GEOSS Ecosystem Mapping for Australia

Prepared for

TERN AusCover

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Executive Summary

Background

The physical drivers of ecosystem formation – **macroclimate**, **lithology** and **landform** – along with vegetation structural formations are key determinants of current ecosystem type. Each combination of these ecosystem drivers – each 'ecological facet' – provides a unique set of opportunities and challenges for life.

Management and conservation should seek to understand and take in to account these drivers of ecosystem formation. By understanding the unique combinations of these drivers management strategies can plan for their full range of variation, and conservation efforts can ensure that unique ecosystems are not lost. Unfortunately, there is currently no Australia-wide standardised map of ecological facets at management-appropriate scales.

By understanding the magnitude and distribution of unique combinations of these drivers, management strategies can plan for their full range of variation, and conservation efforts can ensure that unique ecosystems are not lost. Additionally, by improving our understanding of the past and present conditions that have given rise to current ecological facets this dataset could facilitate future predictive environmental modelling. Finally, this data could assisting biodiversity conservation, climate change impact studies and mitigation, ecosystem services assessment, and development planning

Aims

TERN AusCover GEOSS Ecosystem Mapping for Australia aimed to map ecological facets for continental Australia, using methods modelled after similar prior mapping at continental and global scales, but with modifications for Australia. Each of the three major factors driving ecosystem formation – **macroclimate**, **lithology** and **landform** – were captured with one or two spatial indicators. Finally major vegetation structural formations were mapped and combined with the indicators of ecosystem formation to produce '**ecological facets'**.

Outcomes

The ultimate goal of this work was the production of the Ecological facets data product. These ecological facets allow for a better understanding of the current range of biophysical variation within and across Australian ecosystems. However, it is anticipated that for many applications the precursor spatial indicators will be more useful by themselves.

Macroclimate

Bioclimatic regime, or the availability of water and energy, is a key driver of ecosystem function and biodiversity. There is evidence that the majority of variation in species richness of plants, mammals, butterflies, and bird species at broad scales is determined by climatic variables associated with water and energy availability. Across Australia 59 homogeneous bioclimatic regions were mapped by clustering a large set of bioclimatic variables into regions of similar bioclimatic behaviour. This allows identification of areas with similar rainfall and temperature regimes, and consideration of broad-scale bioclimatic differences or similarities in management.

Lithology

Soil properties, and – especially in Australia – the degree of weathering are known to play important roles in determining vegetation distribution. Simplified surficial lithology (which determines soil properties) and weathering intensity products were derived from existing Geoscience Australia products, and capture the variation these two important variables.

Landform

Land surface form and topographic moisture potential are two important aspects of land form that strongly influence ecosystem formation. Land surface form is a measure of the steepness of terrain, and the amount of variation in elevation, and ten classes were derived from topographic variables (flat plains, smooth plains, irregular plains, escarpments, low hills, hills, breaks/foothills, low mountains, high mountains/deep canyons, and drainage channels). Topographic moisture potential, which models the way topography redistributes rainfall, and the influence of aspect (slope direction) on evaporation, was derived from measures of flow accumulation, aspect, and remotely sensed measures of inundation. Together, these products capture the important impact of topography on ecosystem type.

Ecological facets

A continental dataset of ecological facets – unique combinations of ecosystem drivers and vegetation structural formations – was produced by combining the spatial indicators of macroclimate, lithology, landform, and vegetation structural formations described in the sections above. This final dataset contained 369,439 unique ecological facets at a resolution of 90 m. All attribute values and descriptions for each input indicator were retained for every pixel.

While the ecological facet dataset is incredibly rich in detail, this richness may be perceived as a negative for practical and management perspectives. However, this dataset retains all of the detail of the component indices, and hence allows examination of each ecosystem driver across continental Australia either individually or in combinations. Further, based on the specific need, detail may be reduced by aggregating some of the detail in a lower priority ecosystem driver index.

Conclusions

The physical drivers of ecosystem formation – **macroclimate**, **lithology** and **landform** – along with vegetation structural formations are key determinants of current ecosystem type. While acknowledging that other factors also influence ecosystem occurrence, especially disturbance from anthropogenic and natural sources, understanding the physical drivers should facilitate management and conservation. Each combination of these ecosystem drivers – each '**ecological facet**' – provides a unique set of opportunities and challenges for life. By understanding the magnitude and distribution of unique combinations of these drivers, management strategies can plan for their full range of variation, and conservation efforts can ensure that unique ecosystems are not lost. Additionally, understanding the current range of variation within and across Australian ecosystems is essential for any future predictive environmental modelling.

The dataset of ecological facets for Australia presented herein is a first attempt at mapping the physical drivers of ecosystem formation, and providing insight into the ecological facets of Australia. By improving our understanding of the past and present conditions that have given rise to current ecological facets this dataset could facilitate future predictive environmental modelling. Additionally, this data could assisting biodiversity conservation, climate change impact studies and mitigation, ecosystem services assessment, and development planning.

Acknowledgements

The completion of this work wouldn't have been possible without contributions from four outstanding individuals. Thanks to Trevor Dowling, CSIRO, for many hours assistance tracking down previous related work, chasing contacts for me, and for providing introductions to various very talented people. Thanks to Janet Stein, Fenner School, Australian National University, for invaluable expert advice on potential methods of characterising bioclimate, and for calculating all of the bioclimatic indices used to create the macroclimate product. Thanks to John Wilford, Geoscience Australia, for advice on the lithology reclassification, and for introduction to the weathering intensity product. And finally, thanks to Matt Paget for introductions and advice that got this work moving.

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1 Introduction

Ecosystem type is determined by the interplay of several factors operating at a range of scales: macroclimate, lithology and landform. At the broadest scale, ecosystem type is determined by macroclimate, the energy regime resulting at different latitudes, and the influence of this energy regime on water availability (O'Brien 2006; Bailey 2014). At finer scales, landform and lithology become important drivers of vegetation distribution because they modify the water-energy regime by influencing soil, evapotranspiration, precipitation, temperature, wind and cloud regimes, and these in turn determine substrate chemistry, soil water availability and air saturation, heat balance and photosynthetically active radiation (Guisan and Zimmermann 2000; Sayre et al. 2014).

Each combination of these ecosystem drivers – each 'ecological facet' – provides a unique set of opportunities and challenges for life. Each species will have some facets to which it is highly suited, and many facets to which it is less suited, but which are still habitable. However, species will likely only exist in a subset of these potentially habitable facets due to competition from other species, or historical events like bushfires or land clearing. Finally, the geographic location of ecological facets will slowly move over time. This may seem surprising, as some of the factors that determine ecological facets, like landform and soil chemistry, change very slowly over time. However, other factors, primarily climatic, are now changing on an ecologically significant time scale due to human-induced climate change.

Management and conservation should seek to understand and take in to account the major ecosystem drivers. By understanding the unique combinations of these drivers, management strategies can plan for their full range of variation, and conservation efforts can ensure that unique ecosystems are not lost. Unfortunately, there is currently no Australia-wide standardised map of ecological facets at management-appropriate scales. There are maps of somewhat related factors, such as the national biogeographic stratification (IBRA, Department of Sustainability, Environment, Water, Population and Communities, 2013) and the national hierarchical vegetation mapping (NVIS Commonwealth of Australia (Department of the Environment and Energy) 2016). And there is a global ecosystem map of broad ecosystem types at moderate resolution (Sayre et al. 2014), and one state has ecosystem mapping at a finer resolution (Qld, Regional Ecosystem mapping Neldner et al. 2017). Therefore there is a need for ecological facet mapping as an efficient method for condensing and summarising the vast amount of information contained in all of the continental maps of ecosystem drivers.

Thus, the TERN AusCover GEOSS Ecosystem Mapping for Australia aimed to map ecological facets for continental Australia, using methods modelled after Sayre et al. (2009) and Sayre et al. (2014). Each of the three major factors driving ecosystem formation – **macroclimate**, **lithology** and **landform** – were captured with one or two spatial indicators. Finally major **vegetation structural formations** were mapped and combined with the indicators of ecosystem formation to produce **'ecological facets'**. The rationale and methods for each of these are described in the sections below with maps to illustrate. The individual indices as well as a combined product are available through the TERN AusCover data portal, and sufficient methods detail is presented here to enable replication.

This is the highest resolution (90 m), Australia-wide terrestrial mapping of its sort to-date. This new map of terrestrial ecological facets allows for a better understand of the current range of biophysical variation within and across Australian ecosystems. This could facilitate any future predictive environmental modelling, as well as assisting biodiversity conservation, climate change impact studies and mitigation, ecosystem services assessment, and development planning.

2 Macroclimate

Bioclimatic regime, or the availability of water and energy, is a key driver of ecosystem function and biodiversity. Indeed, there is evidence that the majority of variation in species richness of plants (Wright 1983; Currie and Paquin 1987; Adams and Woodward 1989; O'Brien 1993, 1998; O'Brien et al. 2000; Venevsky and Venevskaia 2005; Kreft and Jetz 2007), mammals (Currie 1991; Badgley and Fox 2000), butterflies (Hawkins and Porter 2003) and bird species (Currie 1991; Hawkins et al. 2003) at broad scales is determined by climatic variables associated with water and energy availability.

Homogeneous bioclimatic regions were mapped by clustering a large set of un-correlated bioclimatic variables into homogenous classes in a method modelled after that of Metzger et al. (2013). An initial large set of bioclimatic variables and indices (those used by Sayre et al. (2009), as per the method of Rivas-Martinez and Rivas y Sáenz (2009)) was initially calculated from eMast monthly 1976 – 2005 mean daily maximum and minimum temperatures, and monthly mean precipitation grids (0.01 degree resolution). This set was then culled to remove variables dependent on pre-defined thresholds (with no evidence base to support their validity for Australian conditions) and categorical variables, due to the methods reliance on iterative self-organizing data analysis technique (ISODATA clustering)(Ball and Hall 1965). It was hoped that information contained in the categorical variables would be reflected to some degree in other variables, and would therefore have minimal impact on the clustering. For example, while the variable “coldest month” was excluded, the variables “coldest month maximum temperature” and “coldest month minimum temperature” were retained. This reduced set of 86 variables is listed in Appendix 1 Table 12.

To prevent the clustering being unduly influenced by more frequently used or correlated variables a correlation matrix was then constructed for the reduced set of 86 variables. Where correlation coefficients greater than 0.90 were identified, variables were removed from further consideration. If a variable was only highly correlated (> 0.90) with one other variable, the retained variable was chosen arbitrarily. If a variable was highly correlated with more than one variable it was retained and the others discarded. However, an exception to this occurred when three variables were highly correlated with each other (It, Tmax and Tp)(and so only one would normally have been retained), but each was also highly correlated with an exclusive set of other variables. In this case, retaining these three variables allowed for the exclusion of 40 other variables. This process reduced the set of variables to 16 (Appendix 1, Table 13).

Finally, as per Metzger et al. 2013, principal components analysis (PCA) was performed on the set of 16 least correlated variables to determine those with the little information content (eigenvector loadings ≤ 0.1 in the first three principal components; Table 1). All 16 least correlated variables had eigenvector loadings > 0.1 in at least one of the first three principal components and were retained for the ISODATA clustering.

Prior to ISODATA clustering, the remaining 16 variables were z-score normalised using the following equation:

$$z = \frac{x - \mu}{\sigma}$$

Where:

z is the output raster with z-score normalised data values

x is the input raster value

μ is the mean of all values in the input raster

σ is the standard deviation of all values in the input raster

The ISODATA clustering in ENVI 5.3 was used to group the 16 z-scored normalised variables into bioclimatic zones. While 130 classes were requested (an arbitrary choice), 59 classes were returned (class location and distribution in Figure 1). Finally, the mean and standard deviation of each of the 16 input variables was calculated for each class (values in Appendix 1, Table 14 and Table 15 respectively; maps of mean values of each variable per class in Figure 2, Figure 3, Figure 4, Figure 5).

Table 1. Eigenvector loadings of the 16 least correlated bioclimatic variables in the first three principal components. Variables with high information content (eigenvector loading > 0.1) are highlighted in bold.

	Principal component		
Variable name	**1**	**2**	**3**
Ic	-0.09	**0.74**	**0.54**
Io	-0.05	**-0.11**	**0.14**
Ios2	0.08	**-0.20**	**0.12**
It	**0.61**	**-0.22**	0.08
Pcm2	0.00	**-0.17**	**0.12**
Pcm3	**-0.21**	**-0.11**	**0.23**
Pp	0.00	**-0.20**	**0.18**
Psw	**-0.14**	**-0.10**	**0.15**
rain_10	**-0.16**	**-0.16**	**0.31**
rain_11	-0.07	**-0.33**	**0.47**
rain_4	-0.02	-0.09	**0.11**
rain_5	-0.09	-0.07	**0.15**
sm_rain_3_8	-0.06	**-0.12**	**0.13**
sm_rain_7_12	**-0.12**	**-0.23**	**0.28**
Tmax	**0.47**	**0.21**	**0.28**
Tp	**0.52**	-0.03	**0.14**

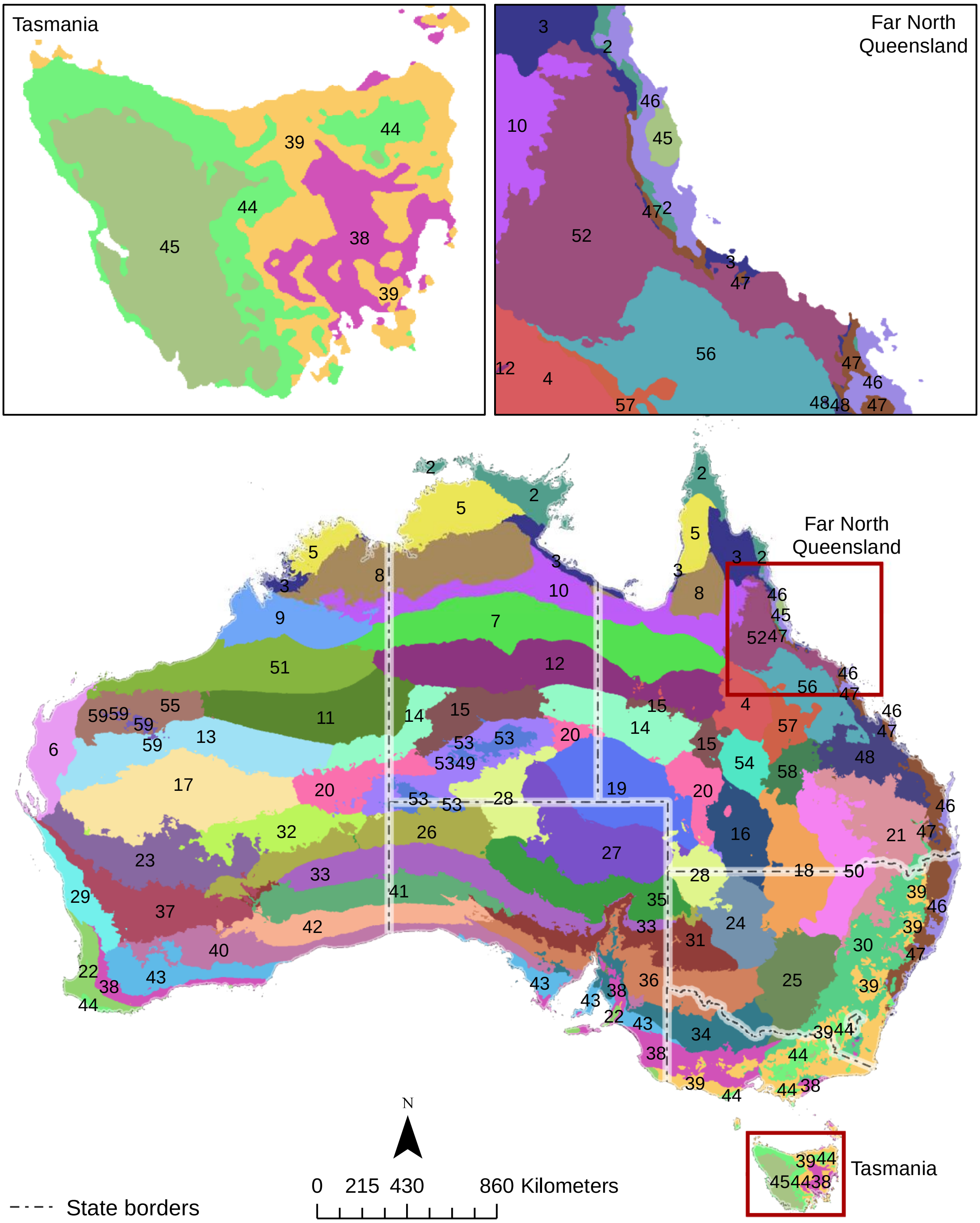

Figure 1. Homogenous bioclimatic regions of Australia. Mean and standard deviation of each of the 16 input variables in Appendix 1, Table 14 and Table 15 respectively. Inset maps of Tasmania to clarify an area of fine spatial detail, and of Far North Queensland to illustrate the regionally anomalous variable behaviour of classes of classes 45 and 46 in Figure 2, Figure 3, Figure 4 and Figure 5.

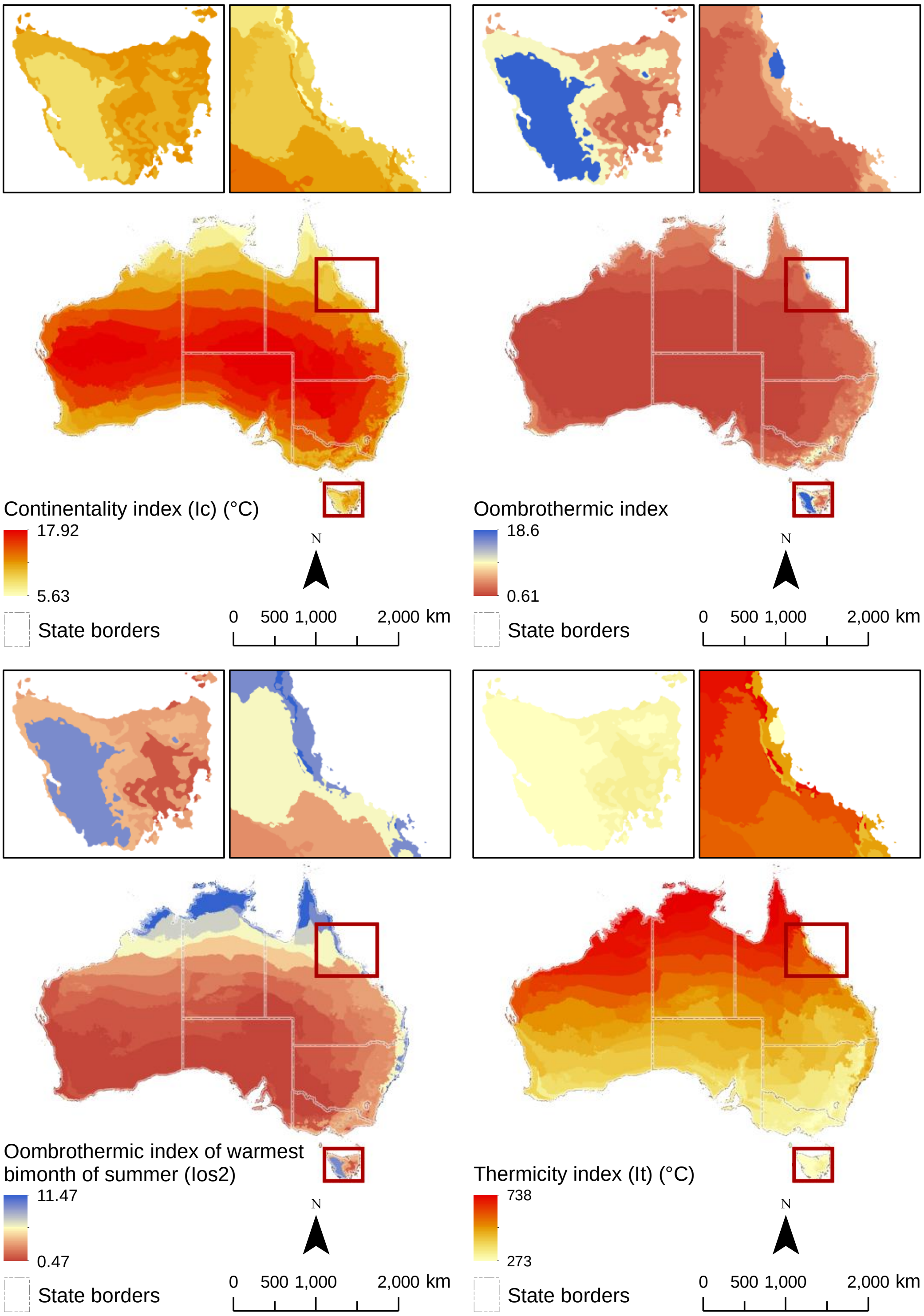

Figure 2. Continentality index (Ic; top left), ombrothermic index (Io; top right), ombrothermic index of the warmest bimonth of summer (Ios2; bottom left), and thermicity index (It; bottom right). Ic is calculated as Tmax - Tmin (Tmax = highest monthly daily average temperature value for each cell; Tmin = lowest monthly daily average temperature value for each cell). Io is ten times the quotient resulting value between the yearly positive precipitation in mm (Pp) and the yearly positive temperature (Tp). It is ten times the sum of T (yearly average temperature), m (average minimum temperature of the coldest month of the year), M (average maximum temperature of the coldest month of the year).

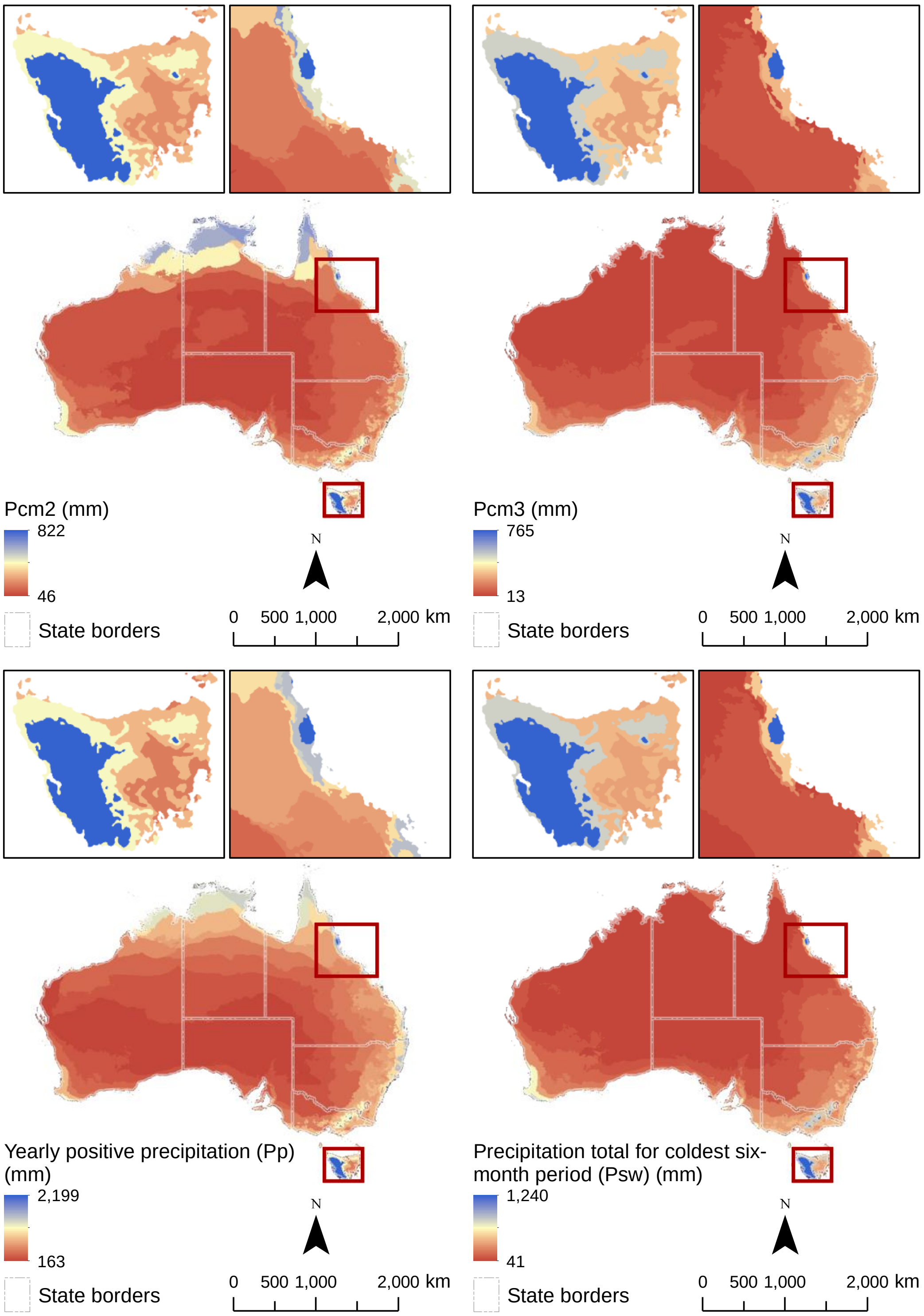

Figure 3. Precipitation for the four month period following the warmest four month period (Pcm2; top left), precipitation for the four month period following the Pcm2 period (Pcm3, top right), yearly positive precipitation (Pp; bottom left), and precipitation for the coldest six-month period (Psw, bottom right). Pp is the total average precipitation of those months whose average temperature is higher than 0ºC.

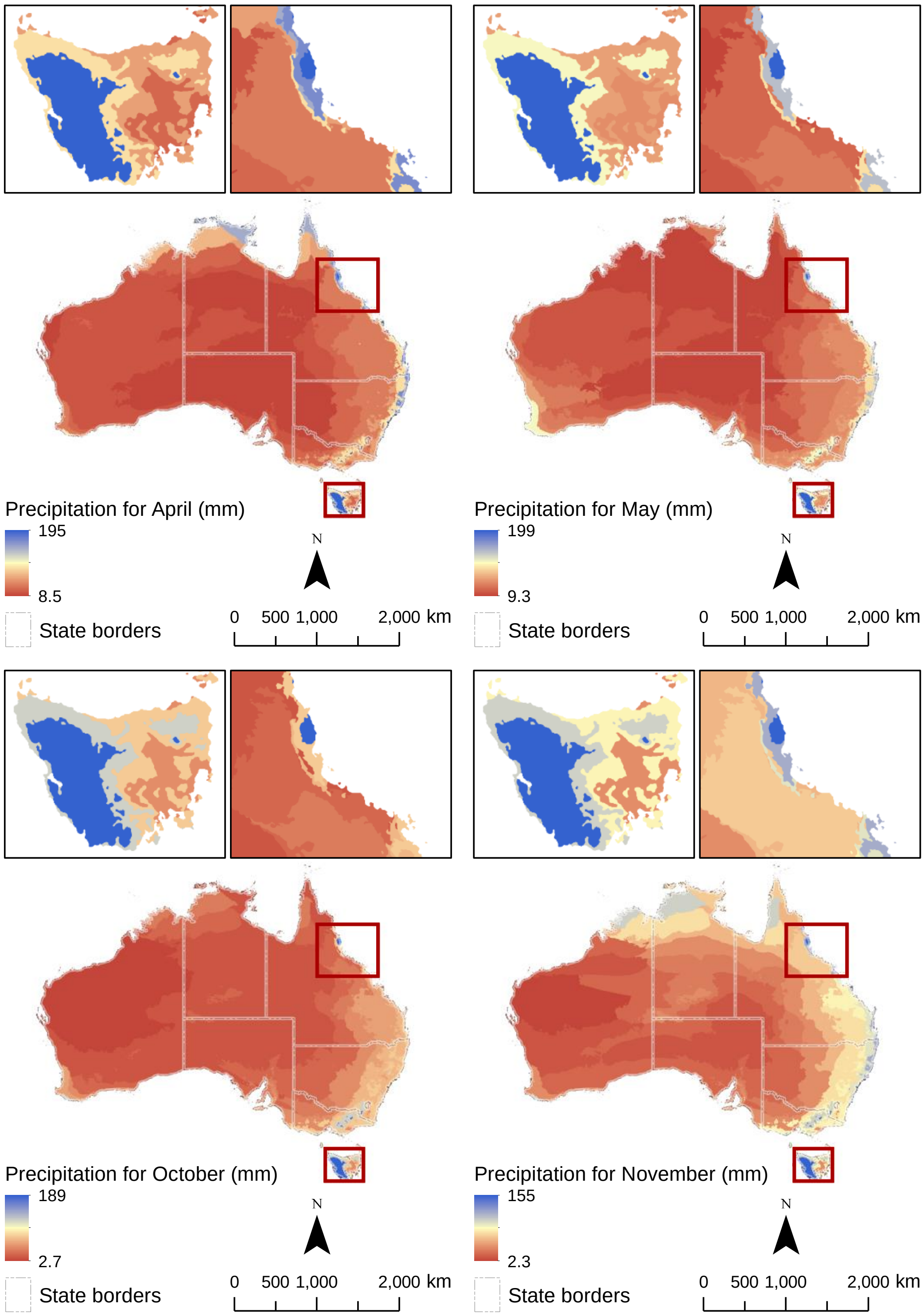

Figure 4. Mean precipitation for April (rain_4, top left), mean precipitation for may (rain_5, top right), mean precipitation for October (rain_10, bottom left), and mean precipitation for November (rain_11, bottom right).

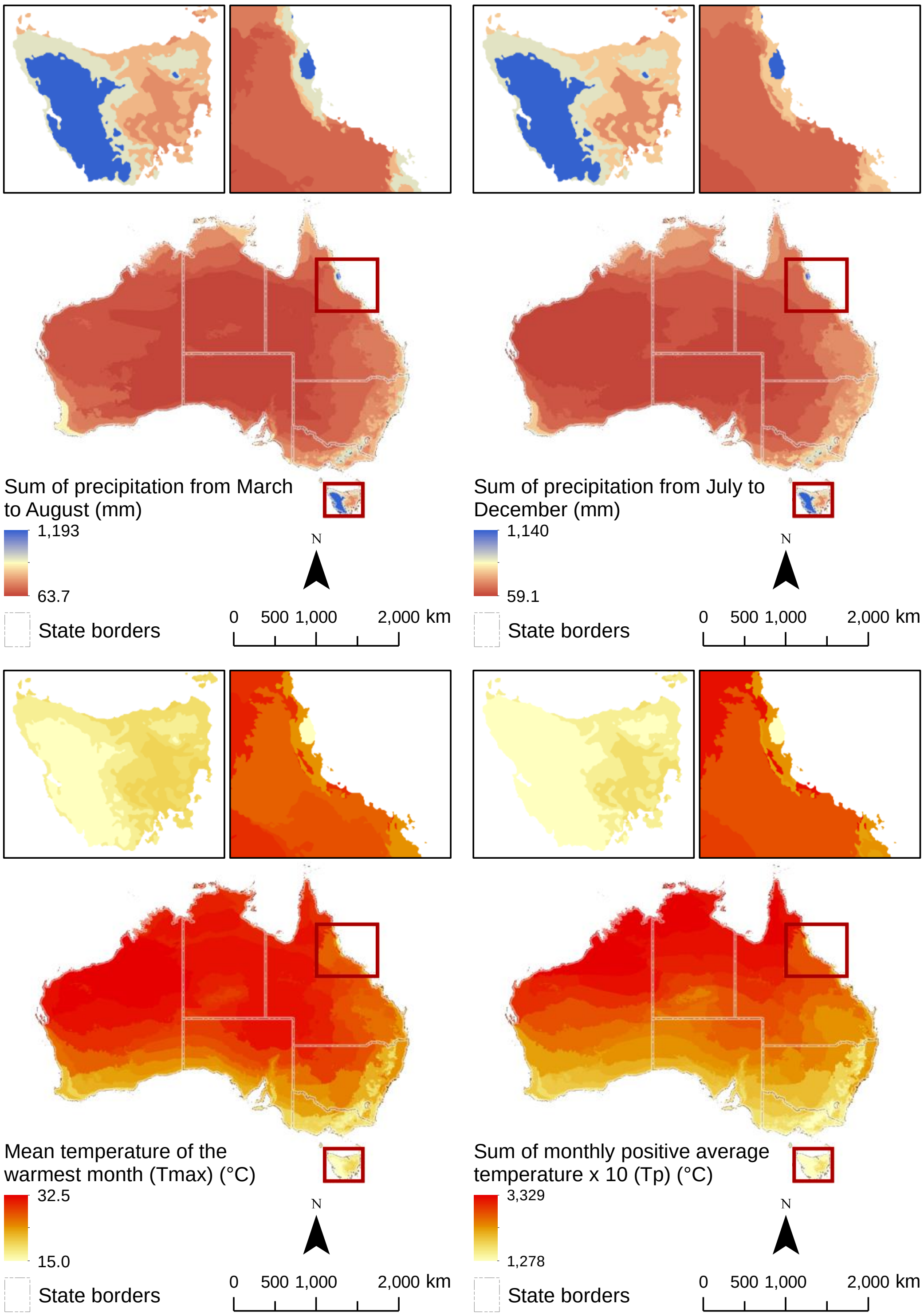

Figure 5. Sum of monthly mean precipitation from March to August (sm_rain_3_8, top left), sum of monthly mean precipitation from July to December (sm_rain_7_12, top right), mean temperature of the warmest month (Tmax, bottom left), and sum of monthly average temperature of those months whos average tmepreature is higher than 0 °C multiplied by 10 (Tp, bottom right).

3 Lithology and weathering intensity

Previous GEOSS ecosystem mapping has used surficial lithology (Sayre et al. 2008; Sayre et al. 2009; Sayre et al. 2013; Sayre et al. 2014) to capture the important role substrate type plays in determining vegetation distribution (Kruckeberg 2004). Indeed, surficial lithology is strongly predictive of several important soil properties, and therefore potentially predictive of ecosystem type. For instance, Gray et al. (2014) classified lithology into eleven classes based on broad chemical composition, and demonstrated that inclusion of this classification could improve ability of soil property modelling to predict soil organic carbon, pH, sum of bases and sand content. However, given the extreme age of most Australian soils, weathering intensity is perhaps just as important as surficial lithology (Gale 1992; Oliver 2001). Weathering is the process whereby chemical and mechanical processes break-down or chemically alter surficial material. Thus, we include both surficial lithology and weathering intensity datasets to capture both substrate type and degree of weathering.

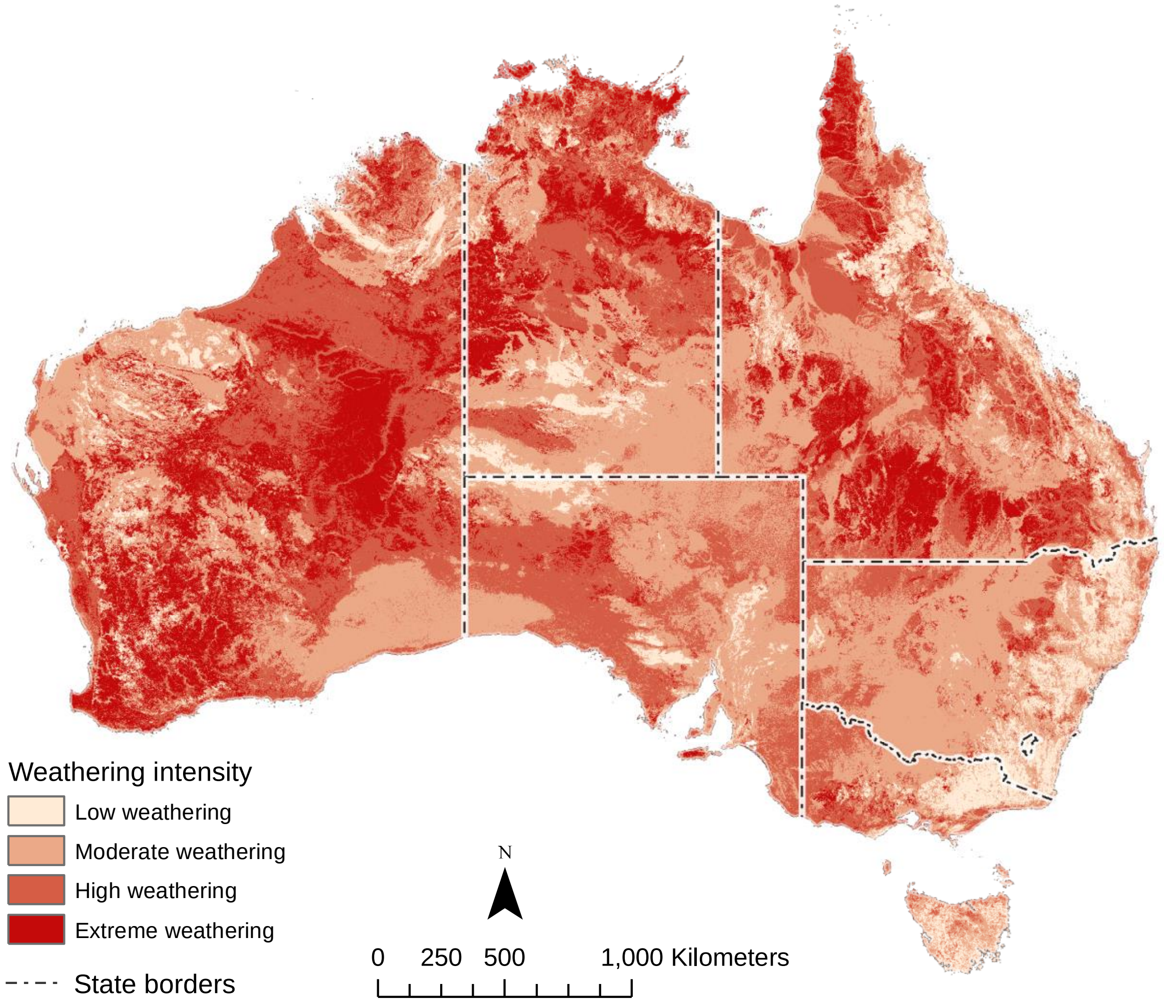

Figure 6. Weathering intensity for Australia as mapped by the weathering intensity index (WII) of Wilford (2012).The WII is modelled from airborne gamma-ray spectrometry and Shuttle Radar Topography Mission (SRTM) digital elevation data and produced at 3” resolution (approximately 90 m).

A Surface Geology dataset produced by Geoscience Australia at 1: 1M scale was used as the surficial lithology dataset. While previous GEOSS mappings have reclassified lithology to few broad categories (e.g., 17 for North America (Sayre et al. 2009)) the Geoscience Australia Surface Geology dataset is quite detailed, distinguishing

244 different lithologies (Appendix 1, Table 16). A similar reclassification of the Geoscience Australia Surface Geology dataset would enable the GEOSS ecological facets to be more globally comparable, and be of benefit for Australia.

Weathering intensity was represented by the weathering intensity index (WII) produced by Wilford (2012). The WII is produced from the integration of two regression models based on gamma-ray spectrometry and topography. The WII has a range from 1 – 6, and for the purposes of this was reclassified to four weathering categories: Low weathering (≤ 2), Moderate weathering (> 2 ≤ 4), High weathering (> 4 ≤ 5) and Extreme weathering (> 5 ≤ 6)(Figure 6).

Finally, the Geoscience Australia Surface Geology dataset was then converted to a raster with the same resolution (3”) as, and snapped to, the WII product.

4 Landform

Both the physical shape of the earth surface, and the effect of geography on moisture availability strongly influence ecosystem type. These two effects were captured with indices of **land surface form**, and **topographic moisture potential**.

4.1 Land surface forms

Land surface form, or the physical shape of the earth surface, plays an important role in influencing the differentiation and distribution of terrestrial ecosystems. Nine land surface form classes (flat plains, smooth plains, irregular plains, escarpments, low hills, hills, breaks/foothills, low mountains, and high mountains/deep canyons) were modelled from topographic variables (slope and local relief). These land surface forms were derived by reclassification of the Australian CSIRO Slope Relief dataset, created by John Gallant (CSIRO) and John Wilford (GA) in 2011. This dataset was produced through classification of slope relief from the 1 second DEM-S, and the 300 m focal median percent slope product. The slope (Table 2) and relief (Table 3) classes in the product were derived from Speight 2009 with some modification.

To make this work more directly comparable to the North American GEOSS mapping (Sayre et al. (2009)), the CSIRO Slope Relief was reclassified to categories more closely approximating the Missouri Resource Assessment Partnership (MORAP) land surface form classes. Firstly, categories with median slope of 0 – 10 % were classified as gently sloping, and those median slope of > 10 % were classified as not gently sloping (Table 2). Next, land surface forms were defined according to the key in Table 4. The complete reclassification key, from CSIRO Slope Relief to MORAP is presented in Table 5.

Finally, a drainage channels class was derived via the slope position classification method of Weiss (2001). A topographic position index (TPI) was calculated from the Geoscience Australia SRTM-derived 1 Second Hydrologically Enforced Digital Elevation Model (DEM-H). The TPI is an index that describes the relative elevation of a cell compared to its neighbourhood within a radius of 564 m (~ 1-km^2). As per Weiss (2001), six slope position classes were then defined by classification of the standard deviation of TPI, and incorporation of slope (from the CSIRO Slope derived from 1” SRTM DEM-S)(slope position classification parameters in Table 6). Two of these classes (valleys and lower slopes) were then reclassified as drainage channels, given a code value of 10, and added to the other landform classes (Table 4).

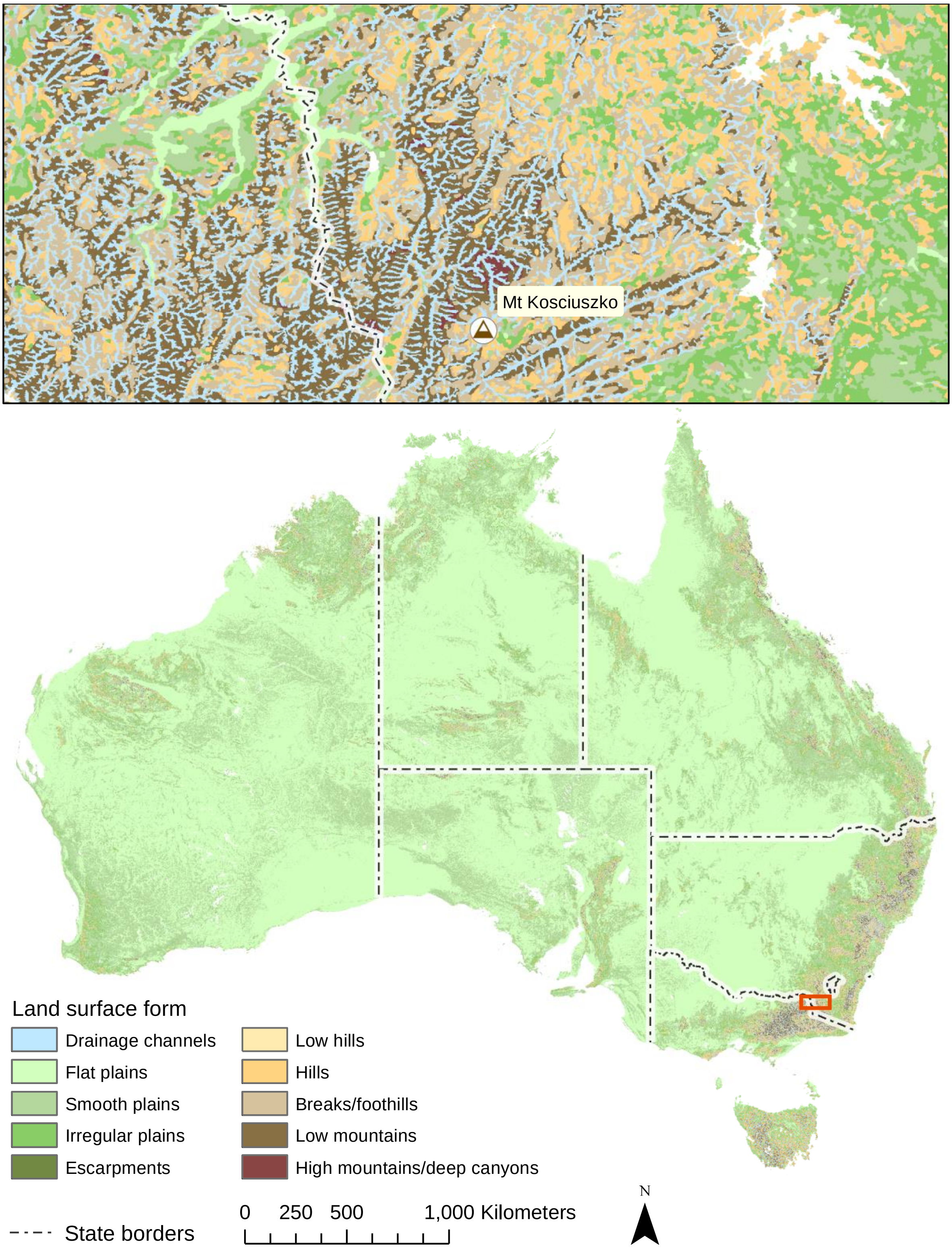

Figure 7. Land surface forms of Australia, derived from slope, relative relief, and modelled position-in-landscape calculated from Shuttle Radar Topography Mission (SRTM) digital elevation model. Resolution is 3” (approximately 90 m). Inset zoom of the region around Mt Kosciuszko, the highest mountain in Australia, to illustrate a region of high land surface form variation at fine scale.

Table 2. CSIRO Slope Relief, slope categories, class names, class abbreviations and raster data codes.

Median slope (%)	Slope class name	Slope class abbreviation	Original data code	Reclassified to	Reclassified data code
< 1	level	LE	10	Gently sloping	10

1 - 3	Very gently sloping	VG	20	Gently sloping	10
3 - 10	Gently sloping	GE	30	Gently sloping	10
10 - 32	Moderately sloping	MO	40	Not gently sloping	20
32 - 56	Steep	ST	50	Not gently sloping	20
56 - 100	Very steep	VS	60	Not gently sloping	20
> 100	Precipitous (cliff-like)	PR	70	Not gently sloping	20

Table 3. CSIRO Slope Relief, relief categories, class names, class abbreviations and raster data codes.

Relief (m)	Relief class name	Relief class abbreviation	Class data code
< 9	Plains	P	1
9 - 30	Rises	R	2
30 - 90	Low hills	L	3
90 - 150	Hills*	H	4
150 - 300	Hills*	H	5
> 300	Mountains	M	6

* The Speight “high” class, 90 – 300 m, was split in to two classes to be more compatible with international work (e.g., the Missouri Resource Assessment Partnership (MORAP) method, from which Sayre et al. (2009) derived their categories.

Table 4. Missouri Resource Assessment Partnership (MORAP) land surface form classes, topographically modelled from combinations of slope class and local relief.

Slope class	Local relief (metres)	Land surface form class	MORAP class data code
		Drainage channels§	10
Gently sloping – Median slope 0 – 10 % within a 300 m diameter	< 9	Flat plains	11
	9 - 30	Smooth plains	12
	30 - 90	Irregular plains	13
	> 90	Escarpments	14†
Not gently sloping – Median slope > 10 % within a 300 m diameter	< 30	Low hills	22‡
	30 - 90	Hills	23
	90 - 150	Breaks/foothills	24
	150 - 300	Low mountains	25
	> 300	High mountains/ deep canyons	26

*Derived by reclassification of CSIRO Slope Relief to approximate as closely as possible the Missouri Resource Assessment Partnership (MORAP) land form classes.

§Drainage channels defined by slope position classification, as per Weiss (2001) via Sayre et al. (2009).

†Areas coded as 25 (median slope 1 – 3 %, relief 150 – 300 m; very gently sloping hills), 35 (median 3 – 10 % slope, relief 150 – 300 m; gently sloping hills) and 36 (median 3 – 10 % slope, relief > 300 m; gently sloping mountains) were recoded as 14 (median slope 0 – 10 % , relief > 90 m; escarpments).

‡Areas coded as 41 (median slope 10 – 32 %, relief < 9 m; moderately sloping plains), 51 (median slope 32 – 56 %, relief < 9 m; steep plains) and 61 (median slope 56 – 100 %, relief < 9 m; very steep plains) were recoded as 22 (slope > 10 %, relief ≤ 30 m relief; low hills)

Table 5. Reclassification key for conversion of CSIRO Slope Relief to the Missouri Resource Assessment Partnership (MORAP) land form classification.

Original slope-relief class	Original class code	MORAP class data code	MORAP land surface form class
Level plains	11	11	Flat plains
-§	12	12	Smooth plains
-§	13	13	Irregular plains
-§	14	14	Escarpments
Gently inclined plains	21	11	Flat plains
Gently inclined rises	22	12	Smooth plains
-§	23	13	Irregular plains
-§	24	14	Escarpments
-§	25†	14	Escarpments
Undulating plains	31	11	Flat plains
Undulating rises	32	12	Smooth plains
Undulating low hills	33	13	Irregular plains
Undulating hills	34	14	Escarpments
Undulating hills	35†	14	Escarpments
-§	36†	14	Escarpments
Rolling plains	41‡	22	Low hills
Rolling rises	42	22	Low hills
Rolling low hills	43	23	Hills
Rolling hills	44	24	Breaks/foothills
Rolling hills	45	25	Low mountains
Rolling mountains	46	26	High mountains/deep canyons
Badlands	51‡	22	Low hills
Steep rises	52	22	Low hills
Steep low hills	53	23	Hills
Steep hills	54	24	Breaks/foothills
Steep hills	55	25	Low mountains
Steep mountains	56	26	High mountains/deep canyons
Badlands	61‡	22	Low hills
Badlands	62	22	Low hills
Very steep low hills	63	23	Hills
Very steep hills	65	24	Breaks/foothills
Very steep mountains	66	25	Low mountains
Precipitous mountains	76	26	High mountains/deep canyons

§Original slope-relief class not named.

†Areas coded as 25 (median slope 1 – 3 %, relief 150 – 300 m; very gently sloping hills), 35 (median 3 – 10 % slope, relief 150 – 300 m; gently sloping hills) and 36 (median 3 – 10 % slope, relief > 300 m; gently sloping mountains) were recoded as 14 (median slope 0 – 10 % , relief > 90 m; escarpments).

‡Areas coded as 41 (median slope 10 – 32 %, relief < 9 m; moderately sloping plains), 51 (median slope 32 – 56 %, relief < 9 m; steep plains) and 61 (median slope 56 – 100 %, relief < 9 m; very steep plains) were recoded as 22 (slope > 10 %, relief ≤ 30 m relief; low hills)

Table 6. Slope position classification parameters.

Class	Description	Category description (in relation to TPI)	TPI range
1	Ridge	> + 1 StDev	> 34.30
2	Upper slope	> 0.5 StDev <= 1 StDev	> 17.16 ≤ 34.30
3	Middle slope	>= -0.5 StDev <= 0.5 StDev, AND slope > 5 deg	≥ -17.12 ≤ 17.16
4	Flat slope	>= -0.5 StDev <= 0.5 StDev, AND slope <= 5 deg	≥ -17.12 ≤ 17.16
5	Lower slope	> = -1.0 StDev, < -0.5 StDev	≥ -34.26 < -17.12
6	Valley	< -1.0 StDev	< -34.26

4.2 Topographic moisture potential

While the long-term climatic effect on water-energy balance is characterised by the isobioclimate mapping, the available moisture is also influenced by topographic redistribution of rainfall and the influence of aspect on evaporation. To account for these influences a topographic moisture potential index was developed (Figure 8). This index was produced from a combination of topographic index, and remotely sensed inundation frequency.

The topographic wetness index (TWI; also known as the compound topographic index (CTI)), is derived from slope and flow accumulation, and expresses the relative wetness of each point. This index can potentially capture how likely a given part of the landscape is to shed or accumulate rainfall runoff or subsurface flow, and previous work in North America had established a strong link between the TWI and areas of known wetland versus non-wetland (Sayre et al. 2009), and to subdivide the non-wetland landscape in to several categories of dryness. However, the effect of topography in influencing soil water retention is known to be greater in more wet conditions (Pachepsky et al. 2001) so it was unknown whether TWI would be a strong indicator of wetland-liklihood in Australia, due to the generally higher aridity.

To test this, the CSIRO product “Topographic Wetness Index derived from 1” SRTM DEM-H”(Gallant and Austin 2012c) was compared to known wetlands from two sources, 1) Wetlands GIS of the Murray-Darling Basin Series 2.0, (MDB wetlands) and 2) the South Australian Wetlands Inventory Database (SAWID wetlands) for the South East of South Australia.

The SAWID wetlands database contains almost 19,000 wetland entries distributed over the smallest area (approximately 19,000 km^2 in the far south east of South Australia) but contains the most attribute detail relating to inundation frequency. The MDB wetlands database contains the most entries (almost 36,000 entries; but some are for non-wetland entities, and some are multiple entries for the same wetland), is distributed over the Murray Darling Basin, an area of over 1 million square kilometres in the south-eastern corner of Australia, but distinguishes only four different inundation categories.

For both the SAWID and MDB wetlands database mean, median and standard deviation of TWI were extracted for wetland and non-wetland areas. Mean and standard deviation were calculated from a floating point version of the TWI, while median was calculated from an integerised version. For the SAWID database a ‘Not wetland’ area was defined as the whole of the South East region (the area south of 35.8 °S) not already recorded as wetland. It is worth noting that this region is heavily modified for agriculture, and many former wetlands have been drained. Hence, many parts of the landscape prone to inundation are not recorded as wetlands. So, our ‘not wetland’ class certainly contain areas with a high topographic wetness index value. However, these areas made up a relatively small proportion of the area sampled.

For both wetland datasets there was little difference in TWI between categories, and standard deviation was relatively large. Thus, for the parts of Australia examined TWI appeared to have no ability to predict wetland and non-wetland parts of the landscape.

Further visual inspection of TWI at a continental scale revealed high TWI (≥ 12) throughout much of arid Australia, notably the Tanamai desert (in the Northern Territory), the Nullabor Plain (in Western Australia and South Australia) and the large arid area between Kalbarri and the Great Victoria Desert (in Western Australia); areas notably not characterised by inundation. However, TWI was appropriately high in the Riverina region (in southern New South Wales) and the floodplain region around Brewarrina (in northern New South Wales), both areas prone to flooding.

Therefore, TWI appears to be a poor indicator of potential wetland location for much of Australia. However, TWI should still capture some of the effect of topography on redistribution of rainfall. Hence TWI was used to define 'Upper slope' (TWI ≤ 6), 'Mid slope' (TWI > 6 and ≤ 9) and 'Lower slope' (TWI > 9) categories from indicative values in the CSIRO TWI product metadata. Additionally, to capture the important role aspect plays in determining evaporation on steeper slopes (Wu et al. 2006; McVicar et al. 2007; Wang et al. 2011), the 'Upper slope' category was reclassified to 'Dry upper slopes' where slope was greater than 25% and aspect was northerly. Slopes greater than 20 % were calculated from the 3" version of the CSIRO product "Slope derived from 1" SRTM DEM-S"(Gallant and Austin 2012b), and northerly aspect was derived from CSIRO product "Aspect (3" resolution) derived from 1" SRTM DEM-S"(Gallant and Austin 2012a).

To capture wetter areas of the landscape the Geoscience Australia Water Observations from Space (WOfS; Mueller et al. 2016) product was compared to the above defined wetland / non-wetland areas (Table 8). The WOfS product summarises long-term inundation frequency (1987 to present) for all of Australia, and is produced from all clear Landsat 5 and 7 observations for that period. Two additional categories, 'Intermittently flooded' and 'frequently or permanently inundated' were defined as ≥ 2 % and < 10 % inundation frequency, and ≥ 10 % inundation frequency respectively. The TWI and WOfS defined categories were then combined, with the WOfS derived categories overriding the TWI derived categories.

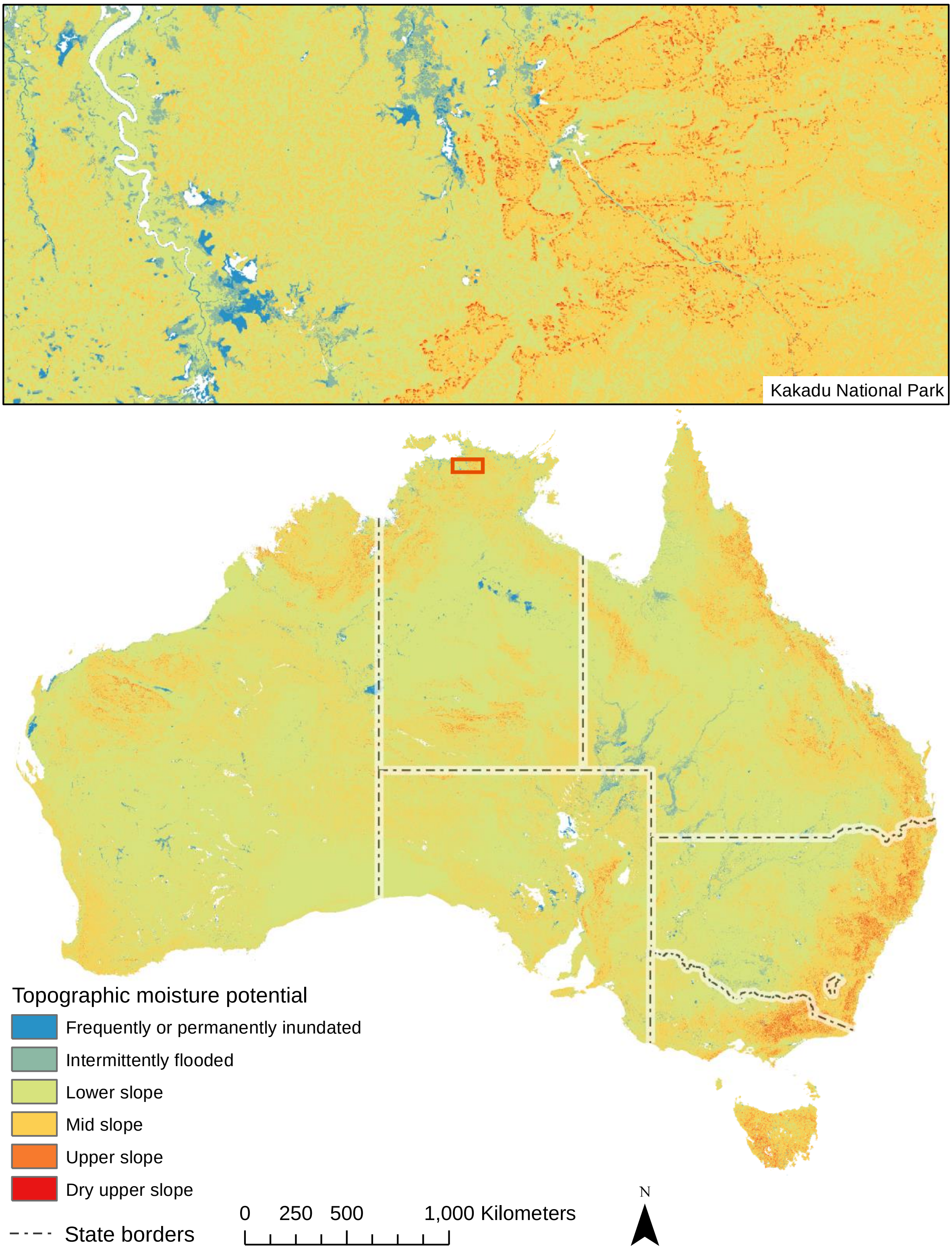

Figure 8. Topographic moisture potential for Australia, derived from slope and flow accumulation calculated from Shuttle Radar Topography Mission (SRTM) digital elevation model (Gallant and Austin 2012c); and from satellite measured inundation frequency (Water Observations from Space(WOfS); Mueller et al. 2016). Resolution is 3” (approximately 90 m). Inset zoom Kakadu National Park to illustrate a region of high variability in topographic moisture, from wetlands and floodplains in the west to steep dry escarpments to the east.

Table 7. TWI mean and standard deviation for South Australian Wetland Inventory Database (SAWID) wetlands, and non-wetland area; and for Wetlands GIS of the Murray-Darling Basin Series 2.0 wetlands, and non-wetland areas.

	Mean	Median	Standard Deviation
SAWID			
Not wetland	9.94	9	1.63
Intermittent	10.57	10	1.33
Seasonal	10.57	10	1.44
Semi-permanent	11.21	11	1.56
Permanent	10.40	10	1.43
MDB			
Not wetland	11.11	10	1.52
Floodplain wetlands	11.27	11	1.65
Freshwater lake	11.07	10	1.58

Table 8. Water Observations from Space (WOfS) inundation frequency mean and standard deviation (from the WOfS long term inundation frequency summary product, filtered to remove low confidence observations) for South Australian Wetland Inventory Database (SAWID) wetlands, and non-wetland area; and for Wetlands GIS of the Murray-Darling Basin Series 2.0 wetlands, and non-wetland areas.

	Mean	Standard Deviation
SAWID		
Not wetland	0.11	2.22
Intermittent	0.95	3.18
Seasonal	4.03	9.17
Semi-permanent	13.87	20.63
Permanent	74.34	34.70
MDB		
Not wetland	0.20	2.09
Floodplain wetlands	2.39	9.58
Freshwater lake	46.50	37.39

Table 9. Topographic moisture potential class name, class characteristics, and data code.

Topographic moisture potential class	Class characteristics	Data code
Frequently or permanently inundated	Inundation frequency* ≥ 10 %	1
Intermittently flooded	Inundation frequency* ≥ 2 % and < 10 %	2
Lower slope	TWI > 9	3
Mid slope	TWI > 6 and ≤ 9	4
Upper slope	TWI ≤ 6 AND (slope < 25 % OR NOT northerly aspect†)	5
Dry upper slope	TWI ≤ 6 AND slope ≥ 25 % AND northerly aspect†	6

*Measured from Water Observations from Space (WOfS) long term inundation frequency summary product, filtered to remove low confidence observations.

†Northerly aspect defined as being in the range ≥ 0 to < 90, or > 270 to ≤ 360, and calculated from the product “Aspect (3” resolution) derived from 1” SRTM DEM-S”(Gallant and Austin 2012a)

5 Vegetation structural formations

Whereas the previous sections have modelled the drivers of ecosystem formation, vegetation cover is the vegetative response to those drivers (Sayre et al. 2014). The density and structure of the dominant vegetation type plays a significant role in influencing ecosystem type. The amount of vegetation is a determining factor of system-wide primary productivity, and all higher trophic levels are dependent for their energy requirements on this primary productivity. In conjunction with the magnitude of primary productivity, the vegetation structure determines the number and type of niches present.

Thus, the final step in producing ecological facets was to produce a map of vegetation structural formations for Australia. This was done by re-classifying the National Vegetation Inventory System (NVIS) Major Vegetation Group (MVG) data to capture the major vegetation structural formations. The original NVIS MVG contained 33 classes, and each class was a combination of dominant upper story species and vegetation structural formation (e.g., Eucalypt Open Forests), and the reclassified major vegetation structural formations contained 6 vegetation structural classes, and four non-vegetation classes. Our reclassification transformed the NVIS MVG data to the vegetation structural formations outlined by Specht (1972), ignoring height classifications since many of the original NVIS MVG classes did not contain height descriptors. Additionally, the vegetation structural formations layer was reprojected to the same projection and resolution as the other data layers (GDA94 and 3” respectively).

This approach was taken to keep the focus on vegetation structure. An alternative and equally defensible approach would have been to simply use the NVIS MVG data. As it is, our approach produced 369,439 unique ecological facets, and using the full NVIS MVG data would have produced approximately five times as many.

Table 10. Vegetation structural formations in Australia, adapted from Specht 1972.

Life form and height of Tallest Stratum	**Projective Foliage Cover of Tallest Stratum**			
	Dense (70 – 100 %)	**Mid-dense (30 – 70 %)**	**Sparse (10 – 30 %)**	**Very sparse (< 10 %)**
Trees	T1 – Closed-forest	T2 – Open-forest	T3 – Woodland	T4 – Open-woodland
Shrubs	S1 – Closed-scrub / Closed-heath	S2 – Open-scrub / Open-heath	S3 – Shrubland / Heathland	S4 – Open-shrubland / Open-heathland
Herbs and grasses	—	H2 – Herbland / Grassland	H3 – Open-herbland / Open-grassland	H4 – Ephemeral-herbland / Ephemeral-grassland

Table 11. Remapping key from NVIS Major Vegetation Group (MVG_NAME) to vegetation structural formations, as per those outlined in Table 10.

Original NVIS MVG_NAME	Reclassified vegetation structural formation description
Rainforests and Vine Thickets; Low Closed Forests and Tall Closed Shrublands	T1 - Closed-forest
Eucalypt Tall Open Forests; Eucalypt Open Forests; Eucalypt Low Open Forests; Acacia Forests and Woodlands; Callitris Forests and Woodlands; Casuarina Forests and Woodlands; Melaleuca Forests and Woodlands; Other Forests and Woodlands	T2 - Open-forest
Eucalypt Woodlands; Tropical Eucalypt Woodlands/Grasslands; Mallee Woodlands and Shrublands	T3 - Woodland
Eucalypt Open Woodlands; Acacia Open Woodlands; Other Open Woodlands; Mallee Open Woodlands and Sparse Mallee Shrublands	T4 - Open-woodland
Acacia Shrublands; Other Shrublands; Heathlands; Chenopod Shrublands, Samphire Shrublands and Forblands	S3 – Shrubland / Heathland
Tussock Grasslands; Hummock Grasslands; Other Grasslands, Herblands, Sedgelands and Rushlands	H2 – Herbland / Grassland
Cleared, non-native vegetation, buildings	Cleared, non-native vegetation, buildings
Mangroves; Unclassified native vegetation; Naturally bare - sand, rock, claypan, mudflat; Regrowth, modified native vegetation; Unclassified Forest	Other
Unknown/no data	Unknown
Inland aquatic - freshwater, salt lakes, lagoons; Sea and estuaries	Water

6 Ecological facets

A continental dataset of ecological facets – unique combinations of ecosystem drivers and vegetation structural formations – was produced by combining the spatial indicators of macroclimate, lithology, landform, and vegetation structural formations described in sections 2 to 5 above. This final dataset contained 369,439 unique ecological facets at a resolution of 90 m. All attribute values and descriptions for each input indicator were retained for every pixel.

While the ecological facet dataset is incredibly rich in detail, this richness may be perceived as a negative for practical and management perspectives (Sayre et al. 2014). However, this dataset retains all of the detail of the component indices, and hence allows examination of each ecosystem driver across continental Australia either individually or in combinations. Further, based on the specific need, detail may be reduced by aggregating some of the detail in a lower priority ecosystem driver index. By gathering these data into one source and ensuring spatial consistency, this ecological facets dataset will allow for better research and management of the biophysical variation within and across Australia.

7 Summary and recommendations

The physical drivers of ecosystem formation – **macroclimate**, **lithology** and **landform** – along with **vegetation structural formations** are key determinants of current ecosystem type. While acknowledging that other factors also influence ecosystem occurrence, especially disturbance from anthropogenic and natural sources, understanding the physical drivers should facilitate management and conservation. Each combination of these ecosystem drivers – each 'ecological facet' – provides a unique set of opportunities and challenges for life. By understanding the magnitude and distribution of unique combinations of these drivers, management strategies can plan for their full range of variation, and conservation efforts can ensure that unique ecosystems are not lost. Additionally, understanding the current range of variation within and across Australian ecosystems is essential for any future predictive environmental modelling.

While superficially similar to the Interim Biogeographic Regionalisation of Australia (IBRA), the method for producing the ecological facets of Australia is intended to be more data driven and transparent. We hope that this will allow the ecological community to better understand this product, and adopt it where appropriate, and elsewhere take our methods and adapt them to better suit their needs.

Future refinements of this work should consider predicted (future) bioclimatic variables, and improve the classification of lithology. Incorporation of predicted bioclimatic variables would enable prediction of the impact of changing climate on the range and location of ecological facets. This would potentially assist in mitigating any ecological impacts. By aggregating the base lithologies to fewer, more ecologically significant categories, as per Sayre et al. (2009), the total number of modelled ecological facets would be reduced, and they would become more meaningful and more easily understood. Additionally, the NVIS uncertainty data could potentially be incorporated to clarify where vegetation structural information is more or less reliable.

The dataset of ecological facets for Australia presented herein is a first attempt at mapping the physical drivers of ecosystem formation, and providing insight into the ecological facets of Australia. By improving our understanding of the past and present conditions that have given rise to current ecological facets this dataset could facilitate future predictive environmental modelling. Additionally, this data could assisting biodiversity conservation, climate change impact studies and mitigation, ecosystem services assessment, and development planning.

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Appendix 1

Table 12. Subset of bioclimatic variables, excluding those indices that involved adjustment or reclassification based on thresholds (where the thresholds and adjustments were of unknown validity for Australia).

Variable name	Variable description
anntemp	Yearly average temperature (in degrees celcius)
coldmaxt	mean max temp of coldest month
coldmint	mean min temp of coldest month
Ic	Continentality Index (yearly thermic interval) (Tmax - Tmin (Tmax = highest monthly daily average temperature value for each cell; Tmin = lowest monthly daily average temperature value for each cell)
Io	Ombrothermic Index (Ten times the quotient resulting value between the yearly positive precipitation in mm (Pp) and the yearly positive temperature (Tp) (see "Pp" and "Tp" above)
Ios2	Ombrothermic index of the warmest bimonth of the summer quarter
It	Thermicity Index (Ten times the sum of T (yearly average temperature), m (average minimum temperature of the coldest month of the year), M (average maximum temperature of the coldest month of the year)
Pcm1	precipitation for warmest 4 month period
Pcm2	precipitation for 4 month period immediately following the Pcm1 period
Pcm3	precipitation for 4 month period immediately following the Pcm2 period
Pp	Yearly Positive Precipitation (In mm, total average precipitation of those months whose average temperature is higher than 0ºC)
Pss	Precipitation total for warmest six-month period
Psw	Precipitation total for coldest six-month period
rain_1	Precipitation for month 1
rain_2	Precipitation for month 2
rain_3	Precipitation for month 3
rain_4	Precipitation for month 4
rain_5	Precipitation for month 5
rain_6	Precipitation for month 6
rain_7	Precipitation for month 7
rain_8	Precipitation for month 8
rain_9	Precipitation for month 9

Variable name	Variable description
rain_10	Precipitation for month 10
rain_11	Precipitation for month 11
rain_12	Precipitation for month 12
sm_rain_1_4	Sum of precipitation for four month period from month 1 to month 4
sm_rain_1_6	Sum of precipitation for six month period from month 1 to month 6
sm_rain_2_5	Sum of precipitation for four month period from month 2 to month 5
sm_rain 2 7	Sum of precipitation for six month period from month 2 to month 7
sm rain 3 6	Sum of precipitation for four month period from month 3 to month 6
sm rain 3 8	Sum of precipitation for six month period from month 3 to month 8
sm rain 4 7	Sum of precipitation for four month period from month 4 to month 7
sm rain 4 9	Sum of precipitation for six month period from month 4 to month 9
sm rain 5 10	Sum of precipitation for four month period from month 5 to month 10
sm rain 5 8	Sum of precipitation for six month period from month 5 to month 8
sm rain 6 11	Sum of precipitation for four month period from month 6 to month 11
sm rain 6 9	Sum of precipitation for six month period from month 6 to month 9
sm rain 7 10	Sum of precipitation for four month period from month 7 to month 10
sm rain 7 12	Sum of precipitation for six month period from month 7 to month 12
sm rain 8 1	Sum of precipitation for four month period from month 8 to month 1
sm rain 8 11	Sum of precipitation for six month period from month 8 to month 11
sm rain 9 12	Sum of precipitation for four month period from month 9 to month 12
sm rain 9 2	Sum of precipitation for six month period from month 9 to month 2
sm rain 10 1	Sum of precipitation for four month period from month 10 to month 1
sm rain 10 3	Sum of precipitation for six month period from month 10 to month 3
sm rain 11 2	Sum of precipitation for four month period from month 11 to month 2
sm rain 11 4	Sum of precipitation for six month period from month 11 to month 4
sm rain 12 3	Sum of precipitation for four month period from month 12 to month 3
sm rain 12 5	Sum of precipitation for six month period from month 12 to month 5

Variable name	Variable description
sm temp 1 4	Sum of monthly daily average temperature for four month period from month 1 to month 4
sm temp 1 6	Sum of monthly daily average temperature for six month period from month 1 to month 6
sm temp 2 5	Sum of monthly daily average temperature for four month period from month 2 to month 5
sm temp 2 7	Sum of monthly daily average temperature for six month period from month 2 to month 7
sm temp 3 6	Sum of monthly daily average temperature for four month period from month 3 to month 6
sm temp 3 8	Sum of monthly daily average temperature for six month period from month 3 to month 8
sm temp 4 7	Sum of monthly daily average temperature for four month period from month 4 to month 7
sm temp 4 9	Sum of monthly daily average temperature for six month period from month 4 to month 9
sm temp 5 10	Sum of monthly daily average temperature for four month period from month 5 to month 10
sm temp 5 8	Sum of monthly daily average temperature for six month period from month 5 to month 8
sm temp 6 11	Sum of monthly daily average temperature for four month period from month 6 to month 11
sm temp 6 9	Sum of monthly daily average temperature for six month period from month 6 to month 9
sm temp 7 10	Sum of monthly daily average temperature for four month period from month 7 to month 10
sm temp 7 12	Sum of monthly daily average temperature for six month period from month 7 to month 12
sm temp 8 1	Sum of monthly daily average temperature for four month period from month 8 to month 1
sm temp 8 11	Sum of monthly daily average temperature for six month period from month 8 to month 11
sm temp 9 12	Sum of monthly daily average temperature for four month period from month 9 to month 12
sm temp 9 2	Sum of monthly daily average temperature for six month period from month 9 to month 2
sm temp 10 1	Sum of monthly daily average temperature for four month period from month 10 to month 1
sm temp 10 3	Sum of monthly daily average temperature for six month period from month 10 to month 3
sm temp 11 2	Sum of monthly daily average temperature for four month period from month 11 to month 2
sm temp 11 4	Sum of monthly daily average temperature for six month period from month 11 to month 4
sm temp 12 3	Sum of monthly daily average temperature for four month period from month 12 to month 3
sm temp 12 5	Sum of monthly daily average temperature for six month period from month 12 to month 5
tavg_1	Average temperature of month 1
tavg_2	Average temperature of month 2
tavg_3	Average temperature of month 3

Variable name	Variable description
tavg_4	Average temperature of month 4
tavg_5	Average temperature of month 5
tavg_6	Average temperature of month 6
tavg_7	Average temperature of month 7
tavg_8	Average temperature of month 8
tavg_9	Average temperature of month 9
tavg_10	Average temperature of month 10
tavg_11	Average temperature of month 11
tavg_12	Average temperature of month 12
Tmax	Average temperature of the warmest month
Tmin	Average temperature of the coldest month
Tp	Sum of monthly positive average temperature * 10

Table 13. Subset of bioclimatic variables, retaining only those least mutually correlated.

Variable name	Variable description
Ic	Continentality Index (yearly thermic interval) (Tmax - Tmin (Tmax = highest monthly daily average temperature value for each cell; Tmin = lowest monthly daily average temperature value for each cell)
Io	Ombrothermic Index (Ten times the quotient resulting value between the yearly positive precipitation in mm (Pp) and the yearly positive temperature (Tp) (see "Pp" and "Tp" above)
Ios2	Ombrothermic index of the warmest bimonth of the summer quarter (
It	Thermicity Index (Ten times the sum of T (yearly average temperature), m (average minimum temperature of the coldest month of the year), M (average maximum temperature of the coldest month of the year)
Pcm2	precipitation for 4 month period immediately following the Pcm1 period
Pcm3	precipitation for 4 month period immediately following the Pcm2 period
Pp	Yearly Positive Precipitation (In mm, total average precipitation of those months whose average temperature is higher than 0ºC)
Psw	Precipitation total for coldest six-month period
rain_4	Precipitation for month 4
rain_5	Precipitation for month 5
rain_10	Precipitation for month 10

Variable name	**Variable description**
rain_11	Precipitation for month 11
sm rain 3 8	Sum of precipitation for six month period from month 3 to month 8
sm rain 7 12	Sum of precipitation for six month period from month 7 to month 12
Tmax	Average temperature of the warmest month
Tp	Sum of monthly positive average temperature * 10

Table 14. Mean of variables for each bioclimatic class.

Class	Ic	Io	Ios2	It	Pcm2	Pcm3	Pp	Psw	rain_4	rain_5	rain_10	rain_11	sm rain 3 8	sm rain 7 12	Tmax	Tp
1*	6.80	3.87	6.76	612.52	379.09	123.27	1038.64	256.18	95.31	60.39	34.46	51.07	437.19	304.69	25.97	2749.37
2	5.63	4.50	11.47	737.76	659.33	32.48	1437.40	208.79	147.79	38.72	19.89	60.85	504.65	305.15	29.12	3201.46
3	7.56	3.34	9.55	704.92	330.90	27.97	1053.74	96.90	58.92	20.95	16.97	50.88	280.40	236.95	29.51	3158.20
4	13.27	1.48	3.15	583.23	101.08	49.74	431.35	92.43	27.19	21.03	20.77	39.02	124.02	145.46	29.85	2906.47
5	7.19	4.05	11.46	733.12	624.14	16.49	1315.23	97.00	64.52	16.16	34.69	94.87	314.85	353.48	30.14	3250.43
6	13.74	0.83	1.04	599.03	116.83	23.49	246.62	122.04	16.08	32.65	3.01	2.25	164.01	59.12	31.30	2968.18
7	12.11	1.67	4.52	649.76	95.07	32.85	525.53	41.31	14.95	9.39	20.40	38.61	100.96	157.69	31.15	3147.23
8	9.60	2.68	7.60	706.63	405.03	13.41	869.54	51.98	29.31	9.43	23.26	63.24	184.93	241.38	31.09	3252.23
9	10.69	1.93	6.00	708.60	255.00	15.81	641.31	56.99	22.29	16.57	6.41	18.96	161.29	118.13	32.07	3329.07
10	10.34	2.27	6.50	677.29	196.38	25.56	721.03	46.02	21.35	9.29	20.34	49.14	145.43	197.99	30.68	3172.96
11	15.05	1.08	2.27	627.48	101.89	22.08	338.29	62.44	17.79	19.27	6.72	18.42	113.61	91.67	32.51	3135.18
12	13.91	1.30	3.19	608.64	74.24	34.55	395.86	48.65	13.69	12.74	18.16	29.91	84.16	126.72	31.12	3042.61
13	16.76	0.93	1.70	580.52	92.62	23.96	275.23	80.89	21.08	21.17	3.44	9.53	122.85	67.59	32.30	2955.15
14	15.92	0.98	1.88	567.47	68.33	34.35	287.43	60.05	15.55	17.12	14.11	24.14	84.06	100.34	31.42	2938.96
15	15.51	1.19	2.24	560.29	85.84	41.02	337.36	73.20	19.43	21.39	19.09	29.41	100.94	117.51	30.28	2826.31
16	17.63	1.22	1.50	476.20	98.80	76.01	322.67	123.66	26.36	34.74	19.30	31.84	141.82	124.81	30.32	2649.33
17	17.89	0.90	1.27	527.92	87.35	30.25	245.17	91.83	25.42	21.99	4.97	9.06	126.31	69.73	31.34	2732.09
18	17.14	1.61	1.74	441.22	127.33	103.64	398.49	164.78	34.24	41.84	28.30	37.87	179.92	166.93	28.77	2476.41
19	17.67	0.67	1.02	513.01	50.91	37.69	188.60	59.30	11.24	14.55	13.43	15.96	71.33	72.88	31.61	2809.04
20	17.12	0.96	1.39	529.06	68.58	49.47	269.16	79.56	18.35	20.56	13.28	24.30	103.21	101.23	31.08	2796.51
21	14.54	2.75	3.13	438.08	161.01	181.85	634.47	220.01	43.24	48.95	56.24	69.04	240.72	296.79	25.96	2314.11
22	10.49	4.29	0.86	389.68	436.86	308.83	826.06	660.94	44.96	106.46	56.22	39.83	585.77	472.23	21.73	1941.12
23	17.05	1.02	0.91	479.67	108.19	51.78	255.15	127.37	22.10	29.71	9.99	10.77	154.52	95.48	29.41	2511.11

Class	Ic	Io	Ios2	It	Pcm2	Pcm3	Pp	Psw	rain_4	rain_5	rain_10	rain_11	sm rain 3 8	sm rain 7 12	Tmax	Tp
24	17.34	1.22	1.10	413.40	92.56	87.27	287.90	130.42	17.20	29.18	26.25	23.43	132.75	136.71	28.14	2363.57
25	16.29	2.11	1.45	353.42	146.00	145.33	432.42	228.84	29.51	41.84	40.29	32.85	214.19	221.10	25.24	2058.24
26	16.44	0.96	1.04	466.28	65.07	54.17	234.95	83.20	16.23	18.03	14.35	19.27	100.16	100.37	28.22	2452.14
27	17.92	0.61	0.80	479.46	46.30	38.97	162.57	58.20	8.65	12.29	14.33	12.45	63.69	68.48	30.76	2669.38
28	17.75	0.87	1.06	469.66	71.47	50.35	225.53	79.01	13.85	18.62	18.28	18.71	91.96	92.83	29.95	2587.94
29	13.67	1.81	0.47	447.36	233.09	129.71	412.24	325.80	22.33	61.36	18.76	14.67	310.96	211.56	26.23	2296.03
30	14.67	3.76	3.07	340.66	199.60	224.52	678.89	314.65	44.06	53.41	59.85	65.35	301.69	343.98	22.37	1821.51
31	15.67	1.01	0.76	403.00	71.48	78.91	225.92	112.77	12.57	20.66	22.54	18.28	104.22	118.62	26.35	2240.01
32	17.28	0.92	1.19	491.44	71.45	40.73	236.62	85.85	20.31	21.44	8.38	14.93	108.44	82.24	29.72	2580.38
33	15.59	0.78	0.73	443.96	50.02	53.53	186.96	73.89	11.34	14.75	14.20	16.06	79.42	89.21	27.45	2398.62
34	13.90	1.88	0.89	341.72	130.73	141.94	356.34	222.97	20.89	33.31	35.05	28.81	188.78	204.99	22.89	1903.63
35	16.98	0.67	0.75	445.68	45.63	47.46	167.28	65.86	8.48	13.24	15.18	12.36	68.54	76.13	28.88	2482.56
36	14.56	1.29	0.78	377.25	90.98	102.53	267.87	154.01	14.67	24.35	28.16	21.93	131.00	150.55	24.57	2083.16
37	15.39	1.30	0.81	435.32	134.08	78.97	296.13	175.12	22.67	38.24	13.57	15.27	190.88	130.16	26.74	2278.15
38	10.93	3.19	1.30	334.00	223.24	213.96	547.56	361.77	36.00	53.63	48.90	39.43	318.22	312.49	20.15	1741.83
39	11.78	5.53	3.30	300.93	279.13	302.16	832.99	446.96	60.34	66.05	76.59	73.99	417.11	445.94	18.65	1529.85
40	12.26	1.43	0.86	401.71	116.01	98.39	297.01	171.14	20.54	32.25	19.54	22.72	167.72	150.93	23.36	2082.41
41	14.15	0.82	0.68	433.84	54.51	55.57	189.16	79.64	12.89	15.75	13.21	16.03	86.27	91.95	26.06	2314.33
42	12.83	1.00	0.73	417.88	73.23	69.50	219.74	108.85	15.01	21.31	14.77	18.85	111.21	108.27	24.49	2199.80
43	11.47	1.96	0.88	382.96	165.46	140.33	382.80	257.19	23.90	41.90	28.41	24.71	233.25	209.52	22.13	1962.12
44	10.94	9.67	3.94	273.89	470.39	484.90	1231.02	777.39	83.90	109.84	115.24	94.05	686.88	707.53	16.77	1342.93
45	8.50	18.60	9.57	272.52	822.35	765.20	2198.95	1240.73	194.52	199.20	188.58	154.55	1193.22	1140.02	14.99	1279.75
46	9.70	6.54	9.28	497.16	496.49	264.79	1536.56	487.40	162.45	139.40	72.68	111.51	716.48	480.17	24.05	2363.96
47	11.21	4.57	5.98	456.59	274.49	225.60	1018.04	324.54	85.34	87.35	66.56	91.41	424.57	386.84	23.93	2261.20

Class	Ic	Io	Ios2	It	Pcm2	Pcm3	Pp	Psw	rain_4	rain_5	rain_10	rain_11	sm rain 3 8	sm rain 7 12	Tmax	Tp
48	12.02	2.60	3.55	519.49	153.29	173.22	672.43	201.05	45.33	51.54	52.86	71.61	243.01	292.94	26.89	2596.37
49	17.11	1.13	1.47	508.94	86.26	51.53	296.57	83.11	18.48	21.78	19.43	28.84	111.38	117.29	29.67	2626.38
50	16.19	2.20	2.50	434.90	147.73	144.64	525.71	195.86	38.52	46.07	41.90	55.02	216.63	231.16	27.52	2391.53
51	12.53	1.31	3.44	677.35	112.15	17.05	431.39	61.84	19.21	19.85	3.89	12.47	139.68	86.08	32.47	3280.70
52	9.63	2.64	6.50	608.61	162.51	52.22	722.10	108.49	37.50	29.46	22.57	59.72	188.67	212.83	26.84	2734.35
53	16.91	1.31	1.65	494.70	91.80	59.95	325.72	93.03	20.35	23.50	22.51	32.98	121.60	133.00	28.46	2487.96
54	15.50	1.45	2.32	530.85	119.08	64.48	405.44	127.65	35.05	36.47	21.55	35.55	152.88	144.25	30.16	2794.16
55	14.79	1.22	2.65	630.26	102.26	22.36	375.94	88.26	26.09	24.00	2.68	6.63	160.27	72.45	32.41	3095.69
56	11.50	2.07	3.64	571.39	149.80	84.14	573.51	143.23	38.72	38.59	31.49	58.32	192.03	216.73	28.03	2778.85
57	13.25	1.76	3.04	556.77	129.15	74.17	489.67	132.80	33.93	33.19	27.59	50.40	166.01	187.36	28.88	2783.86
58	14.90	2.04	2.99	500.73	141.08	107.78	524.35	166.39	38.41	44.39	33.85	51.54	195.72	207.42	28.10	2574.15
59	15.36	1.52	3.11	604.16	104.51	28.72	430.16	109.38	35.34	25.01	4.29	8.83	181.69	91.93	30.59	2838.75

*Class 1 corresponded to coastal/oceanic, and was reclassified to NoData

Table 15. Standard deviation of variables for each bioclimatic class.

Class	Ic	Io	Ios2	It	Pcm2	Pcm3	Pp	Psw	rain_4	rain_5	rain_10	rain_11	sm rain 3 8	sm rain 7 12	Tmax	Tp
1*	2.03	1.83	4.57	166.62	198.35	128.34	479.30	201.04	69.78	42.21	29.13	32.48	203.30	151.75	4.83	649.58
2	1.13	0.71	2.33	28.90	153.09	25.07	208.12	65.51	34.61	17.38	10.14	21.19	89.19	60.04	1.07	118.34
3	1.31	0.38	1.22	25.21	135.51	15.53	105.78	32.19	19.04	9.05	4.84	14.28	49.94	34.34	1.25	124.38
4	0.75	0.13	0.50	15.87	10.50	5.19	35.20	12.85	4.58	3.77	1.42	4.65	12.79	9.03	0.46	39.00

Class	Ic	Io	Ios2	It	Pcm2	Pcm3	Pp	Psw	rain_4	rain_5	rain_10	rain_11	sm rain 3 8	sm rain 7 12	Tmax	Tp
5	1.15	0.53	1.67	20.88	96.28	5.77	171.94	23.25	17.28	4.68	12.88	25.10	58.50	64.60	0.58	70.88
6	1.24	0.07	0.45	34.11	14.87	10.67	28.96	21.72	2.84	6.07	2.04	1.17	14.34	15.11	1.27	147.56
7	0.69	0.17	0.55	15.76	15.47	4.51	53.33	7.40	3.64	2.39	4.09	5.37	12.46	16.52	0.41	60.08
8	1.01	0.31	0.98	22.21	51.78	3.91	98.04	12.69	8.23	3.46	5.21	12.66	29.40	34.01	0.65	88.02
9	1.00	0.28	1.03	15.25	87.63	2.71	90.79	12.81	6.91	5.12	3.80	8.40	31.33	21.37	0.75	64.57
10	0.99	0.28	0.90	16.81	79.80	8.94	85.08	9.09	5.61	3.03	5.15	7.03	24.45	19.20	0.72	76.82
11	0.67	0.10	0.37	14.45	8.79	2.50	32.79	5.60	2.02	1.44	3.49	3.08	11.26	8.25	0.34	51.65
12	0.58	0.12	0.41	18.72	10.54	3.65	37.17	9.14	3.70	2.17	1.84	3.57	11.28	10.24	0.39	65.05
13	0.51	0.10	0.40	16.56	8.95	3.37	29.26	12.61	3.56	3.44	1.02	5.32	17.08	11.86	0.51	73.21
14	0.53	0.09	0.37	20.21	14.89	6.13	27.46	8.93	3.28	2.81	2.39	2.55	15.39	8.97	0.46	47.39
15	0.52	0.08	0.38	15.92	12.08	4.06	24.10	11.57	3.15	3.83	1.71	2.95	13.76	7.24	0.46	68.91
16	0.40	0.12	0.24	19.39	9.08	7.36	28.45	11.67	3.74	4.32	2.09	2.89	12.60	11.32	0.51	76.03
17	0.45	0.09	0.36	15.43	13.71	5.00	24.23	11.79	4.36	2.76	1.50	3.02	14.94	7.72	0.45	67.62
18	0.27	0.14	0.29	21.32	9.62	10.76	30.76	14.71	4.36	3.13	3.87	5.61	12.39	15.01	0.57	84.25
19	0.42	0.07	0.19	13.66	4.62	3.97	21.72	6.88	2.20	1.83	2.17	2.51	7.84	7.46	0.23	46.64
20	0.40	0.08	0.24	19.39	9.88	9.34	21.23	10.20	2.67	2.83	3.74	3.52	12.26	11.20	0.43	60.99
21	1.04	0.28	0.48	27.55	14.98	14.56	46.73	26.15	5.07	5.08	6.17	7.60	19.45	22.78	1.00	108.94
22	1.60	0.79	0.29	33.71	78.26	53.33	129.02	113.68	9.26	19.75	12.98	9.44	97.74	78.18	1.96	163.45
23	0.73	0.09	0.23	16.03	14.79	7.13	16.85	20.04	3.18	4.04	2.31	3.02	16.74	9.14	0.70	76.53
24	0.48	0.16	0.13	15.69	11.52	12.61	30.18	17.89	3.32	3.26	4.27	3.31	19.18	17.35	0.89	84.17
25	0.49	0.29	0.30	19.09	17.49	20.20	51.48	29.65	6.22	4.84	4.15	6.42	24.80	28.13	0.90	94.69
26	0.42	0.10	0.12	13.33	12.94	5.67	21.05	12.98	2.90	3.63	3.19	3.11	16.75	9.36	0.47	53.48
27	0.19	0.05	0.07	10.85	5.61	3.89	13.86	6.55	1.82	2.05	2.11	2.22	6.47	6.10	0.45	52.70
28	0.26	0.08	0.11	15.31	8.77	9.54	17.97	13.47	1.82	3.87	2.15	3.64	9.11	9.56	0.51	58.95

Class	Ic	Io	Ios2	It	Pcm2	Pcm3	Pp	Psw	rain_4	rain_5	rain_10	rain_11	sm rain 3 8	sm rain 7 12	Tmax	Tp
29	0.93	0.38	0.13	32.22	47.72	33.57	78.86	74.33	2.36	11.19	5.30	4.16	62.94	50.98	1.04	125.07
30	1.19	0.53	0.93	35.30	22.93	21.70	75.09	42.41	6.23	6.86	5.90	12.39	31.62	34.05	1.85	192.26
31	0.67	0.12	0.19	13.50	8.73	8.79	23.90	13.58	2.75	3.28	2.90	1.87	13.07	11.85	0.66	61.56
32	0.35	0.06	0.16	10.19	10.89	5.37	15.73	9.56	3.60	2.79	1.67	3.97	12.58	8.26	0.47	51.07
33	0.45	0.06	0.12	14.03	5.33	6.99	15.78	8.97	2.72	1.69	3.12	1.77	7.19	7.36	0.38	41.40
34	0.88	0.28	0.17	19.25	17.65	16.49	39.55	29.07	3.61	4.63	3.91	3.69	23.88	22.44	0.82	82.96
35	0.44	0.07	0.09	11.86	5.98	4.95	15.05	8.65	1.72	2.51	1.92	1.84	7.23	7.95	0.49	49.64
36	0.84	0.15	0.17	15.28	12.22	10.51	28.58	22.42	2.41	4.14	2.60	2.22	18.66	14.85	0.72	72.21
37	0.73	0.13	0.22	21.65	23.84	10.62	20.46	32.99	2.93	6.34	2.11	3.47	26.65	15.70	1.06	105.13
38	1.62	0.56	0.55	41.81	39.45	26.02	60.40	55.13	7.08	10.47	8.94	9.75	49.66	36.24	1.56	164.83
39	2.01	0.99	1.26	34.19	49.82	39.87	105.67	82.41	13.77	12.30	9.94	14.13	66.21	55.64	1.86	189.56
40	1.22	0.16	0.26	11.03	17.13	12.45	28.89	27.58	3.36	4.67	3.89	3.19	22.73	17.19	0.79	47.13
41	0.50	0.10	0.13	6.60	9.70	6.99	21.92	10.92	2.47	2.87	2.59	2.16	14.91	8.59	0.51	37.85
42	0.68	0.12	0.18	6.51	11.38	8.88	24.62	15.47	2.55	4.00	3.17	2.68	16.35	12.19	0.63	39.12
43	1.09	0.22	0.25	13.65	22.28	18.71	37.34	34.77	3.41	5.99	6.00	4.20	28.12	25.95	0.83	61.96
44	2.46	2.89	1.39	45.95	85.05	75.75	175.59	129.32	19.25	22.45	20.70	18.03	111.58	106.36	2.36	272.68
45	1.32	5.54	4.75	117.57	208.01	161.02	551.89	205.80	105.45	45.36	46.04	25.57	255.53	201.78	4.02	535.96
46	1.31	1.28	3.73	82.66	160.13	58.95	345.93	105.18	56.39	30.20	18.59	19.99	153.32	63.28	2.15	318.53
47	1.03	0.81	1.55	66.82	54.40	40.34	132.39	53.89	17.28	16.49	11.11	11.42	72.65	36.11	1.91	281.96
48	1.10	0.36	0.65	28.93	22.75	22.37	83.23	24.56	8.08	7.40	8.20	8.75	39.32	30.99	0.97	118.63
49	0.49	0.08	0.32	18.39	13.70	10.52	21.12	9.70	1.88	1.82	3.21	2.92	11.80	10.76	0.46	56.71
50	0.55	0.19	0.43	21.93	12.44	11.52	41.45	21.21	3.57	4.33	4.22	7.14	14.54	20.73	0.61	75.46
51	0.85	0.17	0.69	15.22	22.55	4.38	59.73	10.07	3.08	3.44	2.71	6.24	16.62	18.79	0.45	53.03
52	1.01	0.34	0.94	22.09	37.58	18.28	89.65	37.45	12.39	11.02	4.06	8.21	49.42	20.57	0.95	110.64

Class	Ic	Io	Ios2	It	Pcm2	Pcm3	Pp	Psw	rain_4	rain_5	rain_10	rain_11	sm rain 3 8	sm rain 7 12	Tmax	Tp
53	0.28	0.10	0.28	15.87	13.18	11.13	21.53	9.90	2.08	1.80	3.72	4.17	11.18	10.33	0.57	71.94
54	0.62	0.13	0.17	15.55	11.04	12.89	29.87	12.63	4.26	4.46	2.46	3.69	14.80	15.19	0.42	64.63
55	0.72	0.15	0.46	16.08	15.66	5.07	44.43	10.26	3.73	4.38	1.14	2.06	19.16	11.36	0.61	92.07
56	0.79	0.14	0.62	19.31	16.98	26.67	34.99	16.53	4.17	4.63	6.52	5.73	17.45	22.89	0.56	65.64
57	0.68	0.11	0.34	15.67	6.66	8.56	28.73	11.43	2.43	3.88	2.86	5.48	9.58	16.64	0.41	52.23
58	0.93	0.17	0.31	18.29	10.74	18.12	37.33	10.19	3.97	2.46	4.73	5.14	11.44	18.11	0.64	70.04
59	0.55	0.12	0.27	13.28	10.95	2.49	36.55	12.01	2.53	2.95	0.75	0.80	19.67	6.39	0.49	71.45

*Class 1 corresponded to coastal/oceanic, and was reclassified to NoData

Table 16. Lithology codes and attribute descriptions.

Lithology Code	Lithology Description
1	alkaline ultrabasic
2	anthropogenic
3	argillaceous detrital sediment
4	argillaceous detrital sediment; feldspar- or lithic-rich arenite to rudite
5	argillaceous detrital sediment; igneous felsic-intermediate intrusive
6	argillaceous detrital sediment; igneous felsic-intermediate volcanic
7	argillaceous detrital sediment; igneous felsic volcanic
8	argillaceous detrital sediment; igneous mafic volcanic
9	argillaceous detrital sediment; igneous volcanic
10	argillaceous detrital sediment; metasedimentary
11	argillaceous detrital sediment; metasedimentary siliciclastic
12	argillaceous detrital sediment; mineralisation
13	argillaceous detrital sediment; organic-rich rock
14	argillaceous detrital sediment; quartz-rich arenite to rudite
15	argillaceous detrital sediment; sedimentary
16	argillaceous detrital sediment; sedimentary carbonate
17	argillaceous detrital sediment; sedimentary non-carbonate chemical or biochemical
18	argillaceous detrital sediment; sedimentary siliciclastic
19	fault / shear rock
20	feldspar- or lithic-rich arenite to rudite
21	feldspar- or lithic-rich arenite to rudite; argillaceous detrital sediment
22	feldspar- or lithic-rich arenite to rudite; igneous felsic volcanic
23	feldspar- or lithic-rich arenite to rudite; igneous intermediate volcanic
24	feldspar- or lithic-rich arenite to rudite; igneous mafic volcanic
25	feldspar- or lithic-rich arenite to rudite; igneous volcanic
26	feldspar- or lithic-rich arenite to rudite; metasedimentary siliciclastic
27	feldspar- or lithic-rich arenite to rudite; organic-rich rock
28	feldspar- or lithic-rich arenite to rudite; sedimentary carbonate
29	feldspar- or lithic-rich arenite to rudite; sedimentary non-carbonate chemical or biochemical
30	feldspar- or lithic-rich arenite to rudite; sedimentary siliciclastic
31	high grade metamorphic rock
32	high grade metamorphic rock; fault / shear rock
33	high grade metamorphic rock; igneous felsic intrusive
34	high grade metamorphic rock; igneous mafic intrusive
35	high grade metamorphic rock; meta-igneous mafic
36	high grade metamorphic rock; meta-igneous mafic intrusive
37	high grade metamorphic rock; metasedimentary siliciclastic
38	igneous
39	igneous carbonatite
40	igneous felsic-intermediate intrusive
41	igneous felsic-intermediate intrusive; igneous felsic intrusive
42	igneous felsic-intermediate volcanic
43	igneous felsic-intermediate volcanic; argillaceous detrital sediment
44	igneous felsic-intermediate volcanic; feldspar- or lithic-rich arenite to rudite

Lithology Code	Lithology Description
45	igneous felsic-intermediate volcanic; igneous felsic volcanic
46	igneous felsic-intermediate volcanic; quartz-rich arenite to rudite
47	igneous felsic-intermediate volcanic; sedimentary siliciclastic
48	igneous felsic intrusive
49	igneous felsic intrusive; high grade metamorphic rock
50	igneous felsic intrusive; igneous felsic volcanic
51	igneous felsic intrusive; igneous intermediate intrusive
52	igneous felsic intrusive; igneous mafic intrusive
53	igneous felsic intrusive; meta-igneous felsic
54	igneous felsic intrusive; meta-igneous felsic intrusive
55	igneous felsic intrusive; meta-igneous mafic
56	igneous felsic intrusive; metasedimentary siliciclastic
57	igneous felsic intrusive; metasomatic
58	igneous felsic volcanic
59	igneous felsic volcanic; argillaceous detrital sediment
60	igneous felsic volcanic; feldspar- or lithic-rich arenite to rudite
61	igneous felsic volcanic; igneous felsic intrusive
62	igneous felsic volcanic; igneous intermediate volcanic
63	igneous felsic volcanic; igneous mafic volcanic
64	igneous felsic volcanic; igneous volcanic
65	igneous felsic volcanic; meta-igneous felsic volcanic
66	igneous felsic volcanic; metasedimentary
67	igneous felsic volcanic; metasedimentary siliciclastic
68	igneous felsic volcanic; sedimentary
69	igneous felsic volcanic; sedimentary carbonate
70	igneous felsic volcanic; sedimentary siliciclastic
71	igneous foid-bearing volcanic
72	igneous foid-bearing volcanic; igneous mafic volcanic
73	igneous intermediate intrusive
74	igneous intermediate intrusive; igneous felsic intrusive
75	igneous intermediate intrusive; igneous mafic intrusive
76	igneous intermediate intrusive; meta-igneous mafic
77	igneous intermediate intrusive; meta-igneous mafic intrusive
78	igneous intermediate volcanic
79	igneous intermediate volcanic; feldspar- or lithic-rich arenite to rudite
80	igneous intermediate volcanic; igneous felsic volcanic
81	igneous intermediate volcanic; igneous mafic volcanic
82	igneous intermediate volcanic; igneous volcanic
83	igneous intermediate volcanic; sedimentary siliciclastic
84	igneous intrusive
85	igneous kimberlite
86	igneous lamproites
87	igneous lamproites; igneous volcanic
88	igneous mafic intrusive
89	igneous mafic intrusive; high grade metamorphic rock

Lithology Code	Lithology Description
90	igneous mafic intrusive; igneous felsic intrusive
91	igneous mafic intrusive; igneous foid-bearing intrusive
92	igneous mafic intrusive; igneous intermediate intrusive
93	igneous mafic intrusive; igneous mafic volcanic
94	igneous mafic intrusive; igneous ultramafic intrusive
95	igneous mafic intrusive; meta-igneous mafic
96	igneous mafic intrusive; meta-igneous ultramafic intrusive
97	igneous mafic volcanic
98	igneous mafic volcanic; argillaceous detrital sediment
99	igneous mafic volcanic; feldspar- or lithic-rich arenite to rudite
100	igneous mafic volcanic; igneous felsic-intermediate volcanic
101	igneous mafic volcanic; igneous felsic volcanic
102	igneous mafic volcanic; igneous foid-bearing volcanic
103	igneous mafic volcanic; igneous intermediate volcanic
104	igneous mafic volcanic; igneous mafic intrusive
105	igneous mafic volcanic; igneous ultramafic
106	igneous mafic volcanic; igneous ultramafic intrusive
107	igneous mafic volcanic; igneous volcanic
108	igneous mafic volcanic; meta-igneous felsic
109	igneous mafic volcanic; meta-igneous mafic volcanic
110	igneous mafic volcanic; meta-igneous ultramafic
111	igneous mafic volcanic; sedimentary
112	igneous mafic volcanic; sedimentary non-carbonate chemical or biochemical
113	igneous mafic volcanic; sedimentary siliciclastic
114	igneous ultramafic intrusive
115	igneous ultramafic intrusive; igneous ultramafic volcanic
116	igneous ultramafic intrusive; meta-igneous ultramafic intrusive
117	igneous ultramafic intrusive; meta-igneous ultramafic volcanic
118	igneous ultramafic volcanic
119	igneous ultramafic volcanic; igneous ultramafic intrusive
120	igneous ultramafic volcanic; meta-igneous ultramafic intrusive
121	igneous ultramafic; meta-igneous ultramafic
122	igneous volcanic
123	igneous volcanic; argillaceous detrital sediment
124	igneous volcanic; igneous felsic intrusive
125	igneous volcanic; igneous felsic volcanic
126	igneous volcanic; igneous mafic intrusive
127	igneous volcanic; sedimentary
128	igneous; sedimentary
129	igneous; sedimentary siliciclastic
130	low grade metamorphic rock
131	meta-igneous
132	meta-igneous felsic
133	meta-igneous felsic intrusive
134	meta-igneous felsic intrusive; igneous felsic intrusive

Lithology Code	Lithology Description
135	meta-igneous felsic volcanic
136	meta-igneous felsic volcanic; meta-igneous felsic intrusive
137	meta-igneous felsic volcanic; metasedimentary siliciclastic
138	meta-igneous felsic; igneous felsic intrusive
139	meta-igneous felsic; meta-igneous mafic
140	meta-igneous felsic; metasedimentary
141	meta-igneous mafic
142	meta-igneous mafic intrusive
143	meta-igneous mafic intrusive; igneous mafic intrusive
144	meta-igneous mafic volcanic
145	meta-igneous mafic volcanic; igneous mafic intrusive
146	meta-igneous mafic volcanic; igneous mafic volcanic
147	meta-igneous mafic volcanic; meta-igneous ultramafic volcanic
148	meta-igneous mafic volcanic; metasedimentary carbonate
149	meta-igneous mafic volcanic; metasedimentary siliciclastic
150	meta-igneous mafic volcanic; sedimentary non-carbonate chemical or biochemical
151	meta-igneous mafic volcanic; sedimentary siliciclastic
152	meta-igneous mafic; igneous mafic intrusive
153	meta-igneous mafic; meta-igneous ultramafic
154	meta-igneous mafic; meta-igneous ultramafic intrusive
155	meta-igneous mafic; metasedimentary siliciclastic
156	meta-igneous mafic; sedimentary siliciclastic
157	meta-igneous ultramafic
158	meta-igneous ultramafic intrusive
159	meta-igneous ultramafic intrusive; igneous mafic intrusive
160	meta-igneous ultramafic intrusive; meta-igneous mafic
161	meta-igneous ultramafic intrusive; meta-igneous ultramafic
162	meta-igneous ultramafic volcanic
163	meta-igneous ultramafic volcanic; meta-igneous ultramafic intrusive
164	meta-igneous ultramafic; meta-igneous mafic
165	meta-igneous; metasedimentary
166	meta-igneous; metasedimentary siliciclastic
167	metamorphic
168	metamorphic protolith unknown
169	metamorphic protolith unknown; high grade metamorphic rock
170	metamorphic; metasedimentary carbonate
171	metamorphic; sedimentary
172	metasedimentary
173	metasedimentary carbonate; meta-igneous felsic volcanic
174	metasedimentary carbonate; meta-igneous mafic
175	metasedimentary carbonate; metasedimentary siliciclastic
176	metasedimentary non-carbonate chemical or biochemical
177	metasedimentary siliciclastic
178	metasedimentary siliciclastic; argillaceous detrital sediment
179	metasedimentary siliciclastic; feldspar- or lithic-rich arenite to rudite

Lithology Code	Lithology Description
180	metasedimentary siliciclastic; high grade metamorphic rock
181	metasedimentary siliciclastic; igneous
182	metasedimentary siliciclastic; igneous intermediate volcanic
183	metasedimentary siliciclastic; igneous mafic volcanic
184	metasedimentary siliciclastic; meta-igneous felsic
185	metasedimentary siliciclastic; meta-igneous mafic
186	metasedimentary siliciclastic; meta-igneous mafic volcanic
187	metasedimentary siliciclastic; meta-igneous ultramafic
188	metasedimentary siliciclastic; metasedimentary
189	metasedimentary siliciclastic; metasedimentary carbonate
190	metasedimentary siliciclastic; sedimentary carbonate
191	metasedimentary siliciclastic; sedimentary non-carbonate chemical or biochemical
192	metasedimentary siliciclastic; sedimentary siliciclastic
193	metasedimentary; high grade metamorphic rock
194	metasedimentary; meta-igneous
195	metasedimentary; meta-igneous felsic
196	metasedimentary; meta-igneous mafic
197	metasomatic
198	metasomatic; igneous felsic intrusive
199	organic-rich rock; sedimentary siliciclastic
200	quartz-rich arenite to rudite
201	quartz-rich arenite to rudite; igneous felsic volcanic
202	quartz-rich arenite to rudite; organic-rich rock
203	quartz-rich arenite to rudite; sedimentary carbonate
204	regolith
205	regolith; argillaceous detrital sediment
206	regolith; sedimentary carbonate
207	rock
208	sedimentary
209	sedimentary carbonate
210	sedimentary carbonate; argillaceous detrital sediment
211	sedimentary carbonate; feldspar- or lithic-rich arenite to rudite
212	sedimentary carbonate; igneous mafic volcanic
213	sedimentary carbonate; igneous volcanic
214	sedimentary carbonate; sedimentary
215	sedimentary carbonate; sedimentary non-carbonate chemical or biochemical
216	sedimentary carbonate; sedimentary siliciclastic
217	sedimentary non-carbonate chemical or biochemical
218	sedimentary non-carbonate chemical or biochemical; argillaceous detrital sediment
219	sedimentary non-carbonate chemical or biochemical; feldspar- or lithic-rich arenite to rudite
220	sedimentary non-carbonate chemical or biochemical; igneous mafic intrusive
221	sedimentary non-carbonate chemical or biochemical; meta-igneous mafic
222	sedimentary non-carbonate chemical or biochemical; meta-igneous ultramafic
223	sedimentary non-carbonate chemical or biochemical; metasedimentary siliciclastic
224	sedimentary non-carbonate chemical or biochemical; metasomatic

Lithology Code	Lithology Description
225	sedimentary non-carbonate chemical or biochemical; sedimentary carbonate
226	sedimentary non-carbonate chemical or biochemical; sedimentary siliciclastic
227	sedimentary siliciclastic
228	sedimentary siliciclastic; argillaceous detrital sediment
229	sedimentary siliciclastic; feldspar- or lithic-rich arenite to rudite
230	sedimentary siliciclastic; igneous felsic-intermediate volcanic
231	sedimentary siliciclastic; igneous felsic volcanic
232	sedimentary siliciclastic; igneous intermediate volcanic
233	sedimentary siliciclastic; igneous mafic volcanic
234	sedimentary siliciclastic; igneous volcanic
235	sedimentary siliciclastic; metasedimentary siliciclastic
236	sedimentary siliciclastic; organic-rich rock
237	sedimentary siliciclastic; quartz-rich arenite to rudite
238	sedimentary siliciclastic; sedimentary carbonate
239	sedimentary siliciclastic; sedimentary non-carbonate chemical or biochemical
240	sedimentary; igneous felsic volcanic
241	sedimentary; igneous volcanic
242	sedimentary; sedimentary non-carbonate chemical or biochemical
243	unknown
244	vein