem classes). Both types of reporting are needed to track change in ecosystem diversity and inform conservation priorities. This framework provides that clear link between reporting and prioritisation applications of the indicator. To simplify messaging, only total diversity is included in the first *NSW Biodiversity Outlook Report* (DPIE 2020).

To illustrate how the reporting framework is applied in practice, Figure 5 shows how the total and unique diversity perspectives relate for three hypothetical reporting units. Measures of total diversity are stand-alone assessments of reporting regions which quantify biodiversity for each region (shown as elements A, B and C in Figure 5). As reporting regions share some ecosystems, the sum of total diversity across all regions will not equal the total diversity calculated for all New South Wales; it will invariably exceed it (i.e. summing total diversity across regions is double counting some features). The unique diversity assessment quantifies the portion of total diversity that is unique to each reporting region, that is, the areas of each reporting region that do not overlap with any other. Thus, the union of reporting regions A, B and C (shown as A ∪ B ∪ C) equates to the total diversity for a study region (N). In this hypothetical example, as the total diversity of B decreases between time t1 and time t2 (and A and C remain constant), it loses some of the diversity it shares with A and C, resulting in an increase in *unique diversity* of A and C. Figure 6 shows how the mapped pattern of ecosystems overlain by hypothetical reporting Region A is used to calculate total and unique diversity, following removal of habitat from some parts of each ecosystem.

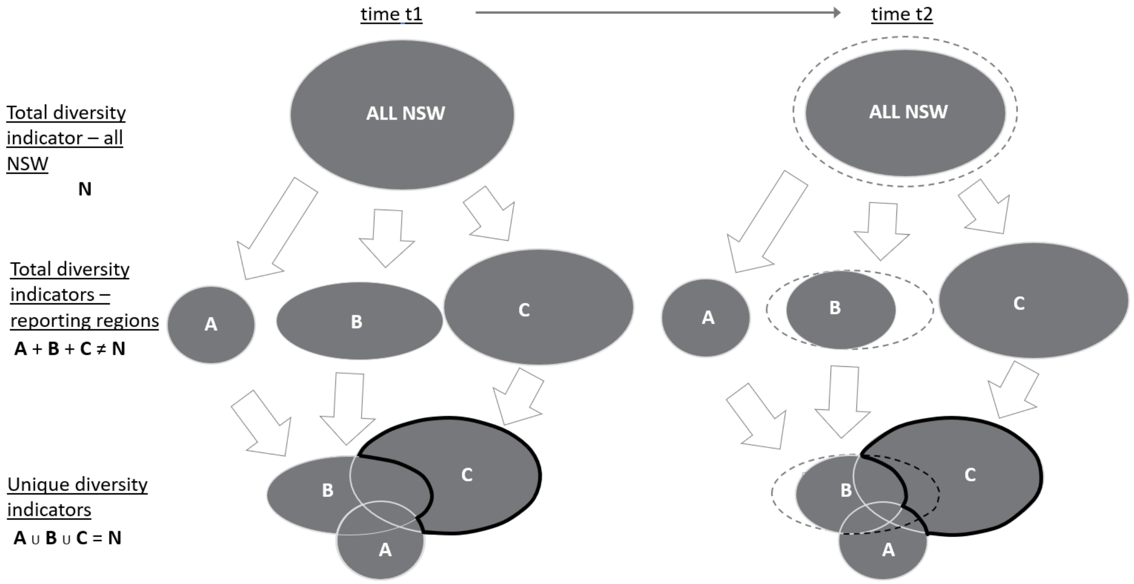


Figure 5 How the total and unique diversity indicators provide complementary information on diversity

The size of each ellipse represents the total diversity: for all NSW (top), and each of three hypothetical reporting regions: A, B and C (below). Unique diversity is represented by the portion of each ellipse that does not overlap with other ellipses (outlined in black for region C). Total diversity of reporting region B, and therefore NSW, reduces between time t1 (left) and time t2 (right), causing the unique diversity of unchanged regions A and C to increase.

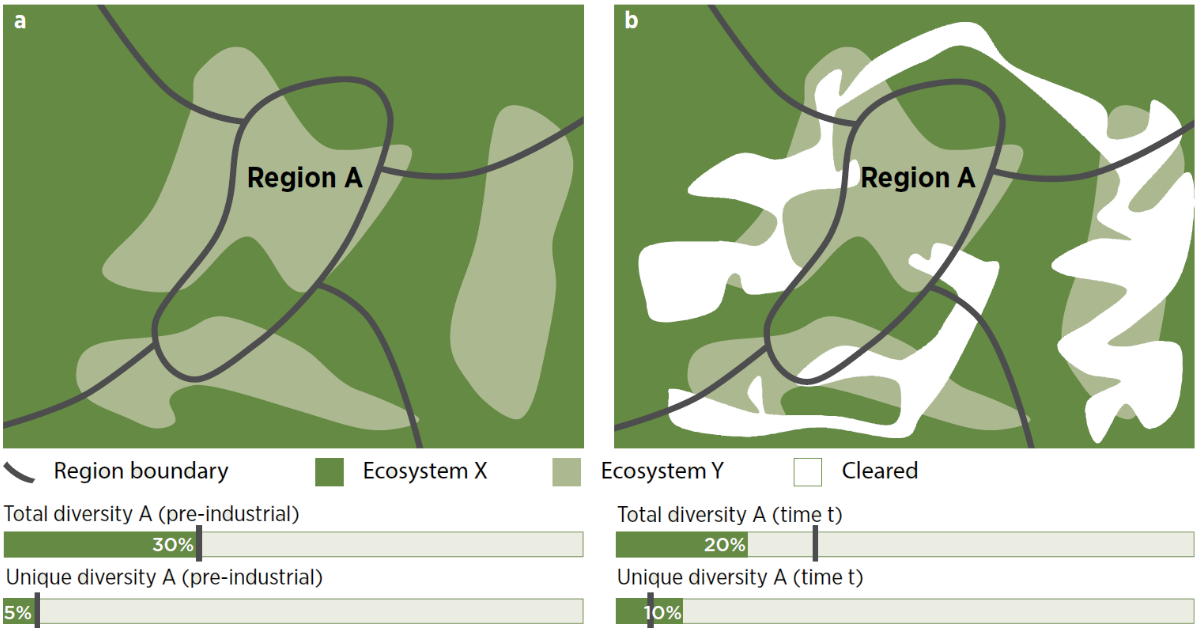


Figure 6 Applying the principle of regional biodiversity complementarity to calculate the total and unique diversity of hypothetical reporting Region A, which shares amounts of two imaginary ecosystems (X and Y) with four other adjacent regions within a jurisdiction (as the bounding box)

Originally (a), the total pre-industrial diversity of Region A was at its maximum (30% of the total diversity of all regions combined) and its unique contribution to diversity was 5%, as its ecosystems were also represented in other regions. At time t (b), clearing of habitat (shown as white), especially of ecosystem Y, left Region A relatively intact with more clearing in the other four regions. Region A's total diversity was reduced to 20% of that originally found there, but its overall unique contribution to the diversity that remains increased to 10%, as some of the diversity shared with neighbouring regions was removed.

2.3 Mapping the distribution of ecosystems

[P07501 and DD07506 workflow components, Appendix A]

Ecosystem persistence for vascular plants is measured by combining either ecological condition or ecological carrying capacity with a generalised dissimilarity modelling (GDM) derived ecosystem classification [class probability stack SD07501, Appendix A] of New South Wales (Ferrier et al. 2007; Manion 2012). The GDM approach is largely data driven, with the modeller guiding the selection of predictor variables and choosing the number of ecosystem classes to derive. The GDM-based classification produces units for calculating the persistence of ecosystems indicator, but they are not used for reporting. Mitchell landscapes (Mitchell 1990, 2008), broad tenure classes, and bioregions (Department of Environment and Heritage 2004; Thackway & Cresswell 1995) are used for the reporting framework.

For the 2013 assessment, an existing 250-group GDM-based ecosystem classification (across the broader NSW and ACT Regional Climate Change Modelling, NARCliM, study region) was adopted (Drielsma et al. 2017; OEH 2016). It is based on the CSIRO Vascular Plant Data Version 5 Revision 11 (VAS_v5_r11_fitted) observation data across south-eastern continental Australia and 25 environmental predictors (19 climate, 6 substrate; see list in Appendix C). This model was originally developed as a preliminary surrogate for all NSW biodiversity, although its effectiveness as a predictor of diversity in other biological groups has not been evaluated. The predicted spatial patterns of ecosystem persistence were derived from a 250-group unsupervised classification of the environmental variables scaled by the coefficients of the fitted GDM model. A stack of 250 probability surfaces using kernel regression modelling (Lowe 1995) was subsequently produced, one for each class. A single maximum probability class grid was also produced from the stack (see Figure 7). For display purposes, a colour palate was produced in the following way. A table of pair-wise Manhattan distances derived for a spatially even sample of the scaled variables was used to create k-means centroids for each class. The k-means centroids were used in a principal coordinate analysis (i.e. metric multidimensional scaling) to generate three axes that best capture predicted dissimilarities between class centroids. Those axes were rescaled between 0 and 255 and associated with red, green or blue (RGB) colour values. Locations mapped with similar colours are predicted to have high ecological similarity, while locations with very different colours are predicted to be highly dissimilar ecologically (Belbin et al. 1983).

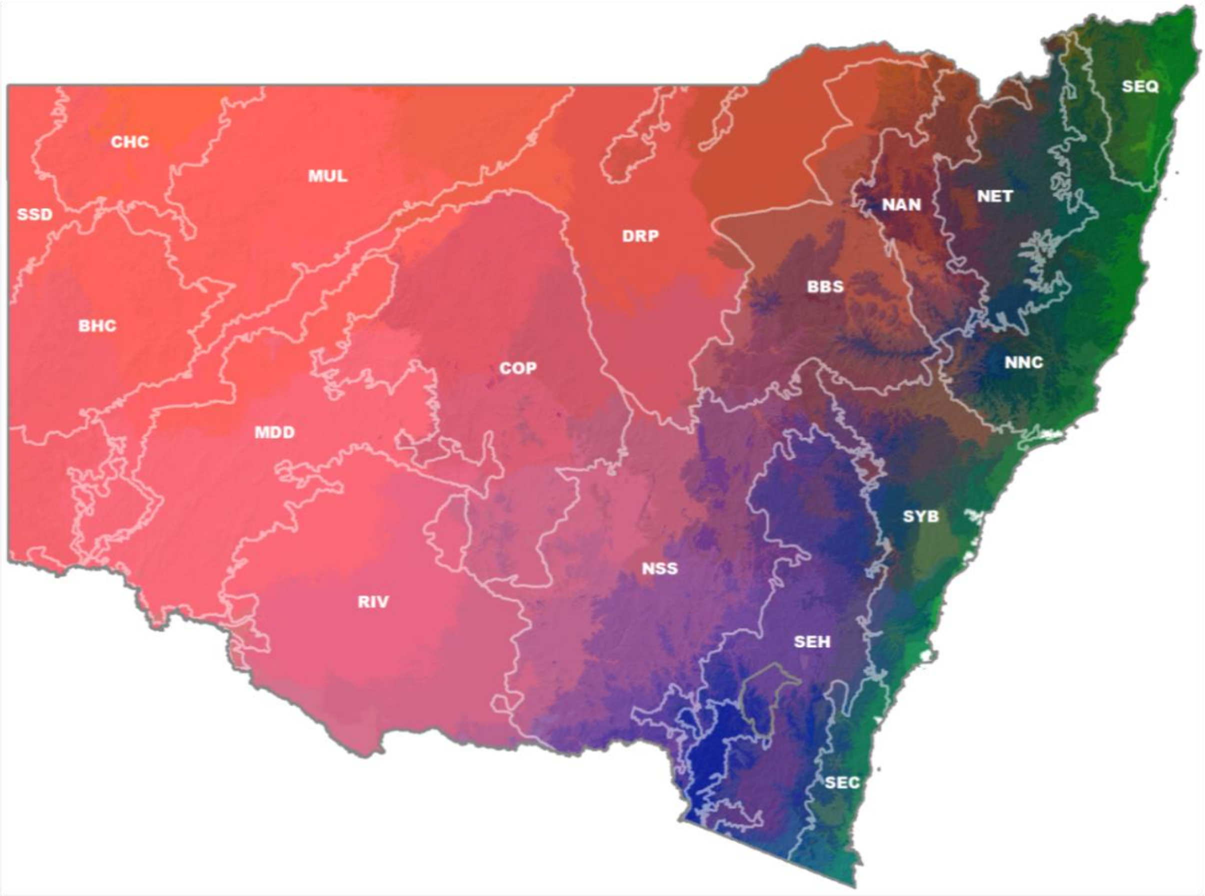


Figure 7 Pre-industrial mapping of ecological similarity of the 250 ecosystem classes across New South Wales

Each ecosystem is coloured according to its compositional overlap with other ecosystems. Ecosystems with similar colours are predicted to have similar biological compositions. Bioregion boundaries are shown with their abbreviated name (see Table 1 for full names).

Although the GDM was informed by a broad range of climatic and substrate variables, in Figure 7 green shades generally depict parts of New South Wales that are relatively warm and summer-rain dominated; blues tend to coincide with cooler areas which are winter-rainfall dominant; and reds tend to associate with hotter and drier conditions. To facilitate analysis at a 90-metre resolution, probability surfaces were bilinearly resampled to 90 metres from their original 250-metre resolution, then normalised so to sum to one at each cell [P07502, see Appendix A].

2.4 Accounting for remaining habitat

2.4.1 Area measurement

Within the method, the amount of habitat is represented by *ecological carrying capacity*, otherwise known as effective habitat area (Ferrier & Drielsma 2010). It integrates area, condition and connectivity (Love et al. 2020). Ecological carrying capacity accords with Fahrig's (2013) habitat amount hypothesis. It is a measure of the amount of habitat available at each location (i.e. each 90-metre grid cell across New South Wales), calculated across a range of spatial scales, without requiring a specific reference to abstractions such as patch size or distance to nearest patch (Drielsma et al. 2007).

2.4.2 Species–area relationship

It is well understood in ecology that as the area of habitat increases, the number of species (or diversity) increases (Haila 2002; MacArthur & Wilson 1967). This general notion applies to the greater diversity observed in larger islands or habitat islands, or in connected networks as compared to isolated fragments. By extension, when all other factors are held constant, diversity in terrestrial environments is also expected to fall as the area, quality and connectivity of habitat is reduced or removed. The often-used general form of the observed empirical relationship between the amount of habitat and persisting diversity is a power law, governed by the species–area relationship (SAR), where the number of species persisting increases according to the proportion of habitat sampled raised to an exponent, z. This is in contrast to the island species–area curve, which describes the species richness of islands as a function of their area (Matthews et al. 2016).

Here, we use the SAR to describe the remaining diversity within each class of an ecosystem classification, where each class is partially connected subject to natural patterning, clearing and variations in habitat quality. Other functional forms for the SAR have been suggested and derived, however, the power law is relatively simple and has been most widely applied (Connor & McCoy 1979). Researchers have attempted to address the issue of determining suitable values for the exponent, *z*There is no simple answer to this as *z* represents the collective outcome of multiple interactions among ecological processes across spatial and temporal scales and has been shown to vary in different contexts. A clear mechanistic explanation for the empirical observation of SAR has been elusive. Many studies have indicated a range of *z* between 0.2 and 0.4, with some consensus around 0.25 (Connor & McCoy 1979; Harte et al. 1999; Matthews et al. 2016; Pereira & Daily 2006; Rosenzweig 1995). A value of 0.25 for the exponent *z*, is therefore adopted here while acknowledging that this is a core assumption that warrants further investigation within this specific context. The sensitivity of the indicator to alternative single *z* values of 0.2 and 0.4 is explored in section 4.1.4. The choice of appropriate form(s) of the SAR through the exponent *z*, is also the subject of current research that will inform future indicator calculations.

2.5 Compositional overlap

[DD07519 workflow component, Appendix A]

To represent the diversity of ecosystems, as discussed in section 2.3, we account for how each ecosystem is related by considering their compositional similarity, a relative measure of how many species each pair of ecosystems share and how many they don't. This ranges from ecosystems that occupy very different parts of the environment where no, or very few species are shared, to those ecosystems that are both environmentally and compositionally similar, having many species in common. Compositional similarity between ecosystems is calculated by applying the 'link' function from the fitted GDM (Ferrier et al. 2007) to all pairs of characteristic vectors for ecosystems. Characteristic vectors are derived by averaging transformed predictor values for a sample of sites from within each ecosystem class. This produces a class-by-class ecosystem-similarity matrix where a value at a cell of the matrix is a GDM-based predicted approximation of the Bray Curtis similarity of species between that pair of ecosystems. This is applied across all cells in the matrix to account for how each ecosystem is related to all other ecosystems.

While the total diversity analysis does not consider the inherent compositional overlap in species shared between reporting regions, it does account for species shared between ecosystems within each reporting region. For example, significant loss of habitat condition within an ecosystem in a reporting region is partially offset by retention of other ecosystems within that region that share some species, but not by the existence of similar ecosystems in other regions. When total diversity is calculated for all of New South Wales (see section 2.8), compositional relationships across ecosystems are considered fully within the state; but not in relation to other Australian jurisdictions. New South Wales is treated as a closed system for reporting and is limited by the extent of the habitat condition indicators which are restricted to New South Wales. The unique diversity analysis also considers how ecosystems are related across reporting regions within New South Wales.

2.6 Biodiversity persistence calculator

[P07503 and P07505 workflow components, Appendix A]

The ecosystem persistence indicator is derived using the ‘scenario evaluation’ and ‘benefits mapping’ functions of the Terrestrial Biodiversity Forecasting Toolkit (T-BFT, Drielsma et al. 2014b), in accordance with Ferrier and Drielsma’s (2010) general approach to biodiversity assessment.

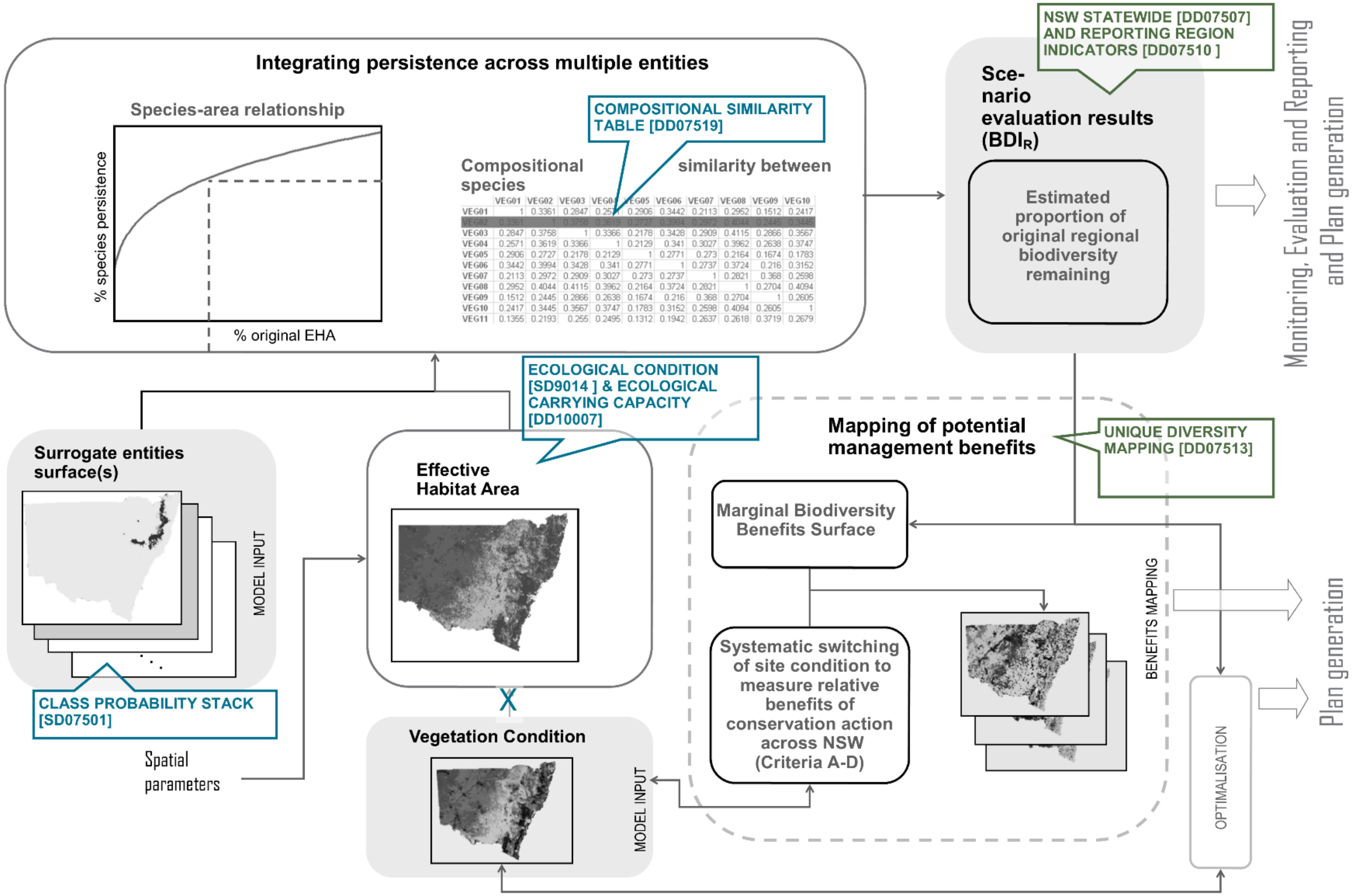
The T-BFT approach has been refined over the 14 years since its inception as part of the Western Regional Assessments (Resource and Conservation Assessment Council 2004). The approach has been used for a number of regional and statewide assessments (listed in Drielsma et al. 2014a), most recently for forecasting future biodiversity losses from climate change across south-east Australia (Drielsma et al. 2017; Drielsma et al. 2015; OEH 2016).

A critical element of the T-BFT approach is the use of the species–area relationship (SAR) (Ferrier et al. 2004), which describes the relationship between the effective habitat area of an ecosystem and the proportion of remaining species that can be supported in that area (see section 2.4.2). The form of the SAR relationship for this application is governed by a single z parameter equal to 0.25. In the T-BFT, the species–area relationship has been integrated into a method for considering compositional similarity between ecosystems and the relative value to biodiversity of ecosystems as higher order, emergent entities. The T-BFT incorporates spatial context habitat connectivity in the form of colonisation potential (Hanski 1999), that has been translated into a method for working with raster data (Drielsma et al. 2007). The broad process, whereby the main inputs are ecosystem distribution mapping and ecological condition, is shown in Figure 8.

For this project, the T-BFT was structured within the total and unique diversity reporting framework to provide a dual-perspective, cross-scale set of comparison measures from the indicator (see section 2.2 for details).

The requisite spatial inputs to the T-BFT are an effective habitat condition grid (here we use ecological condition and carrying capacity) and a grid (or, as is the case here, a probability stack) of ecosystem distributions. In previous applications, the T-BFT calculates the effective habitat area grid as part of the process, based on a user-provided movement parameter range that is relevant to movement abilities for a single spatial scale. Here, it is provided in the form of ecological condition and carrying capacity (see section 2.7 below). The current model utilises best available data at the New South Wales state level at the time of the assessment (c. June 2017, relevant to 2013 conditions). For more information on data inputs, refer to the relevant methods reports (Love et al. 2020; OEH 2016).

All analyses were conducted using 90-metre grids. The ecosystem distributions were derived as 250-metre grids, then resampled to 90 metres (see section 2.3). All other spatial inputs were derived using best available data applied to 90-metre grids.



	VEG01	VEG02	VEG03	VEG04	VEG05	VEG06	VEG07	VEG08	VEG09	VEG10
VEG01	1	0.3361	0.2847	0.2571	0.2906	0.3442	0.2113	0.2952	0.1512	0.2417
VEG02	0.3361	1	0.3758	0.3619	0.2727	0.3994	0.2972	0.4044	0.2445	0.3445
VEG03	0.2847	0.3758	1	0.3366	0.2178	0.3428	0.2909	0.4115	0.2866	0.3567
VEG04	0.2571	0.3619	0.3366	1	0.2129	0.341	0.3027	0.3962	0.2638	0.3747
VEG05	0.2906	0.2727	0.2178	0.2129	1	0.2771	0.273	0.2164	0.1674	0.1783
VEG06	0.3442	0.3994	0.3428	0.341	0.2771	1	0.2737	0.3724	0.216	0.3152
VEG07	0.2113	0.2972	0.2909	0.3027	0.273	0.2737	1	0.2821	0.368	0.2598
VEG08	0.2952	0.4044	0.4115	0.3962	0.2164	0.3724	0.2821	1	0.2704	0.4094
VEG09	0.1512	0.2445	0.2866	0.2638	0.1674	0.216	0.368	0.2704	1	0.2605
VEG10	0.2417	0.3445	0.3567	0.3747	0.1783	0.3152	0.2598	0.4094	0.2605	1
VEG11	0.1355	0.2193	0.255	0.2495	0.1312	0.1942	0.2637	0.2618	0.3719	0.2679

Figure 8 Biodiversity assessment framework using the Terrestrial Biodiversity Forecasting Toolkit (T-BFT), annotated to show how it is used for deriving ecosystem persistence

The scenario evaluation is repeated for each reporting unit (e.g. regions, reserves) (Drielsma et al. 2014b). The workflow components identified in the coloured call-outs are detailed in Appendix A.

2.7 Factoring in extinction lag

The analysis was duplicated alternatively using ecological condition and carrying capacity inputs to estimate the maximum and minimum values of the indicator, respectively (Love et al. 2020). Ecological condition was used to estimate the immediate, irreversible loss of diversity associated with habitat reduction. The method assumes that every location or 'unit' of habitat has some level of unique diversity, however small. Any physical clearing or loss of habitat condition, therefore, is expected to lead to immediate (and irreversible) loss of diversity. Ecological carrying capacity also accounts for the additional gradual loss of diversity attributed to extinction lag, which incorporates indirect losses over time due to reductions in habitat availability across space, and disruption to colonisation and migration opportunities (Didham 2010). Projected losses due to the extinction lag component, theoretically, can be partially reversed through habitat restoration; but success depends on the degree to which the extinction lag has already been realised at the time of this action.

These upper- and lower-bound results broadly correspond with shorter- and long-term expected species persistence. The actual current level could be estimated using local rates of extinction and time since clearing; both of which are currently unknown and are the subject of ongoing research (see section 4.1.2).

2.8 All of NSW indicator

[DD07507 workflow component, Appendix A]

The proportion of original biodiversity that persists across New South Wales was derived by applying the T-BFT evaluation to all of the state. The NSW indicator is a total diversity indicator, that is, New South Wales is treated as a closed system, with no consideration of adjoining jurisdictions.

2.9 Indicators by reporting region

[DD07510 workflow component, Appendix A]

For the proportion of biodiversity that is potentially persistent by region, three categories of reporting region were assessed:

- each of 18 IBRA bioregions represented in New South Wales (Department of Environment 2014)
- NPW reserves (i.e. public reserves gazetted prior to August 2017 managed in perpetuity under the National Parks and Wildlife Act) and 'other tenures'
- 572 Mitchell landscapes (abiotic).

The distributions of these reporting regions are mapped in Appendix D.

The pre-industrial level of the indicator for the whole of New South Wales (total and unique diversity) is 100% by definition. For other reporting regions, the pre-industrial indicator was calculated by setting the ecological condition and carrying capacity grids to 1.0, that is, the maximum attainable value. The 2013 instances were calculated using 2013 ecological condition and carrying capacity grids. The level of the indicator for each reporting region was derived using the two alternative analytical processes for the reporting framework (Figure 9):

1. **Total diversity**. A T-BFT scenario evaluation was performed for each region in isolation. This was undertaken for the pre-industrial and 2013 status of habitat condition. The indicator value is then divided by the corresponding total diversity value for New South Wales.

2. **Unique diversity**. A T-BFT scenario evaluation was performed for each region where, for each instance, the condition of the region was set to zero, thus deriving a value relative to the whole of New South Wales (ignoring the context of adjacent jurisdictions). The region's indicator is the difference between the indicator for all New South Wales with and without that region included. This analysis was repeated for the pre-industrial and 2013 status of habitat condition.

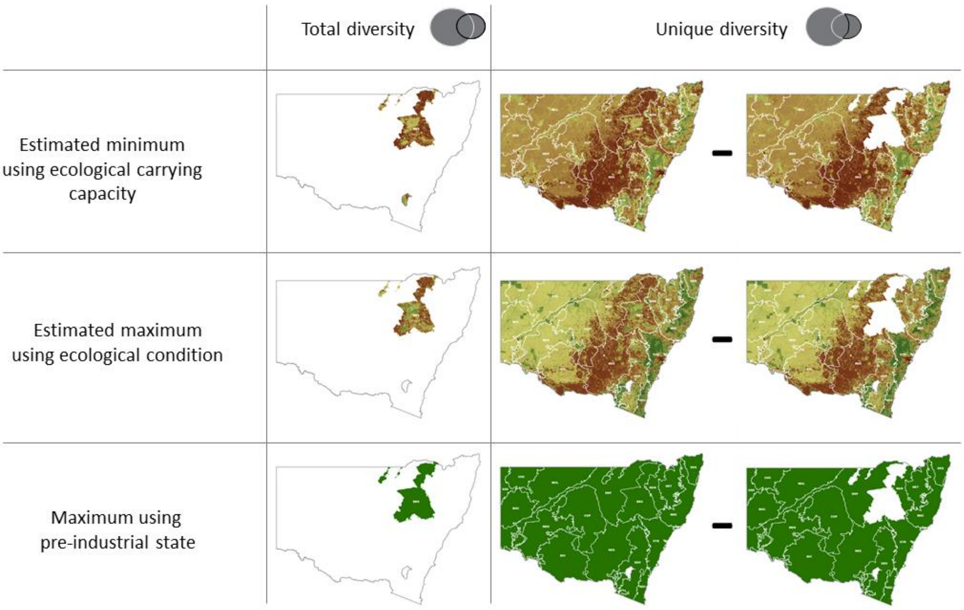


Figure 9 The input calculations required to complete the analysis framework for regional reporting of total diversity and unique diversity

Total diversity perspective (left), treats each bioregion as an isolated closed system; and the unique diversity perspective (right) is derived as the difference in the values for all NSW and NSW without the bioregion (habitat condition is set to a minimum = 0). Each input calculated is derived for the pre-industrial state, and for the two condition states (to calculate upper and lower bounds of the indicator). The same approach applies to NPW reserves as a single reporting region (the inverse being other tenures).

Both the total and unique diversity analyses were applied for reporting on New South Wales, IBRA bioregions, and NPW reserves and other tenures. The large number of Mitchell landscapes made the derivation of unique diversity computationally problematic (but it could be developed in future assessments of the indicator), so only total diversity was calculated.

Bioregions are defined by version 7 of the Interim Biogeographic Regionalisation of Australia (IBRA) (Department of Environment 2014). Each bioregion has been broadly delineated on the basis of its distinctive pre-industrial patterns of regional climate, soils, landforms and vegetation (Thackway & Cresswell 1995). They are irregular shaped geographical units, generally increasing in area towards the western, more arid parts of New South Wales. Bioregions are a key component of the scientific framework for reporting on how well biodiversity is represented in protected areas. They are also central to how comprehensiveness, adequacy and representativeness objectives are assessed for protected areas in Australia (Commonwealth of Australia 1999). There are 18 bioregions within, or partly within New South Wales (see Appendix D and Table 1), and many extend beyond the state boundary into surrounding jurisdictions. However, only the New South Wales extent of bioregions were used in this analysis.

In addition, version 3.1 of the 572 NSW Mitchell landscapes are employed as reporting units. The NSW landscapes (Eco Logical Australia 2008; Mitchell unpub.) is a pre-industrial, abiotic land classification based on physical geomorphology (soils, geology and landform) primarily used in agricultural land capability mapping. It lacks a biological underpinning. New vegetation mapping of plant community types (Sivertsen 2009) is currently being undertaken in New South Wales, and will be combined with the landscapes to derive regional ecosystems (similar to Queensland's approach). In future assessments of the indicator these data may be used as an alternative basis for analysing or reporting on ecosystem diversity.

2.10 Unique diversity mapping

[DD07513 workflow component, Appendix A]

Unique diversity mapping is an estimate of the unique diversity at a site scale. Rather than treating each cell as a reporting unit, it generates a map of fine-scale unique diversity, based on analysis at the (90 metre) grid cell level. The grid cell analysis is not the same as a site assessment undertaken by direct field observation; rather it is a modelled product derived using inferred biodiversity patterns and the ecological carrying capacity indicator. The ecological carrying capacity indicator is derived from temporally informed remotely sensed data, and therefore has a basis in observation. Unique diversity mapping is not explicitly included in reporting on this indicator in the first *NSW Biodiversity Outlook Report* (DPIE 2020).

Unlike the unique diversity reporting analysis (section 2.9) calculated at broader scales (NSW-wide and bioregions), it is not computationally practical to exhaustively calculate unique diversity for each of the more than 94 million 90-metre grid cells. Estimates of unique diversity are therefore calculated using the conservation benefits capabilities of the T-BFT. For each cell, the method estimates the difference made to the NSW total diversity indicator by a cell's hypothetical removal, but relies on a static 'marginal biodiversity benefit grid' (see section 2.10.1) to avoid the need to fully recalculate total diversity across New South Wales when each cell value is hypothetically altered (see section 2.10.1). The results are written to an output grid, where the value of each cell value reflects the change to NSW total diversity resulting from the removal of vegetation from sites at locations corresponding to cells.

This approach is presented in Figure 8 and Figure 10. In this instance, no quantified threat or timeframe is included in the analysis, so the 'do nothing' scenario is assumed to mean a total loss of diversity at a given site. As we are monitoring, rather than forecasting or hindcasting in this instance, the trajectory of change will become apparent in future calculations of the indicator. However, the T-BFT allows for scenarios to be developed and applied through the ecosystem integrity family of indicators (see Theme 5 in DPIE 2020). With future advances of the monitoring program suite of indicators, the capacities of this indicator framework can be more fully utilised when integrating ecosystem persistence with management effectiveness for overall reporting on ecological integrity.

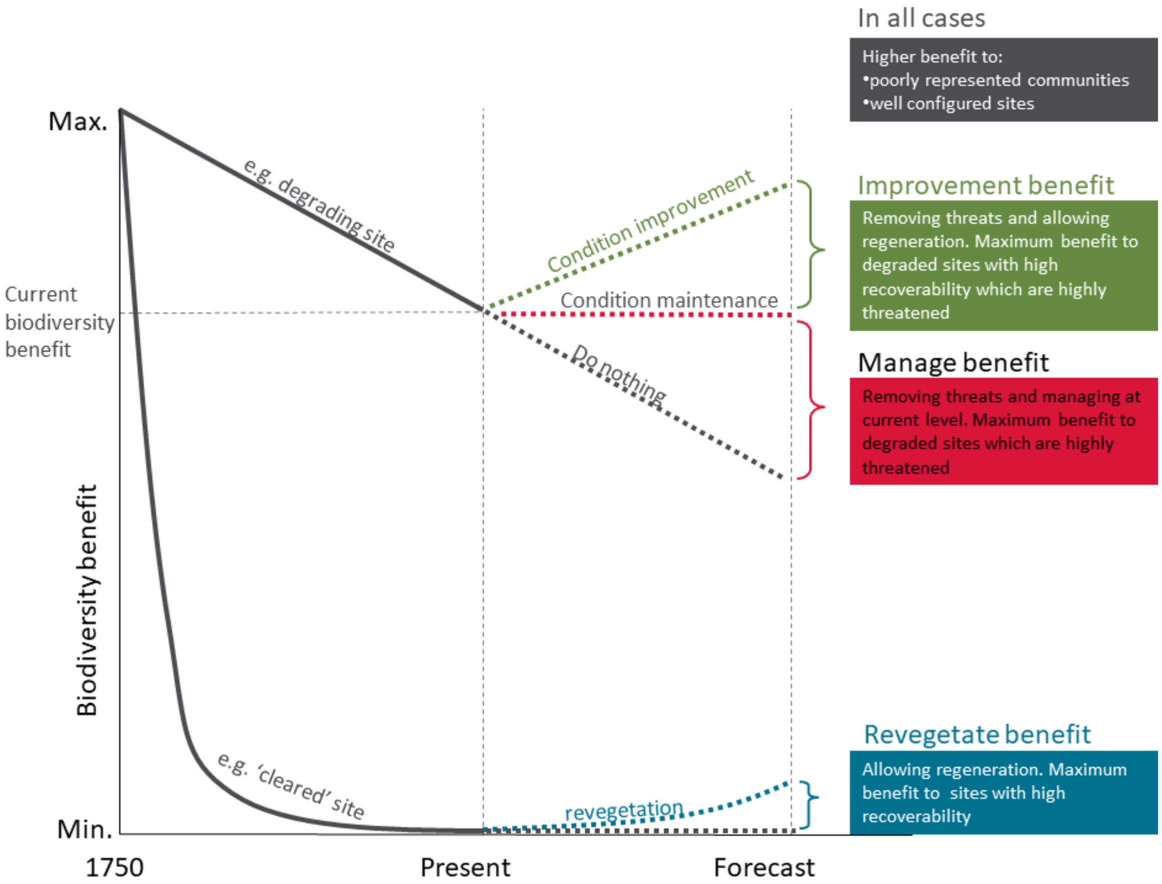


Figure 10 Framework for assessing conservation benefits from the Terrestrial Biodiversity Forecasting Toolkit (T-BFT)

The framework considers a site's contribution to regional diversity from a pre-industrial state (c. 1750), through to the present and into the future. Two possibilities are presented: a degrading site and a cleared site. Any other scenario can be considered. Going forward, management can lead to further loss, maintenance, or improvement in diversity, although in practice the benefit of any site will respond to changes across the region (Drielsma et al. 2014b).

2.10.1 Marginal biodiversity benefit calculations

The benefits mapping approach effectively weights each cell according to the conservation status of the local ecosystem class or classes. This weight is known as the marginal biodiversity benefit (Drielsma et al. 2014b). It is the benefit to pre-industrial ecosystem diversity that is achieved by hypothetically increasing the statewide extent of the ecosystem. We tested three alternative methods: two novel and the other widely applied. These involved increasing the extent of each ecosystem as follows:

1. by one 90 x 90 metre cell
2. back to its original pre-industrial extent
3. by 5% of its pre-industrial extent.

Each method provides a different measure, relevant to different spatial scales at which the result is viewed. The first version (1) estimates unique diversity relative to the NSW total for *each individual cell*. This option equates to treating each cell as a reporting unit for the purposes of measuring 'unique diversity'. This option was ruled out as a suitable indicator as it is positively skewed (i.e. resulted in higher unique diversity) towards ecosystems that are naturally smaller in extent, where each 90 x 90 metre cell makes up a larger proportion of the original extent, and in that sense, is calculated to be more highly irreplaceable than an equal-sized cell in a larger ecosystem. As such, it does not provide a satisfactory map of fine-scale unique diversity and would not be suited to the purpose of spatial prioritisation.

The second version (2) considers the status of the entire ecosystem. This option was ruled out as it favours the most-cleared ecosystems regardless of their size, with little consideration of unique diversity at the cell level. This version has been widely applied in past studies, mostly for prioritisation (e.g. Drielsma et al. 2017; OEH 2016), but also for reporting (Drielsma et al. 2016).

The third version (3), new to this study, achieves an acceptable balance when addressing the inevitable compromises arising from the vagaries of cell and ecosystem areas. It leads to a map that provides a fine-scale measure. It is also best suited for conservation prioritisation purposes.

3. Results

Results were derived for all New South Wales, three sets of reporting regions (IBRA bioregions, NPW reserves and other tenures, and Mitchell landscapes), and at the site level for unique diversity mapping. These span spatial scales from subcontinental to 90 x 90 metre grid cells. Results for the state, each region and for site-level mapping are presented here. See Table 1 and figures in following sections.

The current assessment was undertaken only for habitat condition data current up to or at 2013, and the indicator is assessed in relation to the pre-industrial ecosystem diversity baseline. In future assessments of the indicator, a comparison will be made between each successive 'current' and the 'previous' epochs, at five-yearly or less intervals.

Loss of vascular plant ecosystem diversity since the industrial era is ubiquitous, but unevenly distributed. Reductions in diversity persistence are concentrated in the fertile central wheat-sheep belt, where the main system of farming has well-documented direct impacts on ecosystems such as the grassy woodlands that once dominated extensive parts of central New South Wales (Stol & Prober 2015). Historically, the Great Eastern Ranges and coastal regions of the state have proved less arable and/or suitable for agricultural development (i.e. clearing, cropping and pasture improvement). Mostly for these reasons, larger proportions of these regions have been allocated to nature conservation and forestry rather than agriculture (Margules & Pressey 2000; Pressey et al. 1993), resulting in higher retention of plant diversity.

3.1 First assessment: ecosystem diversity for all of New South Wales

[DD07507 workflow component, Appendix A]

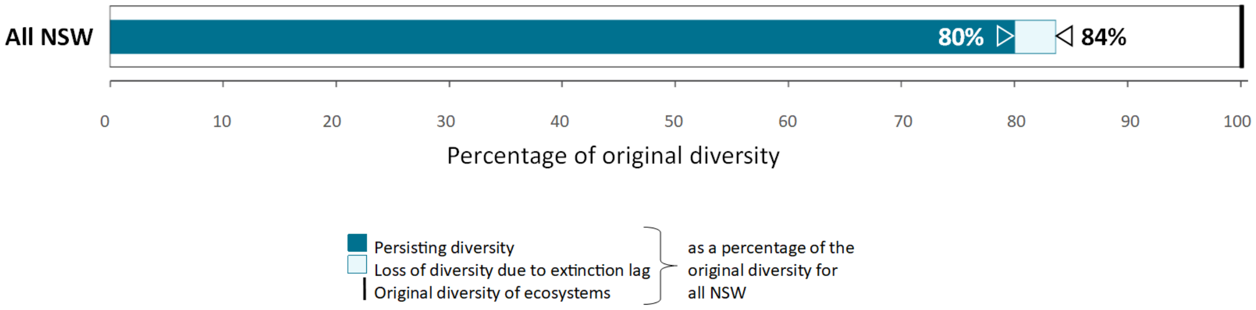


Figure 11 Vascular plant ecosystem diversity for New South Wales in 2013

In 2013, total vascular plant ecosystem diversity for New South Wales is estimated to be between 80.02 and 83.65 (see Figure 11). This means that plant diversity has been reduced to around 84% of the pre-industrial level considering habitat degradation effects only, without considering extinction lag. Considering fragmentation and associated extinction lag and assuming no further changes to habitat condition since 2013, the modelling suggests that total diversity is expected to eventually stabilise at around 80% of the pre-industrial level (16% of diversity has been lost already, with a further 4% probably lost, or at risk of being lost through continuing disruption of ecological processes caused by past fragmentation events).

This measure considers the current condition and distribution of habitats up to 2013; it does not seek to forecast future changes arising from further clearing, changed land use, climate change, or further introductions or spread of pest species and pathogens.

3.2 First assessment: ecosystem diversity by region

[DD07510 workflow component, Appendix A]

3.2.1 Ecosystem diversity for bioregions in 2013

The IBRA bioregion results are shown in Table 1, Figure 12 and Figure 13. The **total diversity** of bioregions (including extinction lag), as a percentage of pre-industrial NSW diversity, ranges from 1.68% for the Simpson Strzelecki Dunefields to 23.48% for the Sydney Basin (Figure 12). The **unique diversity**, as a percentage of pre-industrial NSW diversity, of each bioregion (including extinction lag) ranges from 0.03% for the Simpson Strzelecki Dunefields to 7.08% for the South East Corner (Figure 13).

The persistence indicators suggest that the Sydney Basin has the highest capacity among NSW bioregions in 2013 to support NSW's original plant ecosystems during the industrial era. However, the pie charts in Figure 12 and Figure 13 show that the Sydney Basin retains a smaller proportion of its original diversity (total and unique) than several other bioregions. The South East Corner continues to contribute the most unique diversity to NSW's ecosystem persistence as originally estimated from the pre-industrial era through to 2013. It is likely, however, that the South East Corner will share much of its diversity with eastern Victoria, which is not considered in this analysis. The Simpson Strzelecki Dunefields and the NSW North Coast both contributed less unique diversity in the pre-industrial era but have retained a higher proportion of what they originally had compared to most other bioregions.

In the unique diversity results (Figure 13), the Sydney Basin contributes a higher unique diversity to overall NSW diversity when extinction lags are considered (calculated using the ecological carrying capacity indicator) than when the influence of landscape processes on diversity are not considered. This unexpected result appears to arise because the remaining vegetation in the Sydney Basin is mostly contiguous across vast regions, and is therefore largely unaffected by extinction lag. As other parts of New South Wales are affected and lose diversity accordingly, ecosystems that are shared across bioregions become increasingly unique in the Sydney Basin.

The total 2013 diversity of each bioregion (including extinction lag) as a per cent of the region's pre-industrial level ranges from 68% in the NSW South Western Slopes to 89% in the Australia Alps (see pie charts in Figure 12). In relation to unique diversity, as a per cent of pre-industrial levels, the South East Corner retains the highest proportion (92%) and the NSW South Western Slopes retains the lowest proportion (64%) (see pie charts in Figure 13).

Table 1 Indicators for all of New South Wales, land tenures and bioregions – the percentage of original pre-industrial total and unique diversity

Reporting region		Total diversity			Unique diversity		
	% area of NSW	Pre-industrial	2013 without extinction lag	2013 including extinction lag	Pre-industrial	2013 without extinction lag	2013 including extinction lag
All New South Wales	100	100	83.65	80.02	100	83.65	80.02
NPW reserves	8.98	58.18	54.61	52.11	8.11	9.28	8.73
Other land tenures	91.02	91.89	74.37	71.29	41.82	29.04	27.91
Bioregions (as per cent of NSW diversity):							
Australian Alps (AUA)	0.67	7.81	7.20	6.92	1.47	1.35	1.30
Brigalow Belt South (BBS)	6.58	17.03	13.46	12.49	2.88	2.18	2.02
Broken Hill Complex (BHC)	6.89	4.11	3.52	3.24	0.45	0.40	0.37
Channel Country (CHC)	4.65	4.01	3.43	3.16	0.72	0.62	0.57
Cobar Peneplain (COP)	2.83	8.23	6.67	6.10	1.27	1.05	0.96
Darling Riverine Plains (DRP)	9.17	8.64	6.78	6.27	0.92	0.74	0.68
NSW South Western Slopes (NSS)	11.52	18.82	14.05	12.88	5.20	3.69	3.36
Mulga Lands (MUL)	9.98	5.58	4.75	4.37	0.71	0.61	0.55
Murray Darling Depression (MDD)	8.00	6.20	5.06	4.67	0.45	0.37	0.35
Nandewar (NAN)	2.53	12.63	10.44	9.70	1.15	0.95	0.88
New England Tablelands (NET)	3.48	16.01	13.75	12.91	2.16	1.78	1.64
NSW North Coast (NNC)	4.92	24.52	21.45	20.75	3.48	3.28	3.15
Riverina (RIV)	10.32	8.74	6.63	6.09	2.92	2.24	2.09
Simpson Strzelecki Dunefields (SSD)	8.99	2.10	1.81	1.68	0.03	0.03	0.03
South East Corner (SEC)	1.58	22.70	20.55	20.18	7.71	7.22	7.08
South Eastern Highlands (SEH)	1.99	26.25	22.59	21.48	5.63	4.58	4.30
South Eastern Queensland (SEQ)	1.33	15.58	12.98	12.76	5.11	3.98	3.95
Sydney Basin (SYB)	4.57	27.61	23.67	23.48	4.93	4.15	4.29

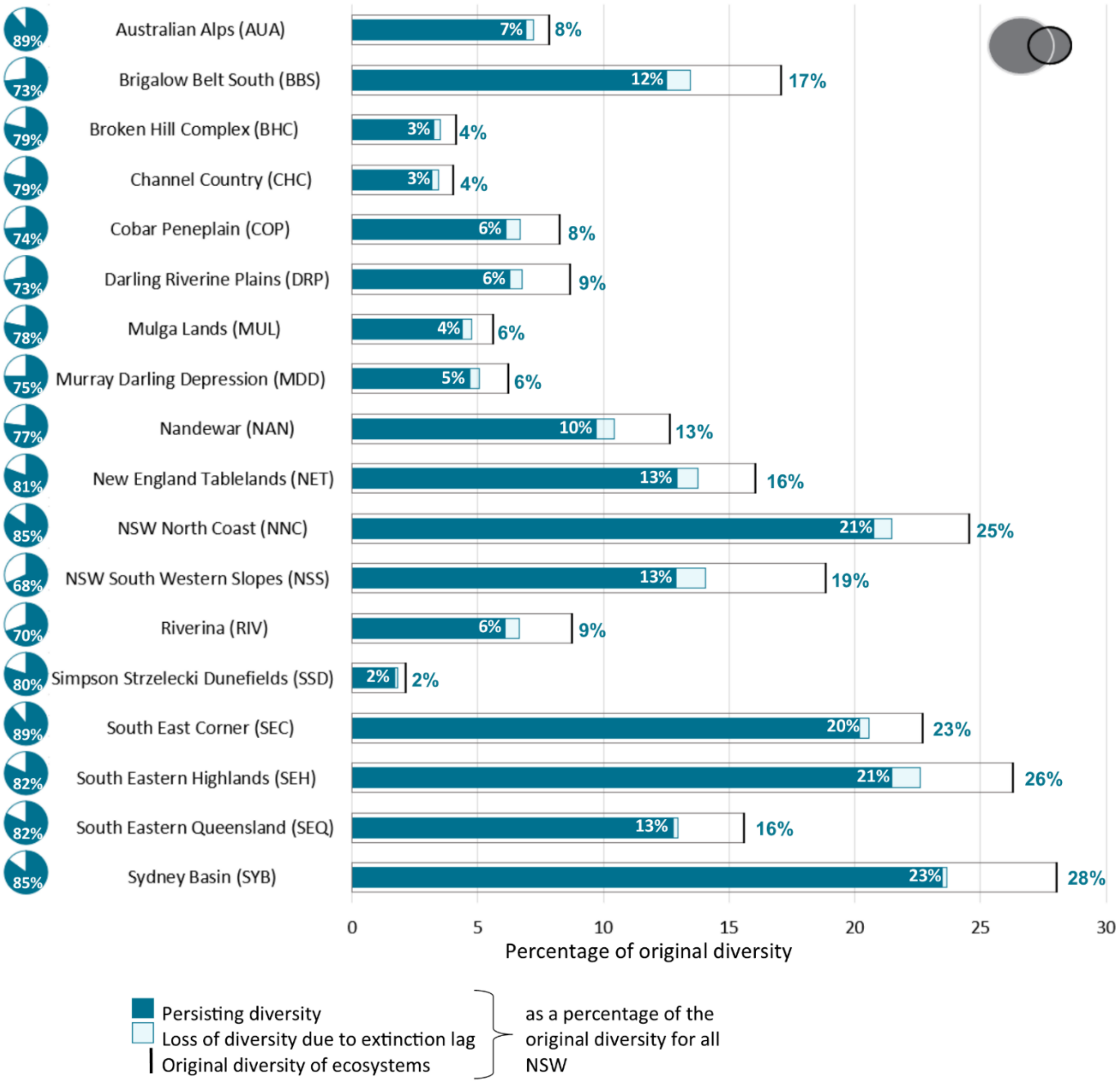


Figure 12 Total plant diversity of bioregions as a percentage of pre-industrial NSW diversity

The pie charts on the left show total plant diversity in each bioregion as a per cent of the region’s pre-industrial level. The bars on the right show total plant diversity in each bioregion as per cent of NSW total diversity. Pre-industrial plant diversity (solid bar on far right and dark number); 2013 ecosystem persistence without extinction lag (dark blue in the left of the bar plus light blue); and including extinction lag (dark blue and white number).

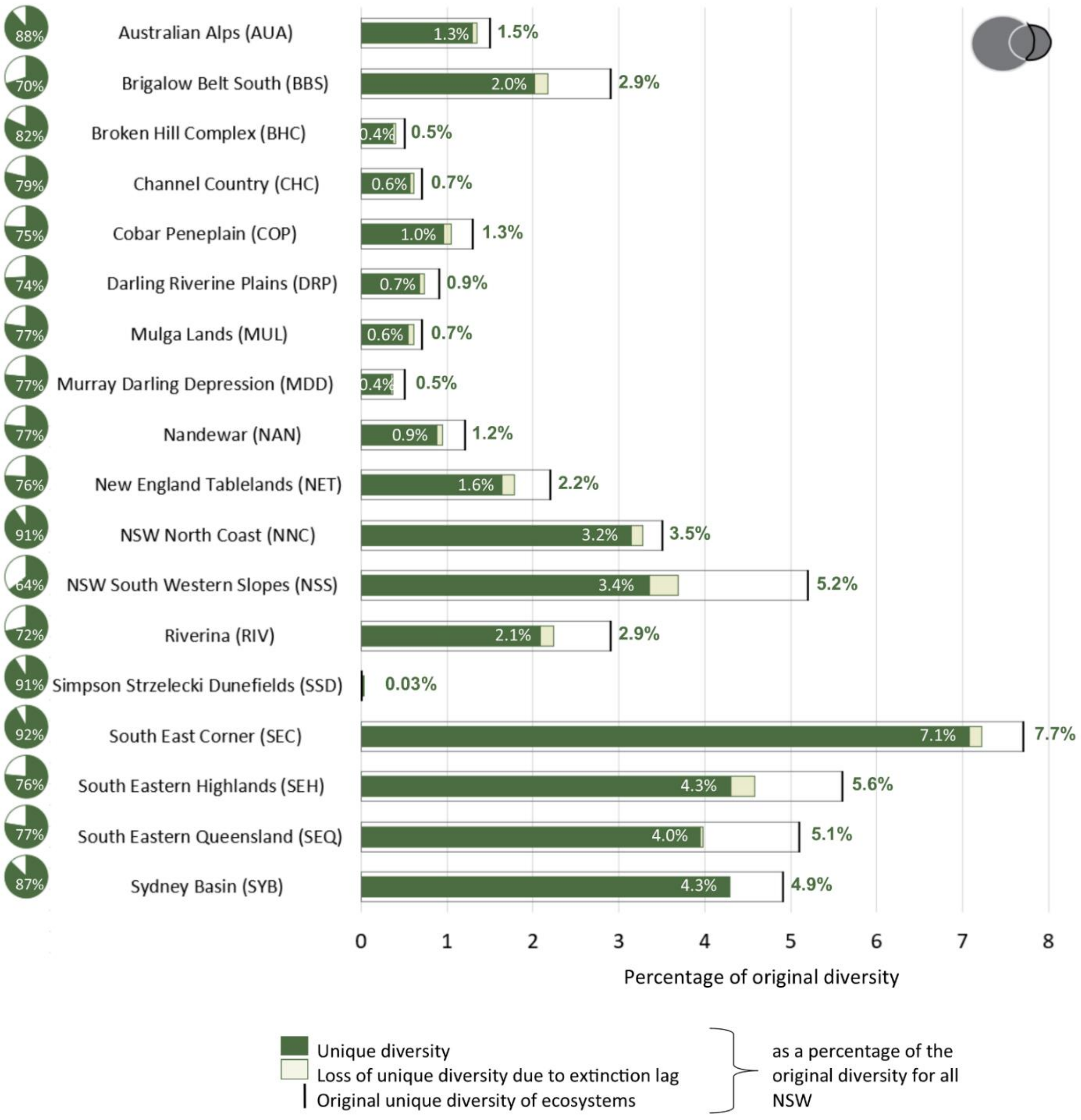


Figure 13 Unique plant diversity of bioregions as a percentage of pre-industrial NSW diversity

The pie charts on the left show unique plant diversity in each bioregion as a per cent of the region’s pre-industrial level. The bars on the right show unique plant diversity in each bioregion as the per cent of pre-industrial NSW diversity. Pre-industrial unique plant diversity (solid bar on far right and dark numbers); 2013 unique plant diversity without extinction lag (dark green in the left of the bar plus light green); and including extinction lag (dark green and white numbers).

Alternative perspective: combined total and unique plant diversity of bioregions

Figure 15 provides an alternative way of communicating the results, showing the total and unique diversity in a single chart for each bioregion. Figure 14 is a key to the chart. Only the lower-bound diversity estimates (see section 2.7 for an explanation) are shown.

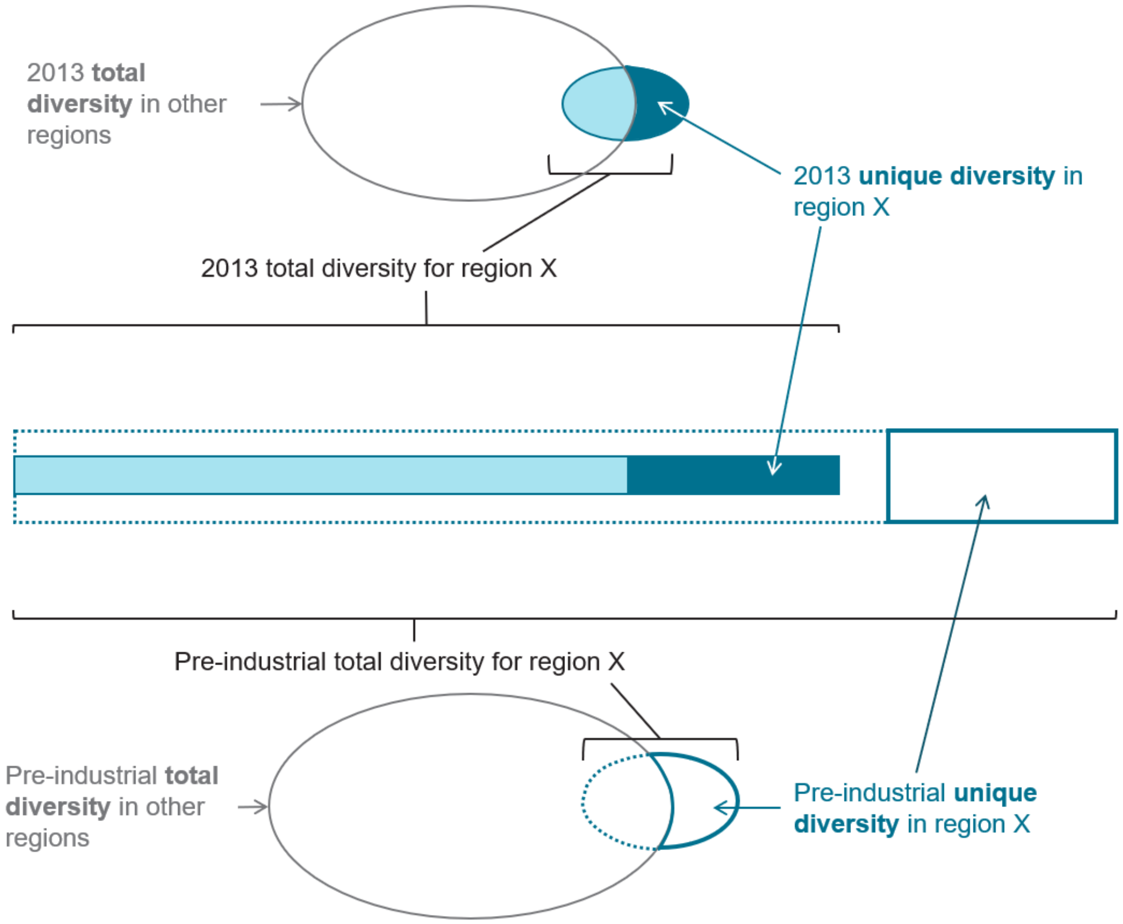


Figure 14 Key to the total and unique plant diversity indicator chart (Figure 14)

Total diversity of all regions is the union of the two ellipses (upper ellipses = 2013 total diversity and lower ellipses = pre-industrial total diversity). Total diversity of region X in 2013 is shown as the filled ellipse, and in the pre-industrial era as the heavy outline ellipse. Total diversity of other regions is the ellipse with the grey outline. For 2013, the dark blue on the right of the ellipses and bar represents unique biodiversity, the light blue on the left of the ellipses and bar represents biodiversity shared with other bioregions.

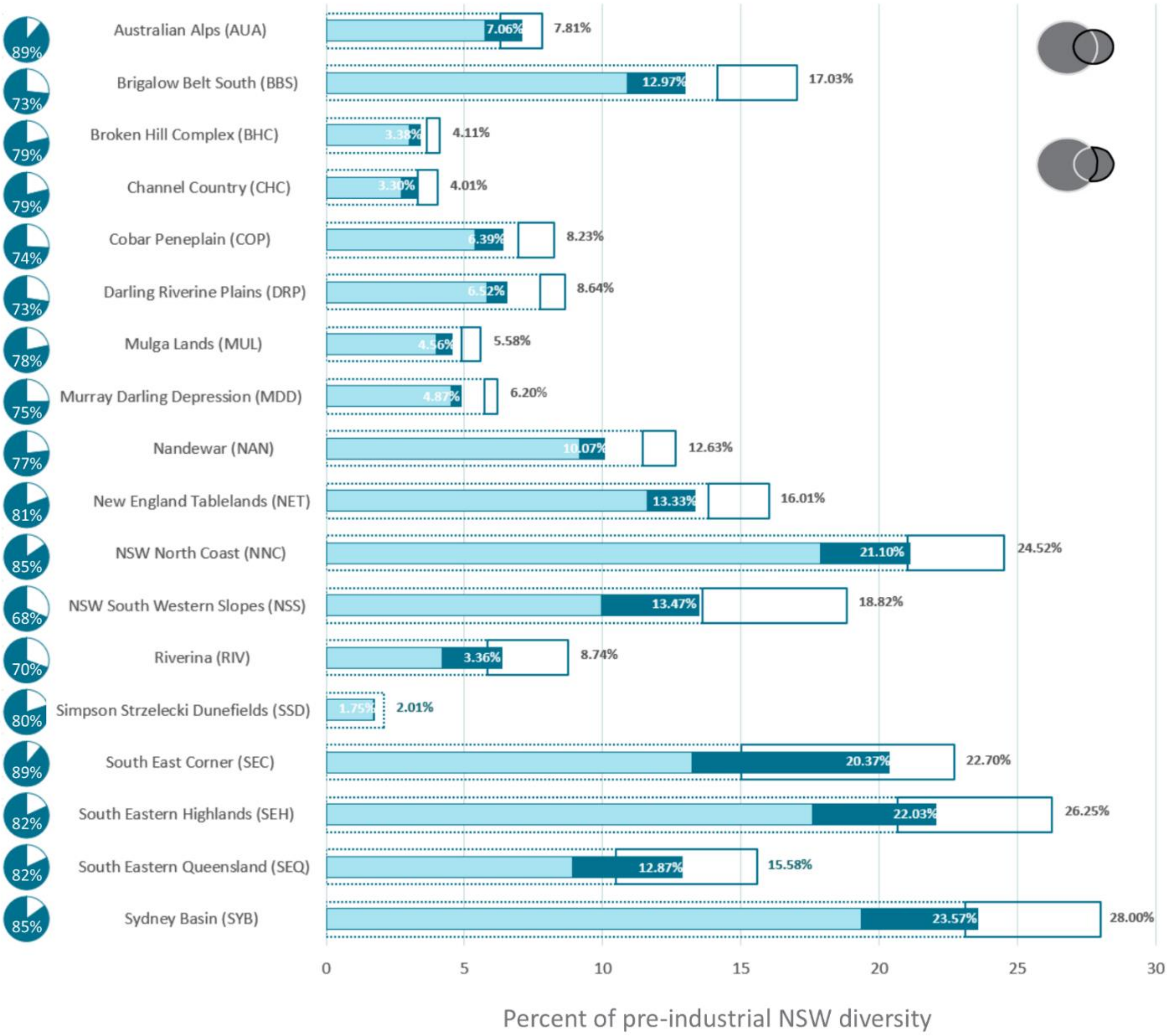
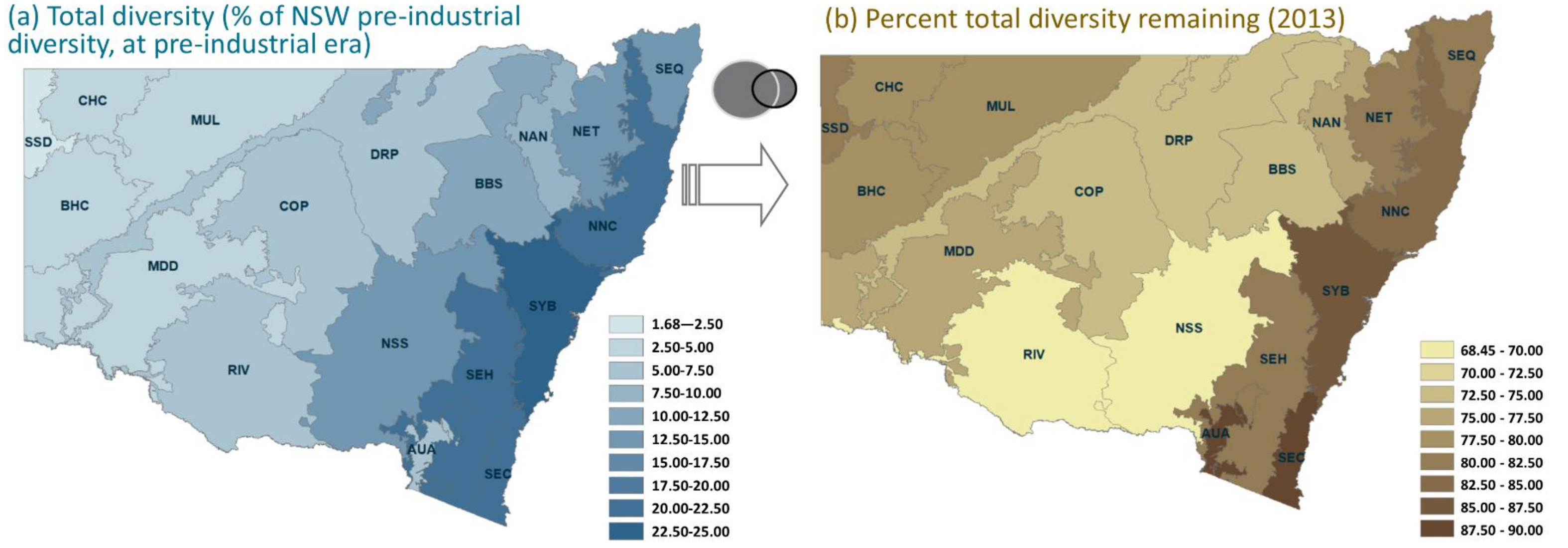


Figure 15 Combined total and unique vascular plant diversity by bioregion, factoring in extinction lag (not showing it as a separate component)

The per cent of the bioregion's original total diversity remaining in 2013 is shown in the pie charts on the left. The bar charts on the right show the per cent of pre-industrial NSW diversity: pre-industrial era (open bars) and 2013 (filled bars), with each bar divided into unique diversity (solid-line open bars and dark blue filled bars to the right) and shared diversity (dot dashed bars and light blue filled bars to the left). See Figure 14 for key.

Spatial mapping by bioregion

Figure 16 shows the distribution of total and unique plant diversity across bioregions for the pre-industrial era and for 2013. The pre-industrial ecosystem, which can be thought of as the inherent or potential plant diversity of bioregions, generally decreases along an east–west climatic gradient. The South Eastern Queensland and South East Corner bioregions both have moderate plant diversity, as shown by the total diversity results; but when their unique diversity across all of New South Wales is considered, they have among the highest values (see Table 1). This is because these regions provide unique plant diversity not well represented anywhere else in New South Wales. The results from these two bioregions highlight the limitations of viewing the state in isolation of its surrounding regions with other jurisdictions. In both cases it is likely that a geographically broader analysis (beyond New South Wales, e.g. the extended NARCliM boundary [OEH 2016]) would find greater representation of the ecosystems found in these bioregions in neighbouring states and territories. However, for this assessment, we have confined the analysis and reporting to how well each bioregion continues to meet its potential contribution to the retention of original ecosystem diversity of New South Wales. The relatively low pre-industrial diversity levels for the Australian Alps Bioregion is probably due to its small area compared to other bioregions.



(a) Total diversity (% of NSW pre-industrial diversity, at pre-industrial era)

(b) Percent total diversity remaining (2013)

(c) Unique diversity (% of NSW pre-industrial diversity, at pre-industrial era)

(d) Percent unique diversity remaining (2013)

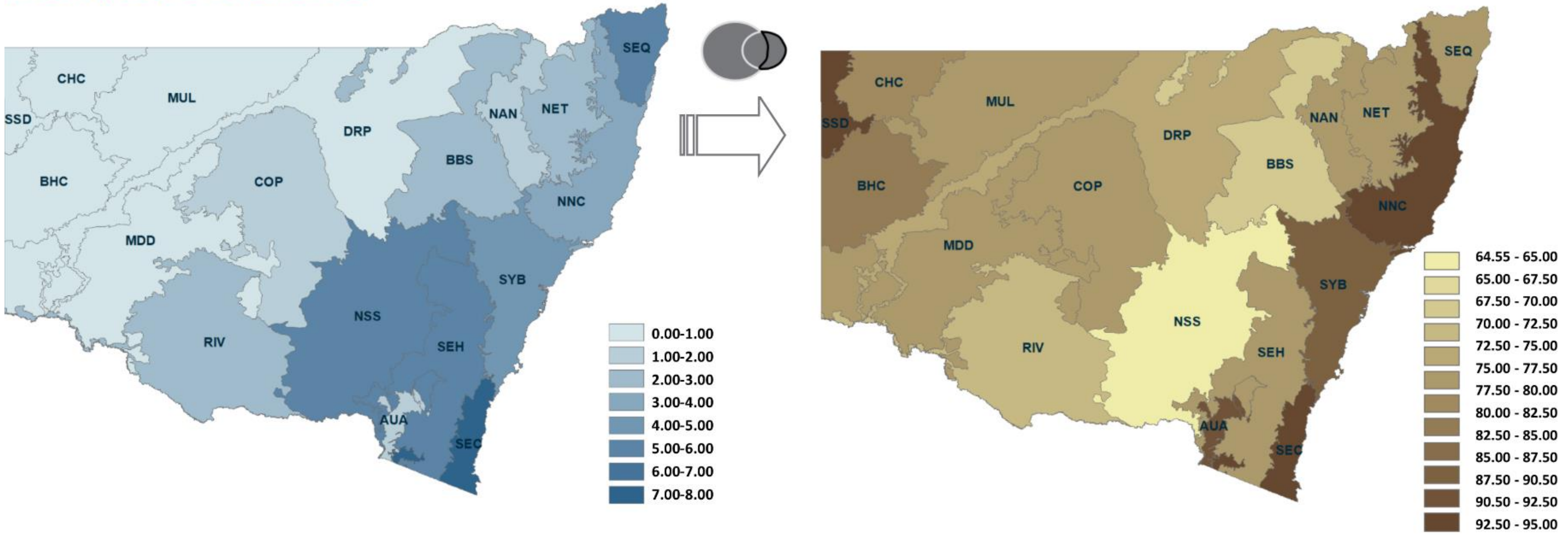


Figure 16 Total and unique vascular plant diversity by bioregion: pre-industrial and at 2013

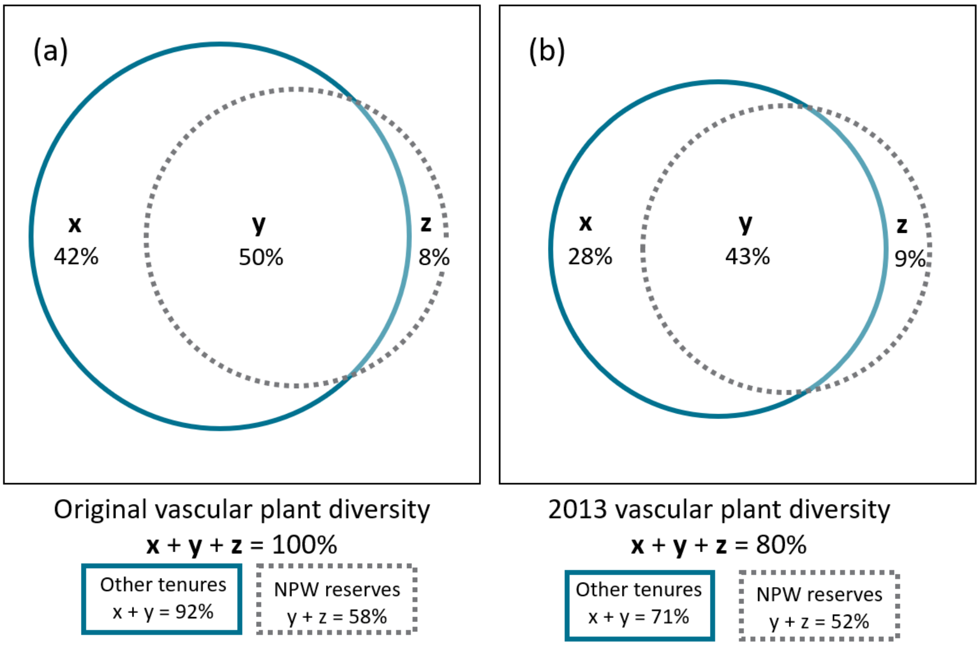
(a) Total diversity shows the percentage of pre-industrial diversity supported in pre-industrial era, by bioregion; (b) shows the per cent of total diversity remaining in 2013; (c) shows pre-industrial unique diversity; (d) shows per cent of unique diversity remaining in 2013.

3.2.2 Ecosystem diversity for NPW reserves and other tenures in 2013

The application of the plant ecosystem persistence reporting framework to NPW reserves and other land tenures is shown in Table 1 and Figure 17. Plant diversity is not confined to, or comprehensively represented in NPW reserves. Other tenures, including private land, continue to support a significant component of NSW's unique biodiversity (Drielsma et al. 2016; Margules & Pressey 2000).

In 2013, the lands currently managed as reserves under the National Parks and Wildlife Act (NPW reserves) contribute disproportionally (by area) to maintaining the pre-industrial total plant diversity of New South Wales. Over half (52%) of the original vascular plant diversity of New South Wales is represented in NPW reserves which cover only about 9% of the state's area. Tenures other than NPW reserves (covering 91% of the state's area) contain over three times the unique diversity found in NPW reserves (28% v's 9%) with extinction lag), but that diversity is spread over an area that is more than 10 times larger. Over 70% of the original vascular plant diversity is found on tenures other than NPW reserves, and around 28% is unique to those other tenures.

The results also show that the unique diversity of NPW reserves has increased as other lands have become disproportionally cleared and their remnant habitat degraded. Both private (though not distinguished here) and public reserves are critical in securing areas where plant ecosystem diversity can persist. This assessment does not factor in differences in threatening processes and management between NPW reserves and other tenures. Remaining diversity within NPW reserves is relatively secure; flora reserves (protected within NSW State Forests) are equally secure; and other forms of protection in the NSW forest estate and privately managed reserves afford varying degrees of security (see Management effectiveness indicator family, DPIE 2020).



Original vascular plant diversity
x + **y** + **z** = 100%

2013 vascular plant diversity
x + **y** + **z** = 80%

Figure 17 Total and unique diversity in NPW reserves and other tenures

The Venn diagrams show indicators for: total diversity (x+y+z); shared diversity (y); and unique diversity for NPW reserves (z) and other tenures (x). Total diversity has declined between the pre-industrial era (a) and 2013 (b), including within areas now reserved (58% to 52%). However, the unique diversity of areas now reserved has increased (from 8% to 9%). Figures used are mid-point between those derived considering and not considering extinction lag.

3.2.3 Ecosystem diversity for Mitchell landscapes in 2013

Total remaining diversity (as a per cent of pre-industrial levels) is mapped in Figure 18 for each of the 572 NSW landscapes. The map reflects the pattern of ecological carrying capacity (i.e. includes extinction lag), with diminished diversity most evident in the central wheat-sheep belt of the state (brown colours); and higher levels of diversity (darker greens) within the Great Eastern Ranges and coastal regions, which often corresponds with a concentration of NPW reserves, state forests and land that is otherwise unsuitable for intensive agricultural development.

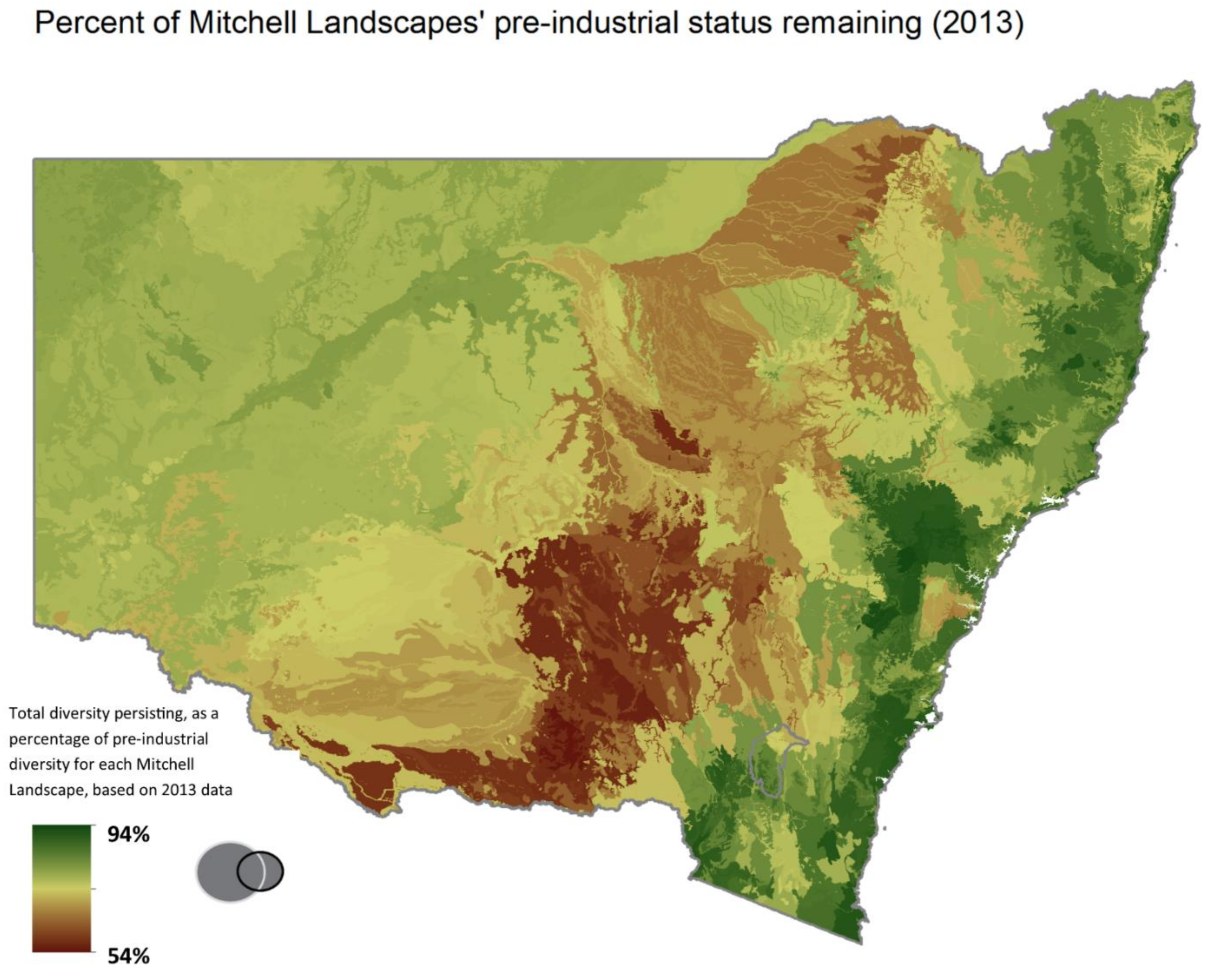


Figure 18 Total 2013 diversity for each Mitchell landscape as a per cent of pre-industrial diversity, based on 2013 ecological carrying capacity

3.3 First assessment: unique diversity mapping

[DD07513 workflow component, Appendix A]

Unique diversity is mapped for each 90 x 90 metre grid cell across New South Wales. The results are presented in Figure 19.

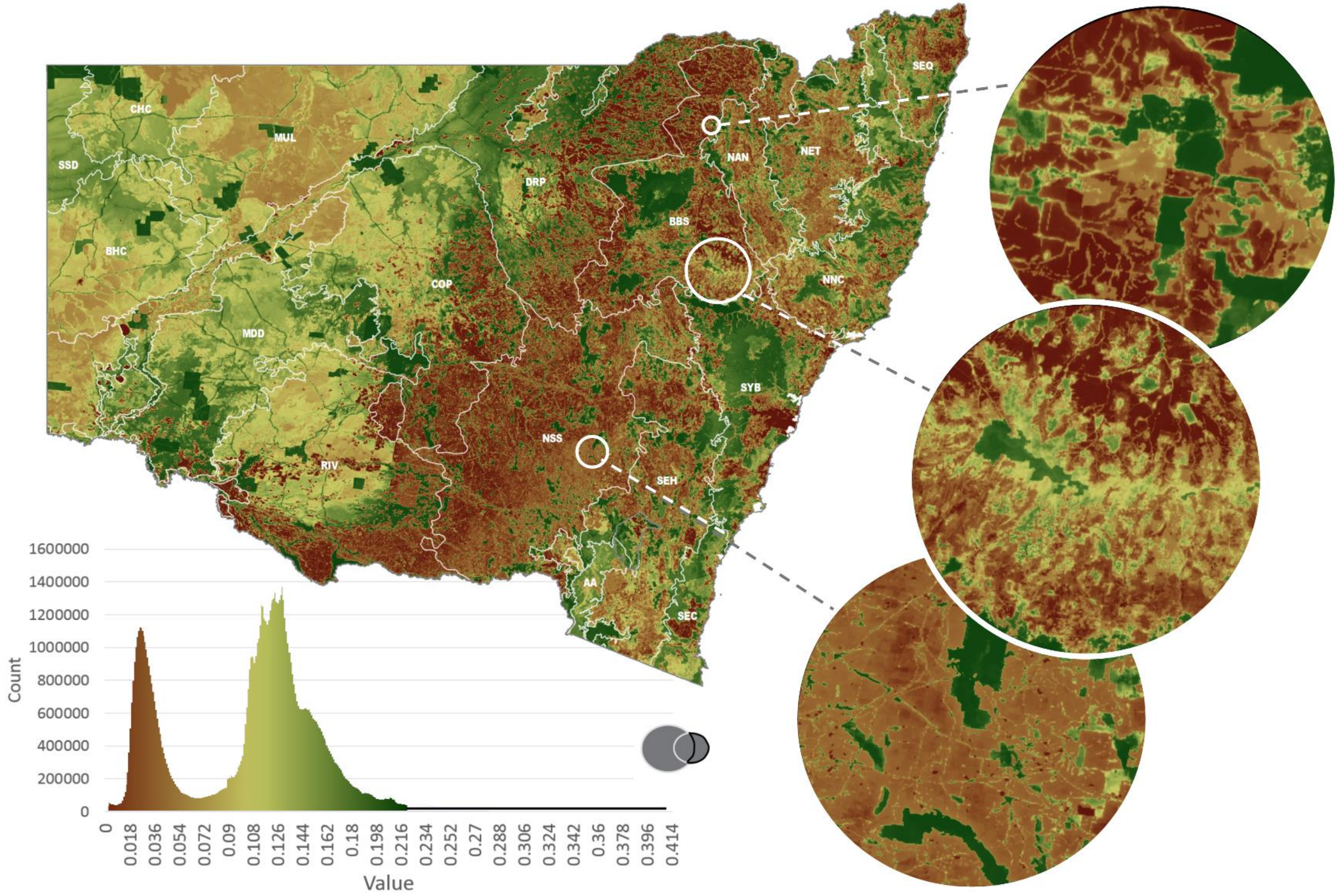


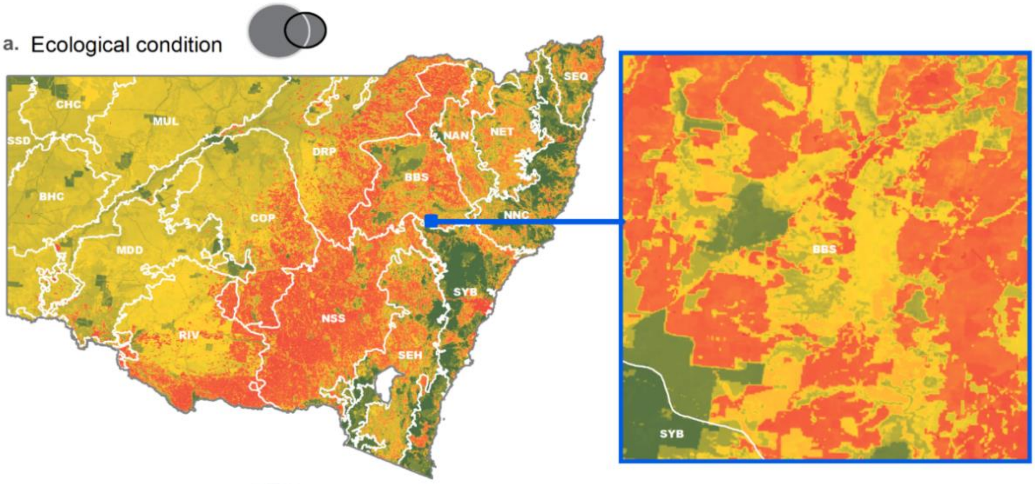
Figure 19 Unique vascular plant diversity mapping of individual 90-metre grid cells in 2013
High levels (green) depict remaining native vegetation of the least conserved ecosystems with high ecological carrying capacity. The histogram shows the distribution of diversity levels across the indicator's numerical range.

Unless there is dramatic change in the quality and distribution of native vegetation between assessments, it will be difficult to detect change in unique diversity in five years when viewing at the broader spatial scale in Figure 19; it is anticipated that change will be more readily detected at finer spatial scales. Individual source datasets from which this map is derived and the high resolution digital image itself are also available. The unique vascular plant diversity map is suitable for viewing and interpretation at c. 1:250,000 scale. More detail can be revealed by ‘zooming in’ and comparing places, and in the future, between epochs (e.g. see insets in Figure 19 and Figure 20).

The accompanying histogram in Figure 19 may also be useful for analysing changes in the distribution of values over time. The 2013 histogram shows three distinct zones from left to right: a cluster of low value sites, mostly associated with the wheat-sheep belt of central New South Wales; a cluster of moderate values made up mostly of sites from the west of the state and the eastern ranges; and a tail of high values representing high quality remnants of largely cleared ecosystems (or ones that share a high proportion of species with largely cleared ecosystems).

Following the schema set out in Figure 4 and Figure 5, ecological condition, which is a closed-system assessment of diversity at a fine (90-metre grid cell) spatial scale, provides the total diversity counterpart to unique diversity mapping at this scale (Figure 20).

a. Ecological condition



b. Unique diversity

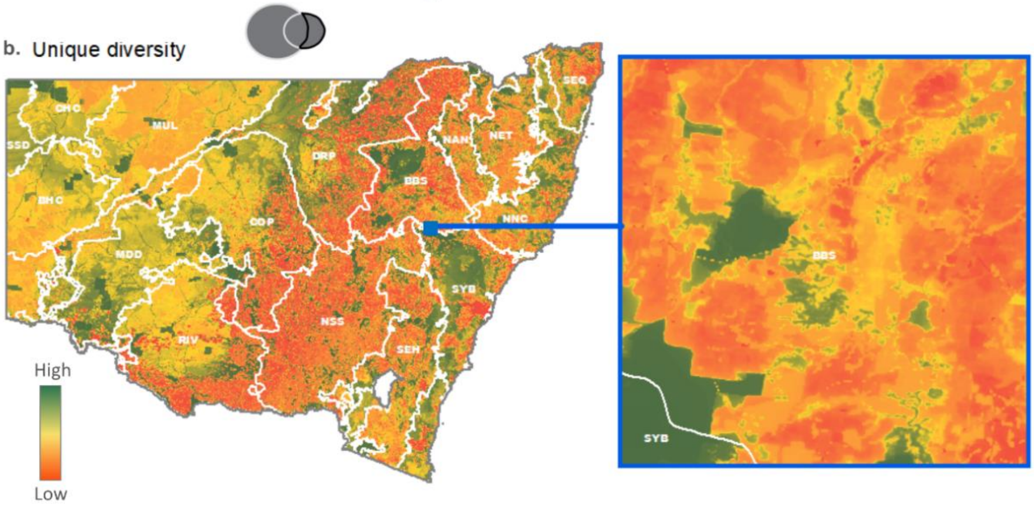


Figure 20 Ecological condition (a) and unique diversity mapping (b)

Unique diversity is the same as Figure 19, but re-coloured. Ecological condition can be thought of as the fine-scale equivalent of total diversity, to complement unique diversity mapping (adapted from Love et al. 2020)

4. Discussion

The results presented here are generally consistent with previous assessments using similar methods (e.g. Drielsma et al. 2012; Drielsma et al. 2017) but draw on improved data inputs and refined methods, and are developed here as a complementary set of indicators.

The assessment quantifies a profoundly complex system of interacting ecological processes in a relatively simple, partial way. Refinement of the model and incorporation of improved data and knowledge is ongoing.

4.1 Future improvements to assessing the indicator

Improvements to the indicator will continue over time, possibly necessitating hindcasting the indicator with newer methods to allow for valid comparisons across time.

Improvements will result from new gap-filling biodiversity surveys, the use of quality-assessed survey data, improved environmental variables, more integrated use of survey sampling methodology and site disturbance covariates, new developments in the statistical application and validation of the generalised dissimilarity modelling method, and new statistical applications in macro-ecological modelling including applications integrating alpha (within site) and beta (between site) diversity.

Work is under way filling knowledge gaps relating to inherent species–area relationships for different ecosystems and rates of decline following initial fragmentation. This will allow more accurate assessment of landscapes in relation to their varying levels of fragmentation.

It is intended that for future assessments of the indicator, the method will be applied to a suite of taxonomic groups for which the model for vascular plants is demonstrated to be a poor surrogate (see Grantham et al. 2010; Ware et al. 2018).

4.1.1 Input data

At the time of the analysis, no statewide, fine-scale consistent classification of ecosystems, other than the GDM-based product, was available. Once the regional ecosystem mapping, broadly founded on the approach of Sattler and Williams (1999), is completed for New South Wales (including a corresponding model of compositional similarity between the regional ecosystems classes), these will supersede Mitchell landscapes for that part of the reporting framework (see section 2.9), potentially offering a single classification for analysis. This would eliminate problems of circumscription that arise due to mismatching boundaries between analysis and reporting.

The GDM model captures compositional components of the floristic survey data. While the floristic survey field data used in the model have been selected to as far as possible represent relatively intact ecosystems, it would imperfectly predict pre-industrial plant diversity. A refined model of compositional patterns that incorporates comprehensive survey data and new suites of 90-metre gridded environmental variables is under development (Mokany et al. in prep.). This refined modelling is expected to result in a step-change in data quality and spatial resolution.

Present-day structural and functional aspects are represented by the habitat condition models (ecological condition and carrying capacity) which are primarily derived from remote sensing of terrestrial vegetation (Love et al. 2020). Habitat condition modelling is subject to several research projects which will lead to continuous improvements to those indicators. For example, land tenure data played a role in predicting the impacts of grazing on ground vegetation. In future assessments, this coarse inference will be replaced with more direct fine-grained measures from remote sensing (Harwood et al. 2016; Tehrany et al. 2017).

4.1.2 Extinction lag

In contrast to other indicators focused on the extinction risk status of biodiversity (see Theme 1, OEH & CSIRO 2019), the family of state of biodiversity persistence indicators (see Theme 2, OEH & CSIRO 2019), including this indicator, takes extinction lag into account. Using the current modelling capabilities, it is less challenging to infer the long-term outlook for diversity across New South Wales (factoring in extinction lag) than it is to estimate current (strictly extant) levels.

Current and projected loss of diversity results from historic disturbances associated with past land use and management. Following direct loss at the time of disturbance, diversity continues to decline, eventually stabilising to predictable levels.

The contemporary status, however, is subject to the specific and collective timing of past disturbances, as well as each ecosystem's responses to these disturbances, both of which are imprecisely known. Thus, with our current knowledge it is not possible to quantify current levels of diversity precisely using an indirect modelling approach. Current diversity estimates are therefore bounded between two sets of results.

A more complete understanding of the unrealised extinction lag, which is the subject of current research, will quantify the potential to avert this loss through timely conservation actions (such as restoration of habitats and connectivity, actively managing threatening processes that degrade habitat, and facilitated species population recovery).

The estimation of the lower-bound indicator (predicting the long-term outcome) could be refined by explicitly including additional threatening processes such as invasions by pest species and pathogens, changed fire regimes and firewood collection, as has been achieved in past regional-scale assessments (Murray CMA & OEH 2012). This would, however, change the nature of the indicator by introducing possible or likely changes to habitat, whereas the current indicator focuses on persistence arising from current conditions.

4.1.3 Species richness

There is potential to include variations in species richness across ecosystems (i.e. giving species-rich ecosystems more weight in the indicator). This would have the effect of aligning the indictor more towards a species-level measure of persistence, with less emphasis on ecosystems as a distinct feature of biodiversity. Again, this could be transitioning the indicator away from its intended focus on measuring extant ecosystem diversity in the method framework (OEH & CSIRO 2019).

Possibly, a more continuous data approach, in contrast to using an ecosystem classification (e.g. Hoskins et al. 2018) will provide useful complementary information, at the species-level of reporting, which is an additional indicator of the state of biodiversity in the method framework (OEH & CSIRO 2019).

4.1.4 Sensitivity of results to the *z* parameter

The choice of the *z* parameter of 0.25 within the species–area relationship (SAR) was based largely on the clear consensus of previous studies. To test the sensitivity of our results to this uncertainty we recalculated the total diversity indicator for all of New South Wales and each bioregion using a range of *z* values reported as plausible (between 0.2 and 0.4). The results of this analysis are provided in Appendix E, and shown in Figure 21.

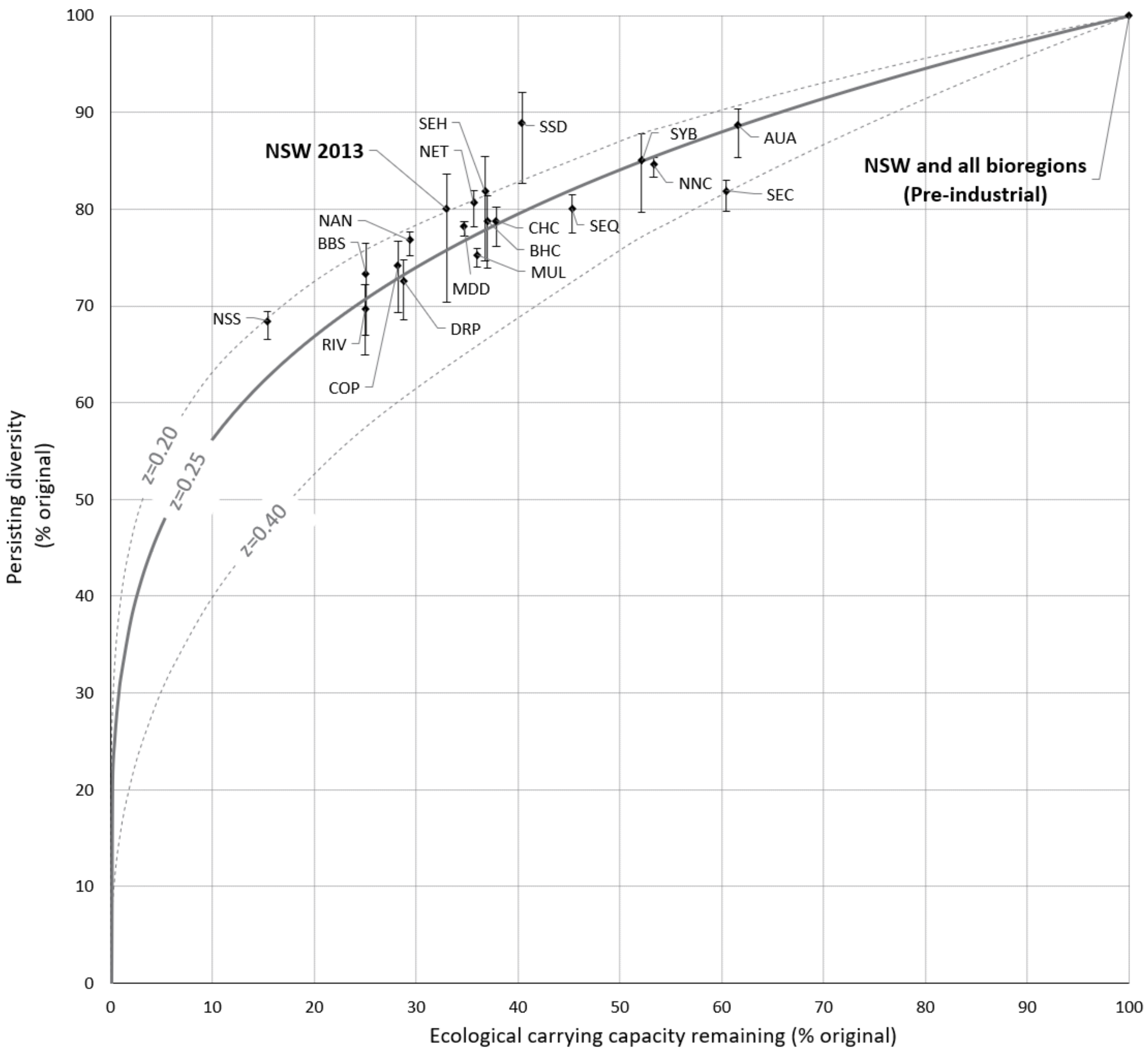


Figure 21 Results of re-analysis of New South Wales and bioregions by applying a range of *z* parameters to the species–area relationship (SAR)

Main value and central (hypothetical) curve based on *z* = 0.25. Range bars indicate results for *z* = 0.2 (upper value) and *z* = 0.4 (lower value). Alternative hypothetical SAR curves are shown for *z* = 0.2 (upper curve), and *z* = 0.4 (lower curve). Estimates include extinction lag. Codes for bioregions can be found in Table 1.

As expected, the choice of *z* value does affect the magnitude of the indicators (by up to 41% deviation from the result for *z* = 0.25). The results for New South Wales as a whole range from 70.3 (when *z* = 0.4) to 83.6 (when *z* = 0.2). The effect on the indicators of varying *z* is consistent in direction (higher *z* always leads to lower indicator), and the order of results (across the bioregions relative to each other) is unaffected by changing the *z* parameter (see Figure 22). However, the uncertainty identified through this analysis varies across the bioregions, as evidenced by the varying size of the range bars. The exact reasons for this variation require further investigation but are likely due to the complex set of interactions involving the location of habitat loss in relation to ecosystem distributions and the compositional overlaps between ecosystems within and between bioregions.

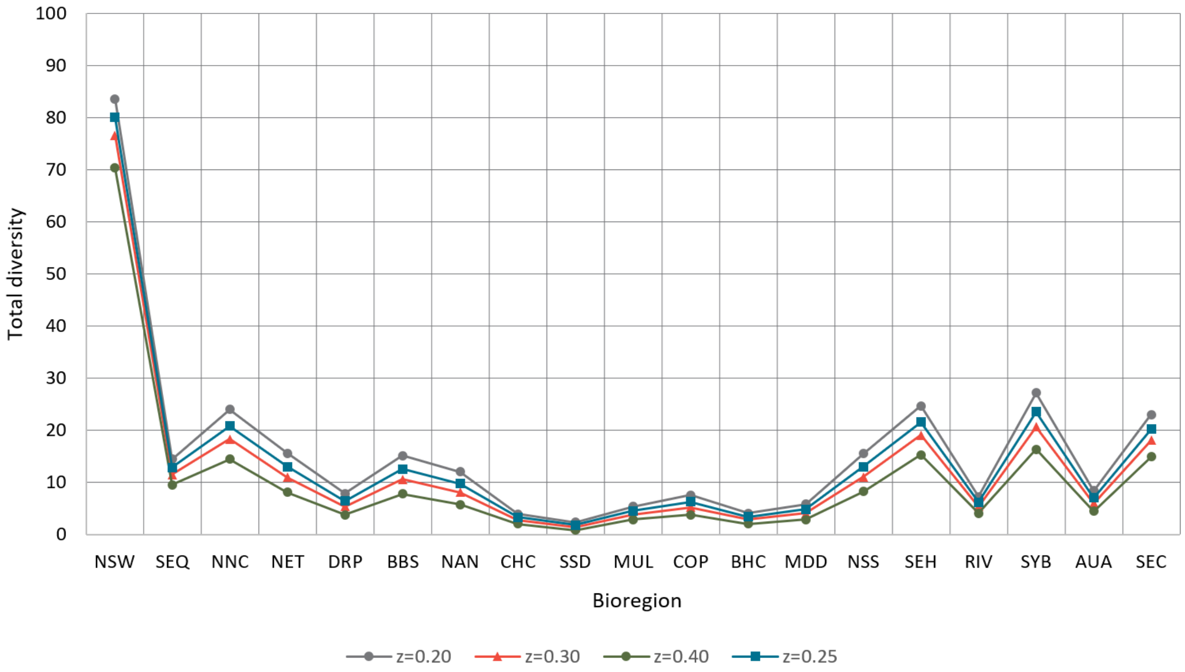


Figure 22 Comparison of alternative *z* values (0.20, 0.25, 0.30 and 0.40)

Uncertainty around the choice of *z* parameter does not preclude the method from ranking bioregions or detecting trends. However, improved parameterisation will improve the 'realism' of the model. Parameters individually tailored for different ecosystems, rather than adopting a global *z* value, could have more significant implications for ecosystem-level reporting, and might lead to re-ordering of bioregions (in terms of proportion of persisting diversity).

4.1.5 Climate change

In this assessment, the type, extent and pattern of (potential) ecosystem distributions was assumed stable from the pre-industrial state, derived using a model that draws on known species occurrence records. This assumption may need to be revisited in order to account for expected distributional shifts arising from climate change (Drielsma et al. 2017; Ferrier & Drielsma 2010). Similarly, ecological condition was assessed based on a data epoch applicable to a 2013 assessment, and is not designed to distinguish between the recent effects of climate change and land use, or other factors that threaten biodiversity persistence. The current assumptions align with the intent of the upper bound of the indicator based on ecological condition, but are likely to have implications for the long-term, lower bound, where extinction lag is considered. This highlights the need to properly interpret the lower-bound values presented here as the long-term equilibrium resulting from current state of habitat. The more realistic consideration of plausible future scenarios including both climate change and continuing land-use pressures will form the basis of ecological integrity indicators that build on the current indicator (Theme 5 indicators, OEH & CSIRO 2019).

Although forecasting climate-induced biodiversity range shifts through modelling is problematic (Sinclair et al. 2010), it is likely that climate change will lead to irreversible losses of diversity, for example in the Australian Alpine Bioregion, where compositional change and diversity losses are inevitable, albeit at a slower rate than in other bioregions (Drielsma et al. 2017; Vanderwal et al. 2014). Interestingly, in conjunction with loss of alpine diversity, climate change could drive increases in diversity in montane regions as species and ecosystems from other regions are driven to concentrate in the relatively cooler, wetter environments provided there (Steinbauer et al. 2018; Thapa et al. in review).

4.1.6 Reporting regions

In relation to the tenure analysis involving NPW reserves and other tenures, the analysis provides a narrow view of public reservation tenures. There are other forms of reservation not included in this assessment, for example flora reserves and private conservation reserves. Other reporting units (e.g. by all reserve types and by IUCN conservation management category) could be adopted in future assessments of the indicator. This indicator, and the Habitat condition indicator family are currently being assessed for the Gondwana Rainforests World Heritage Area.

In future, assessments of other regions like Local Land Services regions could be undertaken. Calculations of the indicator for Mitchell landscapes may be superseded with newly developed regional ecosystem mapping.

4.2 Surrogacy value of indicator

The method presented here (Drielsma et al. 2014b) has been developed as a way of reporting on the persistence of all species diversity, using ecosystems as a surrogate. In the current application, the method has been adapted to report on the extant diversity of ecosystems, using species-level information; in this case based on vascular plants, with similar applications for other taxonomic groups to be derived in the future.

Vascular plants are generally considered to be a useful surrogate for other plant groups (Pharo et al. 1999) and some fauna (Ferrier & Watson 1997; Sætersdal et al. 2004), especially when ecological connectivity is considered. In the absence of a more comprehensive assessment encompassing other taxonomic groups, vascular plants are often used as a surrogate for biodiversity generally (e.g. Drielsma et al. 2012; Drielsma et al. 2017). It is intuitive that when all other variables are held constant, larger, more intact vascular plant–defined ecosystems will support an expanded suite of taxa, including plant and fauna species whose habitat requirements often (but not always) correlate with ecosystem distributions.

The efficacy of vascular plants as surrogates for other biological groups is untested here but will be addressed in future applications, following aspects of the approach developed by Ware et al. (2018).

It is feasible to extend this indicator to other taxonomic groups, but a single indicator, based on a proven surrogate, or through combining results from different taxonomic groups, would also be useful.

4.3 Implications for management

4.3.1 Flexibility for management

In the relatively intact and well-conserved eastern part of New South Wales (e.g. the NSW North Coast Bioregion), individual localities provide modest unique diversity to the whole of the state; but collectively these same bioregions have high levels of unique diversity. Under these circumstances, there is some flexibility with respect to management as any localised disruptions will cause limited permanent damage, from this plant ecosystems persistence perspective. From this limited perspective, disruptions can more easily be offset with improvements elsewhere within the region, potentially resulting in no net loss to statewide diversity (Drielsma et al. 2016). In the heavily cleared central part of the state (e.g. the NSW South Western Slopes), where unique diversity has been severely depleted at the bioregional level, nearly all remnant vegetation has high unique diversity levels (even though parts might be in poor condition and occur in small and isolated patches). In these cases, there is less flexibility for management, as each remaining patch of habitat has a greater role in maintaining NSW’s biodiversity and any further degradation of remnant habitat is increasingly likely to lead to irreversible loss (e.g. species extinctions).

In order to avoid accelerated loss of diversity, extra caution is needed in the most habitat-depleted regions when considering land-use changes that reduce the extent, quality or connectedness of native vegetation. As regions move toward a situation of precipitous extinction (toward the origin on Figure 21), the biodiversity occupying the remaining habitat becomes increasingly irreplaceable. Highly habitat-depleted areas are also at heightened risk of catastrophic biodiversity loss resulting from stochastic natural events (such as fire, storms and drought), so additional caution is necessary in managing these valuable remnant ecosystems.

4.3.2 Prioritisation

This indicator is fit for reporting on broad-scale changes in biodiversity across New South Wales and is informative for directing policy at this scale. It is also suitable for *inclusion* into conservation planning and prioritisation, especially at regional scales. The information presented here is not suitable, on its own, for detailed planning or for local decision-making, especially where the legal, financial or conservation risks associated with an ill-informed decision are high (Funtowicz & Ravetz 2008; Haag & Kaupenjohann 2001).

At the broadest spatial scales, the indicator informs overall trends. If society’s aim is to retain all remaining diversity, any trend toward further loss at the state level should prompt remedial action. The unique diversity indicators provide information on where elevated conservation benefits can be attained through conservation action, but not the feasibility or cost of taking actions. However, the data is in a form that can be combined with cost information where it is available, for example, to produce a benefit to cost ratio surface.

Insight into areas where conservation benefits may be realised are provided by unique diversity mapping. Restoration benefits mapping has been updated in the course of undertaking this project, though not reported here as part of the indicator (but see Drielsma et al. 2014b for description). Ecological connectivity (Love et al. 2020) also further guides where remnant habitat linkages are important candidates for management and restoration.

Unique diversity is mapped for a range of spatial scales, including statewide, bioregions and locations. From this set of products, there is a choice of spatial aggregation suited to informing a range of conservation activities, spanning broad government programs through to actions by community groups, industry and individuals.

Prioritisation will usually benefit from combining complementary data from a range of sources, including local knowledge and non-biodiversity considerations. In some cases, it will provide added detail to broader national and international frameworks, for example, *Australia’s Strategy for the National Reserve System* (Commonwealth of Australia 2009); enabling prioritisation at bioregional and subregional scales, while also reporting against mandated or aspirational representation targets (e.g. Williams et al. 2016).

4.3.3 Vulnerability

The species–area relationship (SAR), applied (with exponent $z = 0.25$), is used here to describe the non-linear relationship between ecosystem diversity remaining and ecological condition and carrying capacity remaining. Any loss in diversity equates to some level of species extinctions and or consequential loss of within-species genetic diversity. However, due to the non-linear nature of the relationship, at the whole of New South Wales and bioregional scales, diversity levels have largely been buffered from precipitous extinctions based on this 2013 assessment, despite relatively high levels of past habitat depletion at local scales (Love et al. 2020).

The relative position of each reporting region in relation to a hypothetical SAR is illustrated in Figure 23. These results show that in 2013, all NSW bioregions and New South Wales are placed on parts of the curve with a slope of less than 1; meaning that based on the 2013 habitat condition data, incremental changes to ecological carrying capacity will lead to proportionally less change to plant ecosystem diversity. The more intensively cleared bioregions, such as the NSW South Western Slopes (NSS), Brigalow Belt South (BBS) and Riverina (RIV) appear on a steeper part of the curve. Their position can be likened to being on a precipice of change (approaching >1 slope on the curve, which happens when ecological carrying capacity falls below around 20% of the original level). If they reach that point, any further reduction in ecological carrying capacity will lead to proportionally greater loss in the plant diversity persisting in those regions. With a slope of 0.94, the remaining ecosystem persistence of the NSW South Western Slopes (NSS) suggests greater sensitivity to further changes in ecological carrying capacity. The Australian Alps (AUA) appears to be least sensitive.

Added caution is, however, necessary. The smooth (albeit non-linear) relationship between ecological carrying capacity and persisting plant ecosystem diversity employed here may prove misleading, as highly localised biodiversity hotspots may not be detected in the GDM model, and declining ecosystems are prone to tipping points (Scheffer et al. 2012) which cannot be reliably predicted, and which can result in abrupt irreversible ecological collapse (Carpenter et al. 1999; Hutchings & Reynolds 2004).

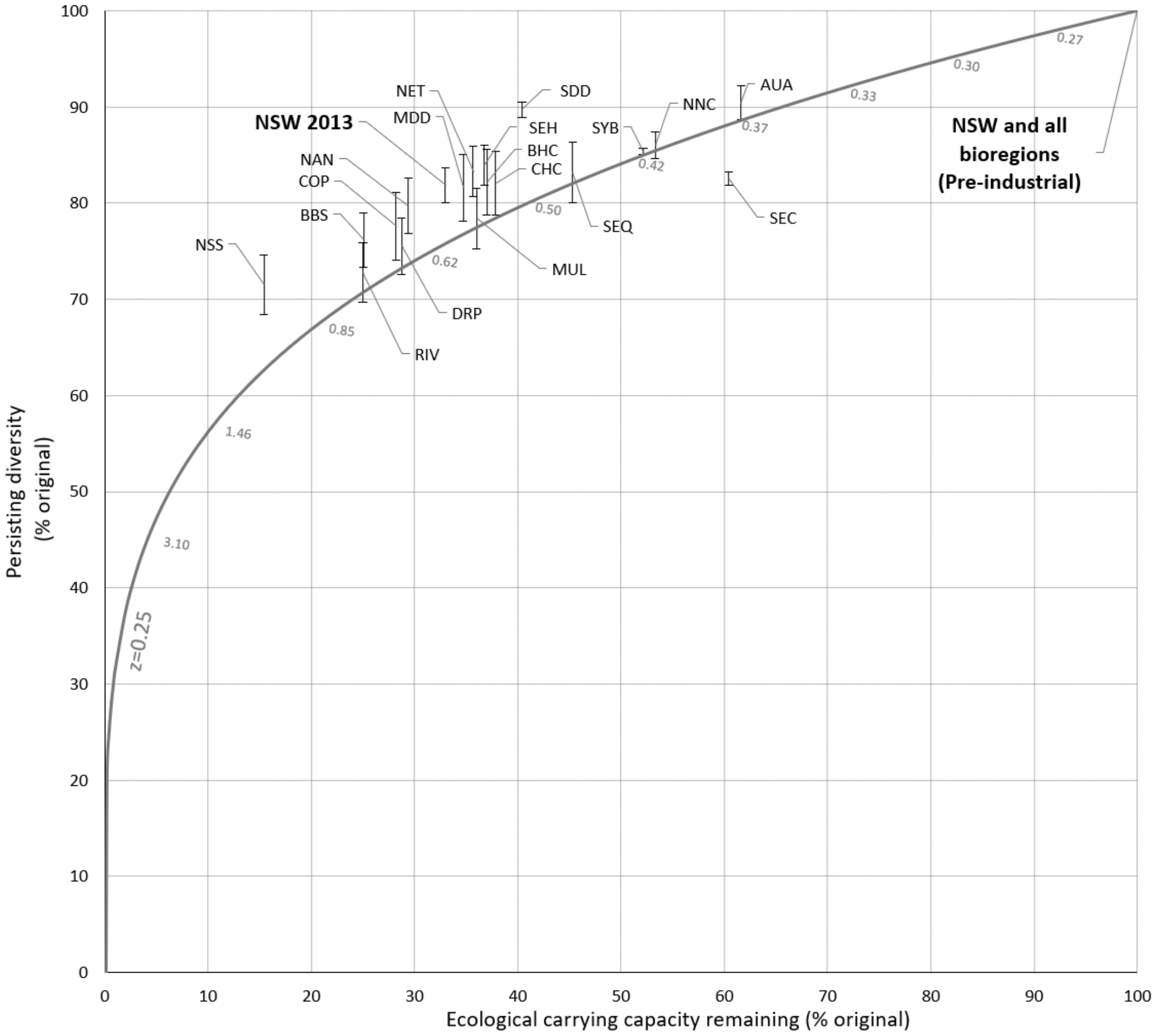


Figure 23 Proportion of remaining ecosystem persistence plotted against ecological carrying capacity

Without extinction lag included (upper bound) and with extinction lag (lower bound). Slopes are shown along the length of the assumed species–area relationship (SAR) curve ($z = 0.25$).

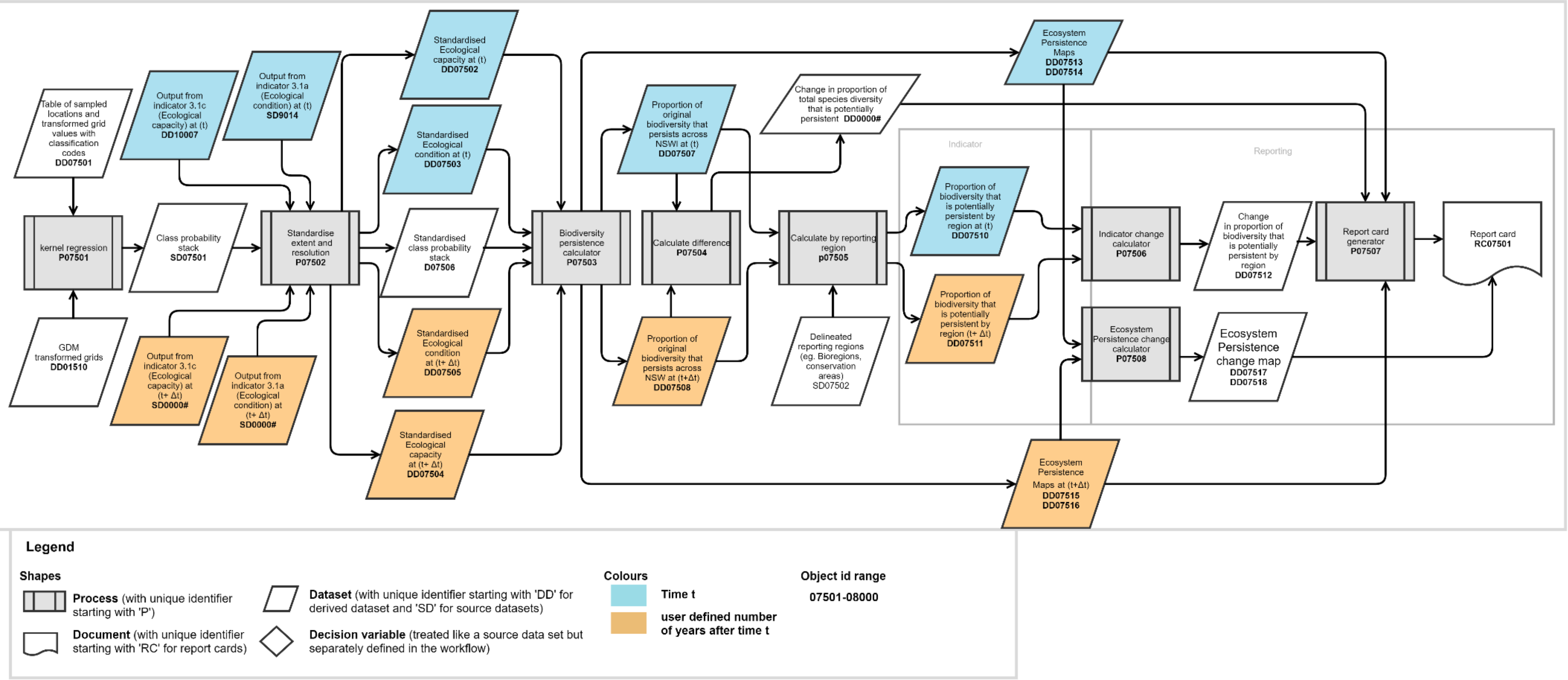
4.4 Conclusion – future assessments of the indicator

This indicator provides indirect measures of ecosystem persistence at the locality, reporting region and state scales. It utilises understandings of how the persistence of pre-industrial ecosystem diversity depends on the remaining extent, condition and connectedness of ecosystems, and the degree of compositional overlap between ecosystems. The indicator relies on the habitat condition family of indicators, ecological condition and carrying capacity, and as those measures improve or change over time (including incorporating historical data), so will this indicator.

This report describes the initial assessment of the indicator. It reports on the state and outlook of ecosystem diversity in 2013, proximal to the commencement of the BC Act in 2017. The indicator will be recalculated to clarify a 2017 baseline (the time immediately before commencement of the BC Act), and subsequently at maximum intervals of five years (or whenever the ecological condition indicators are updated).

Appendix A Workflow for calculating vascular plant ecosystem persistence

Workflow for producing the persistence of ecosystems using vascular plants indictor, including repeated calculation of indicator in five years. This report does not include the lower region of the flow chart that describes calculating change in five years, but does calculate change between the pre-industrial era and 2013. (See larger view.)



Appendix B Key assumptions for calculating vascular plant ecosystem persistence

Area	Description
General	The indicator estimates the remaining ecosystem diversity likely to persist into the long-term future, based on habitat condition data centred at 2013 (subject to currently available data). It does not attempt to forecast future changes in ecological carrying capacity or distributional shifts due to climate change.
Ecosystem classes	Each ecosystem class is approximately equally positioned in biotically scaled environmental space, as determined by the model of biodiversity pattern and an unsupervised classification of the predicted patterns.
Pre-industrial reference state	The pre-industrial era is used as the reference state for the maximum ecosystem diversity, and the levels of diversity are predicted using a model of biodiversity pattern that has been derived using samples of species composition from the most intact examples of ecosystems. Pre-industrial refers to the time before indigenous land use was displaced with European farming practices. This process began in New South Wales after colonisation by Europeans in 1788 and continued into the modern era. Also referred to as ‘original’.
GDM model	The model used species presence-absence data. Therefore, structural distinctiveness is subordinate to composition i.e. the distinction between a snow-gum woodland with shrubby understorey and a subalpine shrubland may not be apparent within the model.
Equal value of ecosystems	The indicator values each ecosystem class equally in its pre-industrial state, that is, each class is assumed to have originally supported equal amounts of diversity. In the contemporary situation, these levels are moderated due to reductions in ecological carrying capacity in the industrial era, which reduces the proportion of original composition of species that can be supported.
Scale of analysis	Each grid cell is assigned a probability of supporting each ecosystem class. This can be interpreted as a way of considering the combined effects of uncertainty as to which class occurs at each 6.25-hectare grid cell, as well as the possibility of multiple classes occurring within the grid cell. Thus, a pseudo-continuous surface of species compositional turnover is employed.
Ecological condition	Assumed to be at the maximum level in the pre-industrial era. Therefore, assumes indigenous land management was sympathetic to persistence of biodiversity.
Habitat connectivity	Connectivity is calculated using the ecological carrying capacity method. It is a generic approach that assesses each cell in terms of its connectivity to neighbourhoods at multiple scales that does not reflect like-to-like connectivity (with a single ecosystem).
Climate change	Climate change is not considered explicitly. Any changes to condition arising from climate change will be captured along with other changes. Climate is assumed in equilibrium based on the 1990-centred 30-year average used in the model of biodiversity.
Climate scenarios	Changes in the distribution of ecosystems due to climate change is not part of this analysis. It is, however, an explicit consideration in the ecosystem integrity theme of indicators, through the concept of spatial resilience, which is under development.

Area	Description
Species–area relationship (SAR)	A SAR with $z = 0.25$ is assumed across all ecosystems. This assumption of constancy is reasonable given the model-based approach to the classification of **ecosystems** which aims to equally represent compositional turnover rates. However, if ecosystems vary in rates of turnover, different z factors may apply. The choice of parameter/s will be reviewed with the next run of the assessment.
Networks	Each ecosystem is assumed to be a semi-connected network with species shared across multiple ecosystems. Effective habitat area (or ecological carrying capacity) is used with the SAC to determine remaining diversity, while considering degrees of compositional overlap in species across ecosystems.
Extinction lag	Extinction lag is assumed to play out over an unspecified time since the time of clearing, which varies across space and is undefined. Thus, remaining diversity is assumed to lie between that expected from loss of habitat alone (upper bound) and that expected from loss of effective habitat area. Temporal mapping of land-use change will inform future extinction lag parameters.
Analysis granularity	The analysis was undertaken using model-based ecosystem surfaces with 250-metre grid cell resolution. Ecosystem carrying capacity was at 90-metre grid cell resolution. A revised model of vascular plants is being developed at 90-metre resolution for the next assessment of the indicator.

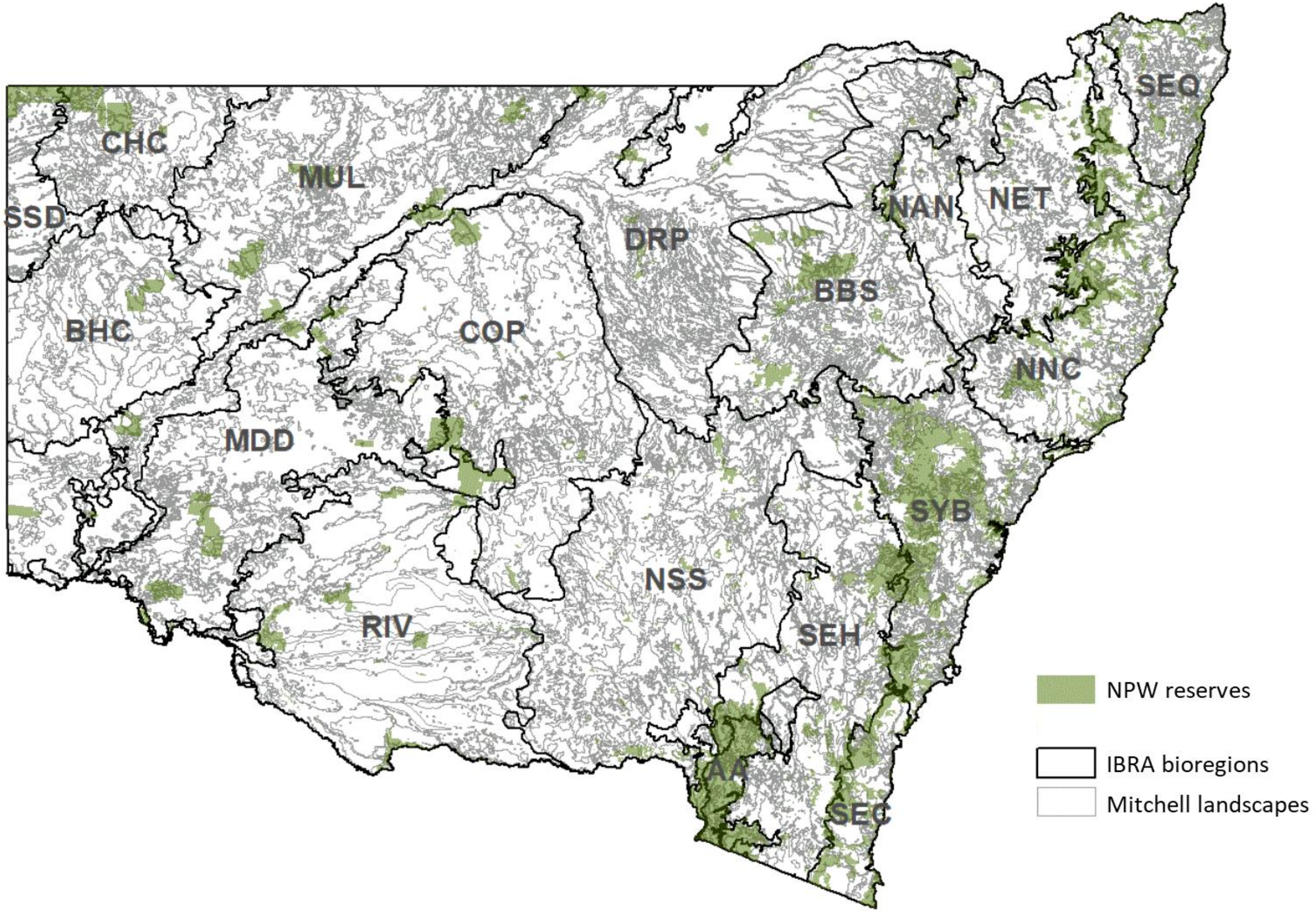
Appendix C Environmental predictors used in the GDM model

(Viscarra-Rossel et al. 2011 [2], Gallant et al. 2011 [3])

Temperature	Precipitation
Temperature Seasonality (Coefficient of Variation)	Precipitation Seasonality (Coefficient of Variation)
Temperature Annual Range (P5-P6)	Precipitation of Wettest Quarter
Mean Temperature of Warmest Quarter	Precipitation of Warmest Quarter
Mean Temperature of Coldest Quarter	
Radiation	**Moisture**
Highest Period Radiation	Annual Mean Moisture Index
Radiation of Driest Quarter	Highest Period Moisture Index
Radiation of Warmest Quarter	Mean Moisture Index of Warmest Quarter
Radiation of Coldest Quarter	Mean Moisture Index of Coldest Quarter
Seasonality	**Landform/Substrate**
Maximum Temperature – Monthly Maximum Temperature	Spectra of surficial topsoils 0–20 cm – PC1_20 [2]
Minimum Annual Temperature – Monthly Minimum Temperature	Spectra of surficial topsoils 60–80 cm – PC2_80 [2]
Annual Evaporation – Maximum Monthly Evaporation	Spectra of surficial topsoils 60–80 cm – PC3_80 [2]
Annual Solar Radiation – Monthly Maximum Radiation	Elevation focal range within 1000 m [3]

(Source: OEH 2016)

Appendix D Map of reporting regions



Appendix E Sensitivity of results to the z parameter

Lower-bound total diversity results (based on ecological carrying capacity analysis) for all of New South Wales and by IBRA bioregion, for alternative SAR constants: *z* = 0.2, 0.25 and 0.4. All figures are per cent of pre-industrial diversity remaining.

Reporting region	Short name	Ecological carrying capacity %	Per cent of total diversity remaining (lower bound) *z* =0.25	Per cent of total diversity remaining (lower bound) *z* =0.2	Per cent of total diversity remaining (lower bound) *z* =0.4
All NSW	NSW	33	80.02	70.33	83.61
Australian Alps	AUA	61.61	88.66	85.32	90.30
Brigalow Belt South	BBS	25.07	73.33	66.95	76.50
Broken Hill Complex	BHC	36.99	78.80	73.89	81.41
Channel Country	CHC	37.87	78.80	76.18	80.19
Cobar Peneplain	COP	28.23	74.12	69.31	76.64
Darling Riverine Plains	DRP	28.76	72.59	68.53	74.81
NSW South Western Slopes	NSS	15.43	68.45	66.51	69.41
Mulga Lands	MUL	34.73	78.18	77.22	78.73
Murray Darling Depression	MDD	36.00	75.25	73.99	75.89
Nandewar	NAN	29.40	76.81	75.13	77.64
New England Tablelands	NET	35.69	80.66	78.20	81.96
NSW North Coast	NNC	53.32	84.60	83.26	85.29
Riverina	RIV	24.99	69.68	64.93	72.17
Simpson Strzelecki Dunefields	SSD	45.33	80.07	77.55	81.47
South East Corner	SEC	40.42	88.94	82.62	92.04
South Eastern Highlands	SEH	36.77	81.82	74.66	85.46
South Eastern Queensland	SEQ	60.44	81.90	79.78	82.96
Sydney Basin	SYB	52.15	85.03	79.72	87.82

Glossary

Note: Terms in italics are also defined in the glossary.

Benefits mapping: Map derived using the *Terrestrial Biodiversity Forecasting Tool*, where each cell value represents its value to regional biodiversity persistence in relation to a conservation action, usually maintain by managing for threats, or restoration.

Biodiversity indicator: A measure of the expected *biodiversity persistence* into the future.

Bioclimatic range shifts: Changes in the distribution of ecosystems due to climate change.

Biodiversity persistence: The maintenance of the variety of life.

Bioregions: 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.

Bray Curtis similarity: Used to quantify the differences in species populations between two different sites. In a similarity index, a value of 1 means that the two communities you are comparing share all their species, while a value of 0 means they share none.

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.

Closed systems: A system that is uninfluenced by external factors e.g. within a confined geographic boundary.

Compositional similarity: A value between 0 and 1, where 0 denotes no species held in common between two ecosystem classes; and 1 denotes complete *compositional overlap* between the classes (i.e. they are essentially the same class).

Compositional overlap: The species held in common between two classes.

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

Diversity: A measures of the variety of species or other taxa that considers both the number of species and their relative abundance.

Ecological carrying capacity: Indicator 3.1c: ecological carrying capacity of terrestrial native vegetation. This indicator is a combined measure of a location’s ecological condition and how well it’s connected with surrounding habitat and can be reported for individual locations and regions including the whole of New South Wales. It estimates the intactness and naturalness of terrestrial habitat for supporting biodiversity and considers how connectivity with surrounding habitat enables biological movement such as foraging, dispersal and migration across multiple ecological scales. It is used to account for the carrying capacity of locations and regions to support their original complement of biodiversity and ecosystems.

Ecological condition: Indicator 3.1a ecological condition of terrestrial native vegetation. This indicator is a measure of the quality of habitat at each location and can be reported for individual locations and regions including the whole of New South Wales. It estimates the intactness and naturalness of terrestrial habitat without considering the indirect effects of surrounding habitat loss and fragmentation.

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

Ecosystem classification: A classification of a biological taxa, where ideally each class is equally spaced in environmental space.

Ecosystem distribution: The geographic extent of an *ecosystem*.

Ecosystem resilience: The capacity of an ecosystem to recover from shocks, such as fire, flood and clearing.

Ecosystems: A dynamic complex of vegetable, animal and microorganism communities and their non-living 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 in tropical seas.

Effective habitat areas: The proportion of residual habitat quality at a site following the impacts of clearing, degradation and fragmentation at the site and in its neighbourhood. Also known as **ecological carrying capacity**.

Emergent properties: Properties of a system of numerous components that are not evident from the components themselves

Entities, biological: *Species* and *ecosystems*.

Exponent: A quantity representing the power to which a given number or expression is to be raised.

Extinctions: No longer living. Usually refers to a species, locally (no longer occurring in a locality region) or globally (the species no longer occurs anywhere).

Extinction lag: The temporal process whereby species are on a trajectory towards extinction due to insufficient access to resources or other threatening processes. The population declines slowly due to its longevity, or while conditions allow.

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.

Grid cell: A grid cell is a location on a map layer or raster dataset that has a value representing some characteristic of that location.

Generalised dissimilarity modelling (GDM): A statistical technique for analysing and predicting spatial patterns of turnover in community composition (beta diversity) across large regions.

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. It is the label given to the family of indicators that measure different facets of condition and include: *ecological condition*, *ecological connectivity*, *ecological carrying capacity* and *ecological function*.

Habitat quality: See *ecological condition*.

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.

K-mean centroid: Algorithm used for deriving ecosystem classes, that clusters data into k groups where k is predefined.

Location: An individual place represented in the analysis by a single grid cell of a specified size.

Manage benefits: Provides a measure of the benefits to regional biodiversity persistence of protecting existing habitat.

Manhattan distance: The distance between two points measured along axes at right angles.

Marginal biodiversity: The amount of biodiversity that could be lost, or secured, through the loss or addition of a unit of habitat.

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

NPW reserves: Reserves managed in perpetuity under the *National Parks and Wildlife Act 1974*.

Persistence: Used here in relation to the ability of biodiversity or its components to sustain through time.

Region: Refers to an area consisting of multiple locations represented in the analysis by a collection of grid cells.

Regional ecosystem mapping: Vegetation communities in a bioregion that are consistently associated with a combination of geology, landform and soil.

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

Reporting region: A portion of the study area (NSW) for which the indicator is calculated. For the current indicator assessment, reporting regions include 90-metre grid cells, Mitchell landscapes, *NPW reserves* and all of New South Wales.

Revegetate: The re-establishment of vegetation on cleared or degraded land, through seed sowing, plantings or natural regeneration

Scenario evaluation: A form of assessment that involves an alternative set of conditions. Can be past, present or alternative plausible or possible futures.

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

Species–area relationship: Describes the relationship between the area of a habitat, or the of part of a habitat, and the number of species found within that area.

Surrogacy: Using a *taxonomic group* (e.g. vascular plants) to represent biodiversity more broadly

Taxonomic groups: A group of organisms at the same level of organisation in biological classification.

Terrestrial Biodiversity Forecasting Toolkit: A regional-scale community-level biodiversity assessment method used to evaluate regional scenarios and produce *benefits mapping*. It integrates *ecological condition* of habitat, habitat connectivity and the distribution of ecosystems.

Threats or threatening processes: A process that threatens, or that may threaten, the survival or evolutionary development of species or ecological communities.

Total diversity: The sum of all biodiversity occurring in a cell or geographic region, regardless of whether it is shared with other cells or regions.

Unique diversity: That part of diversity that is unique to a cell, or a geographic region (e.g. a species, or genetically distinct variety), that occurs nowhere else.

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

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

Vulnerability: Exposure to *extinction*, arising from *threats*.

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