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Environmental zonation across the Australian arid region based on long term vegetation dynamics

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1. Introduction

Classification of arid landscapes into units with characteristic climate, landforms, soils and vegetation provides a foundation for survey, conservation and management. Stratification of the landscape has been practiced worldwide and classifications are refined or updated as more information and data become available (Blasi et al., 2000; Cihlar et al., 1996; Jongman et al., 2006; Mucher et al., 2010; Townshend et al., 1991).

In Australia, as in many parts of the world, an integrated landscape approach to environmental stratification has been adopted. The Interim Biogeographical Regionalization for Australia (IBRA) defines 85 biogeographic regions, 39 of which fall wholly or mostly in the arid zone. The regions are defined on the basis of climate, geology, landform, vegetation and fauna (Thackway and Cresswell, 1997). In highly modified landscapes, such as those of Europe, ecoregions are similarly defined, although in the absence of natural vegetation, potential natural vegetation is inferred (Pesch et al., 2009).

Fundamental to the integrated approach is the assumption that climate, geology and geomorphology interact over time to produce characteristic landscape patterns and influence the distribution of soil and vegetation associations, which in turn influence faunal assemblages. Consequently there are associations of these environmental components and landscape can be classified and mapped into units with characteristic and recurring patterns and a degree of internal homogeneity.

In Australia this approach traces its origins back to the integrated land system survey embodied in the CSIRO Land Use Series (Christian and Stewart, 1953), later developed by Laut et al. (1977) for Environments of South Australia. Environmental units are defined by recurring landscape patterns interpreted from broad scale imagery (initially aerial photography, now more commonly multispectral satellite imagery), drawing on field surveys, broad scale biophysical data and expert knowledge to characterise the mapping units.

This represents, however, a static view of the environment, based on associations of climate, geomorphology, soil and vegetation, and does not necessarily account for the dynamics and function of the landscape. Australian arid landscapes in particular are highly dynamic and far from static, although differences in function may not be readily discerned on the ground, and are expressed over long periods of time.

Long-term sequences of satellite imagery from sensors such as NOAA AVHRR and MODIS now provide a means of observing the dynamics of landscapes over broad areas and long periods, and hence can provide an understanding of the function as well as distribution of landscape types. Actively growing vegetation within landscapes can be detected using the Normalised Difference Vegetation Index (NDVI), which calculates the difference in reflectance between the near-infrared and visible red bands divided by the sum of these two bands (Tucker, 1979). NDVI represents the chlorophyll abundance and energy absorption of the leaves (Myneni et al., 1995) and has been correlated with leaf area index, vegetation cover and biomass. In arid landscapes this is influenced by vegetation response to rainfall and by such factors as soil moisture absorption and holding capacity and vegetation type which itself may change over time as a result of the stochastic events of fire, flood or grazing.

Satellite imagery has been used to investigate temporal patterns in NDVI ever since it became available in the 1980's. Initially based only on few dates within a single year to stratify vegetation using a climatic gradient (Norwine and Greegor, 1983), later studies expanded to multiple dates per year and inter-annual comparisons. Investigations of landscape dynamics have included studies of mechanisms affecting primary production across modified landscapes such as those in Brazil (Barbosa et al., 2006) and monitoring of land use change (Al-Bakri and Taylor, 2003; Neigh et al., 2008; Turcotte et al., 1993; Weiss et al., 2004). Using time-sequences of NDVI these studies generally sought to identify or detect a change in particular landscape features.

The current study, on the other hand, seeks to understand the variability inherent in the landscape. It presents an analysis of the patterns of spatial and temporal variation of vegetative growth across the Australian arid zone, as revealed by a 25 year sequence of NOAA AVHRR bi-monthly NDVI composites. Our aim is to understand the dynamics and functional response of vegetation in the region and use this to inform and potentially improve the IBRA of the Australian arid zone. Specifically we seek to identify the underlying factors influencing patterns of arid vegetation growth and map the distribution of regions with similar response. This new classification is compared with the IBRA and used to evaluate the composition and boundaries of IBRA regions: our analysis sought to determine whether the IBRA classes are consistent with long-term evidence of vegetation response.

2. Methods

2.1 Study area

The limits of an arid zone are not rigid and can be defined according to the purpose of an investigation. The global agro-climatic classification for instance focuses on climate constraints on crop growth, and defines as arid the Australian region too dry to support field crops (Hutchinson et al., 1992; Hutchinson et al., 2005). The modified Köppen classification of world climates indicates a larger arid zone in Australia, comprising two categories, desert and grassland, where evaporation exceeds precipitation, defined by maximum, minimum and mean temperature, and mean rainfall records. (BOM ; Hutchinson, 1995; Stern et al., 2000). This larger arid definition includes, mainly at its margins, some dryland cultivated areas.

To include the maximum area of dry land natural vegetation cover, the current study used the modified Köppen definition of the arid zone. Recognising that cultivated vegetation response within this zone may confound the analysis of natural vegetation response, cultivated areas as indicated on the Australian Land Use Map (ALUM, 2000) were masked from the study area, resulting in the arid zone outline used for the current study (Fig. 1).

Insert Figure 1 approx. here

The approximately 5,250,000 km^2 area contains a great diversity of land types and vegetation, including tussock and hummock grasslands, chenopod shrublands, tall open and closed shrublands and low woodlands both open and closed, with herbaceous, grassland or shrub understorey. Mean annual rainfall ranges up to 400 mm in the north and 250 mm in the south.

2.2 NDVI data

This study used a series of 600 NDVI images which were derived from data collected daily from 1982 to 2006, by the Advanced Very High Resolution Radiometer (AVHRR) aboard the United States National Oceanographic and Atmospheric Administration (NOAA) polar orbiting satellite. The satellite data was corrected for atmospheric effects and cloud cover, calculated at maximum reflectance over half month intervals, and resampled from the original 1.1 km to 8 km spatial resolution, by the University of Maryland Global Land Cover Facility (GLCF) for the Global Inventory Modeling and Mapping Studies (GIMMS) (Pinzon et al., 2005; Tucker et al., 2005). The files had been converted from native binary to GeoTIFF format. NDVI values had been scaled to values ranging from -10000 to 10000, water pixels had been assigned the value of -10000, and masked pixels -5000. This scaling was maintained for the current study because absolute NDVI values were not required. The NDVI range of -1 to 1 can be recovered, if required, using the formula: NDVI=float(raw/10000) (GLCF 2008). The data were obtained as continental files, Albers projection, and were for this study reprojected to South Australian Lambers Conformal Conic.

A visual inspection revealed sensor and mosaicking artifacts in several images. These images were retained within the data stack, noting the image dates, on the assumption that if the artifacts are the source of significant variation, it would be revealed by the principal component analysis, and if not, the anomaly would be consigned to noise.

2.3 Principal component analysis

In order to examine the modes of variation within the 25-year NDVI sequence, principal component analysis (PCA) was applied to the data set. This is a linear transformation of correlated variables into uncorrelated variables retaining the same number of variables but eliminating redundancy. The transformed variables are independent and ordered from the first component representing the maximum variance within the data set, down to the subsequent components representing progressively less variance. It is a useful technique to reveal the areas of greatest spatial and/or temporal variability within a landscape based on the distribution of eigenvalues and explained variance and by linking the interpretation of the principal components to the geography of the area under investigation (Eastman and Fulk, 1993; Roberts, 1994).

The orthogonal character of unstandardised PCA (uPCA), which uses the covariance matrix, imposes constraint (Eastman and Fulk, 1993), and relaxing this constraint by using the correlation matrix (standardised PCA) is claimed to give better temporal or spatial representation of the underlying processes (Fung and Ledrew, 1987; Hall-Beyer, 2003). While such improvement was apparent in shorter time series of, for example, 12 images (Eklundh and Singh, 1993) and standardisation has also been used to improve signal-to-noise ratio, for the current study no advantage appeared to be gained by standardising the analysis. Standardisation may be judicious when using data from several disparate geographical areas (Weiss et al., 2004) but this is not the case for the current study. Inspection of the first PCs while preparing the data revealed little difference between the two methods, apart from inversion of the resultant PC scores. Inversion is of no consequence, as polarisation is a result of the options chosen by the image analysis software in generating the PCs and does not affect the magnitude or meaning of the results. The covariance matrix (uPCA) was therefore used in the study and all bands were included to avoid loss of meaningful information.

PCA transformed the data into 600 PCs. Eigenvalues were inspected to detect the percentage of variation explained by each PC and eigenvector loadings for each PC were plotted against the image dates. The PC image patterns and associated plots were scrutinized together with relevant climate records to analyse the factors that account for the variation in the multidimensional data space. To aid understanding a colour composite was created of the first 2 PCs. The latest available revision of IBRA, v6.1, was used as overlay to indicate locations and to visually detect correlation between the colour composite patterns and IBRA regions.

2.4 Classification

PCA reduced the 600 NDVI images to a small number of main components. Of these the first 14 components, representing 85% of the variance in the data, were used as a basis for unsupervised classification. This selection incorporated as much meaningful variability as possible, including PCs representing broad scale as well as localized events, but excluding PCs representing less than 0.5% of variability and potentially representing sensor artifacts and noise. The PCs were used in unstandardised form, hence were weighted in their relative contribution to the classification. Iso-classification using the selected PCs classified image pixels on the basis of similarity of PC profile, with the resultant classification image showing the distribution of classes across the landscape. The number of classes in which to cluster the data was decided by trial, aiming to approximate the number of large IBRA regions within the arid zone. The factors separating the classes were examined through plots of class PC scores and the classes characterized by extracting, out of the original data stack, mean NDVI time traces for each class. The relationship between classes and the IBRA stratification was investigated using GIS analysis.

3. Results

3.1 Factors in vegetation temporal response

PCA of the 600 image series of the Australian non-cultivated arid zone resulted in 600 principal components and their associated matrices. The greatest source of variation in the data (65.05%) was captured by PC1 (Table 1), which clearly represents the geographic distribution of the sum total of NDVI for each pixel, as shown in the PC1 image, where white indicates low total vegetation grading to black for high vegetation response (Fig. 2).

Insert Table 1 approx. here

Geographically the highest aggregate vegetation occurred towards the tropical and subtropical margins of the arid north and north-east, and in the south and south-east where the arid zone borders on temperate areas, as evidenced in the woodlands of Western Australia and South Australia’s Conservation Parks. Floodplains of the major inland watercourses in Queensland also showed high aggregate NDVI. Lowest vegetation aggregate was evident in the South Australian Stony Plains and Simpson and Strzeleckie Dunefields and the Channel Country of Queensland (Fig. 1). This low total vegetation was noticeably less pronounced across the Great Victoria Desert and the deserts of Western Australia, areas with similarly low rainfall (mean <250mm pa). Salt lakes, as one would expect, show virtually no aggregated vegetation response in the PC1 image.

Insert Figure 2 approx. here

Insert Figure 3 approx. here

The associated plot of band loadings for PC 1 revealed a weak tendency towards seasonality. In some, but not all years, total of actively growing vegetation appears lowest around November and highest during the Austral autumn and winter, March to August (Fig. 3).

The second greatest source of variation, PC 2, captured 7.15% of the variation in the NDVI image sequence. The eigenvector plot shows a clear seasonal contrast with high positive band loadings in October/November and contrasting large negative loadings in

March (Fig. 3). Geographically, this component shows the contrast between the extremes of the northern summer rain influenced (Smith et al., 2008) and southern winter rain influenced (Feng et al., 2010) arid zone. These extremes contrast with the lack of strong seasonal response in the centre of Australia (PC 2 in Fig. 2).

A colour composite illustrates how the two main patterns of variance, that is the aggregate of PC 1 and the seasonality of PC 2, interact (Fig. 4). Cumulatively these two components explain 72.2% of the variance in the data. Dark green in the north shows the main vegetation growth occurs in summer and is overall high. Bright green, mainly in the south, indicates winter growth and high overall greenness, but some darker green shading in the southern region indicates summer growth, consistent with summer green-up characteristic for the native *Eucalyptus* mallee tree areas in Western Australia and South Australia. The dark red areas in the north have overall moderate to low vegetation total with strong summer bias. The centre of the arid zone is not affected by seasonality and has low aggregate vegetation. Some clear contrasts are visible in particular in the north between the Mitchell Grass Downs, with low total vegetation contribution, and adjacent regions with a higher vegetation aggregate, such as the Mount Isa Inlier (Fig. 4).

Insert Figure 4 approx. here

PC 3 explained 2.97% of the remaining variance, showing an irregular east-summer versus west-winter growth contrast (PC 3 in Fig. 2) apparently perturbed by erratically occurring climatic events as shown in the eigenvector plot (Fig. 3). The south west of the arid zone tends to receive winter rain (Feng et al., 2010). Although greening in the east generally occurs in summer, the inland rivers that carry floodwaters from northern rain events through the very arid Channel country, generally do not receive floodwaters until April resulting in the rivers' contrasting appearance (PC 3 in Fig. 2). An exceptionally high loading in July 1990 followed widespread flooding in eastern Australia (Fig. 3). These floods, known as the Charleville, Nyngan Great Floods, at their peak inundated more than one million square kilometres of Queensland and New South Wales, an area larger than all of Germany. In a concurrent but separate event Victoria also was affected by severe flooding (GeoscienceAustralia, 2007). Such periodic rainfall events may cause the otherwise seasonal pattern to become intermittent.

PC 4 captured 2.1% of the remaining variance in the data. Its plot shows no consistent seasonality but for 2006 its eigenvector loadings are more extreme than any other during the 1982 -2006 period (Fig. 3). This variation in the data appears to be linked to the major rainfall event in connection with cyclone Larry, which struck north eastern Queensland in March 2006. Widespread flooding caused strong vegetation growth. The geographical location of this is clearly evident in NE QLD (PC 4 in Fig. 2).

Further components explained ever smaller proportions of variance. In time series PCA, as in multispectral PCA, later components, though representing a low proportion of total dataset variance, may represent informational variance for small regions (Hall-Beyer, 2003), or significant one-off events. Component 5, for instance, shows a strong seasonal response in the eigenvector plot with extremes in January contrasting with those in June

(Fig. 3). The PC image shows clear contrast between various regions (PC 5 in Fig. 2), it becomes however increasingly difficult in the successive PCs to determine the source of variation in vegetation temporal response in each of the contrasting areas.

The first 14 components captured over 85% of the variation within the total data, as revealed in mean eigenvalues (Table 1). Although components from PC 7 to PC 14 explained a very small percentage of the remaining variation, from 1% incrementally down to 0.5 %, they are likely to hold information of some significance because of the very large geographic and temporal extent of the dataset. From PC 20 onwards some PCs showed evidence of sensor artifacts and noise.

3.2 Classification of vegetation temporal response

The geographic distribution of classes resulting from the unsupervised classification is shown in Fig. 5, together with a three dimensional view of the class PC scores in relation to the dominant factors derived from the PC analysis. The classes are ranked and numbered by the value of the mean scores of PC 1, the greatest source of variation between classes.

As expected from the PCA, the dominant factor separating the classes is total vegetation growth, with lesser separation according to seasonality of growth, both between north and south and to a less well defined degree between east and west (Fig. 5 b). Classes 1 and 24 form the extremes of the high-low vegetation growth continuum (PC 1). Classes 2, 4 and 8 are positioned opposite 1, 3 and 5 illustrating the extremes of the north-south seasonal contrast (PC 2), and classes 10, 14 and 18 opposing 5, 7 and 15 show the extremes of the east-west contrast (PC 3).

Insert Figure 5 approx. here

Mean NDVI temporal traces for the dominant classes indicate how NDVI varies over 25 years (Fig. 6). Class 1 has high vegetation response in winter and spring. Geographically it dominates the southwest regions in Western Australia, the conservation parks in the Murray Darling Depression of South Australia and parts of the Cobar Peneplain in New South Wales and it occurs in the Mulga Lands of Queensland (Fig. 1). These areas all have mallee (*Eucalyptus* sp.) vegetation cover in common and are similar to class 3, which occurs generally to the north west of class 1 and shows the same NDVI signature, though at a lower magnitude (Fig. 6). Class 5, occurring in the arid non-cultivated part of the Riverina district, also shows extreme amplitude and fluctuation, and spring growth. The NDVI of this class is likely influenced by rainfall response of the saltbush plains as well as riparian response along the rivers and lakes some of which are fed by rain falling in the temperate zone to the east (Gov-NSW, 2002).

Classes 2, 4, 8 and 9 also show high NDVI and pronounced seasonality of vegetation growth. Their temporal signatures are quite similar with onset of growth often coinciding, although class 2 has greater magnitude, with peaks tending to persist longer than class 4. Class 8 has the lower vegetation response of these, with sharp narrow peaks followed by rapid decline. Geographically these classes occur in the north of the arid zone. For these classes vegetation appears at its lowest from October to December and increases sharply from December onwards, high peaks generally occurring in March.

By contrast a large part of the landscape showed a fairly uniform response, especially in the most arid part of the arid zone. Classes 21, 22 and 23 are characterised by very low vegetation response with very little seasonality, as indicated by the temporal NDVI plot (Fig. 6). These classes have almost identical temporal signatures, differing from each other only in magnitude. The shape of the NDVI signatures is quite erratic, with one peak in July in each 1983, 88, 89 and 90, but in other years several peaks occur at different times. These classes dominate the north east of South Australia and the south west of Queensland (Fig. 5), which is a sparsely vegetated area, traditionally grazed by cattle. Class 24 shows lowest NDVI, representing the usually dry salt lakes that are a dominant feature in many regions of the Australian arid zone (Fig. 5 a).

Class 7, located at the eastern margins of the arid zone in Queensland and New South Wales, shows high NDVI levels. Class 15 shows a similar pattern to class 7, with onset of peaks coinciding, but peaks are of different magnitude, with one or the other exceeding at different instances. Class 15 in the eastern region and to a lesser extent class 19 in the western (NT) region of the Mitchell Grass Down shows in some years extremely sharp increases in vegetation growth between December and March. This is when wet season rains activate the Mitchell Grass tussocks (*Astrebla* spp.) and inter-tussock ephemeral herbs and annual grasses (Fisher et al., 2002). Class 19 peaks are generally of lesser amplitude than those of class 15 (Fig. 6).

Insert Figure 6 approx. here

Classes 17, 18 and 20 dominate the deserts of Western and South Australia. The eastern Nullarbor responded similarly to the Great Victoria Desert to the north of it, but the western and southern parts of the Nullarbor are uniquely identified as class 14 with the south and west margins revealed as class 3 and 4, identified with *Eucalyptus* (mallee) woodland. The non-seasonal arid Nullarbor Plain carries chenopod shrubs with low open woodland at the peripheries (FloraBase, 2009)

Class 10 occurs mainly in the Carnarvon, and western Murchison and Pilbara area of Western Australia. The NDVI signature for class 10 shows regular high winter vegetation response. Similarity in response was revealed between the eastern Pilbara/north west Great Sandy Desert area and the Central Ranges area, which is located across the South Australian border; at least part of each region was categorized as class 13. The Pilbara features the Hammersley Ranges which are similar to the Central Ranges, however the north western edge of the Great Sandy Desert is a flat monsoonal influenced landscape, arid tropical with summer rain (FloraBase, 2009). Further exploration revealed that the classes 13, 16 and 20 show great similarity in vegetation fluctuation and amplitude (Fig. 6), are characterized by low vegetation response, and appear to be part of the desert continuum reaching north east- south west across the Great Sandy Desert. This underlines the observation that traditional stratification is not able to display the boundary gradations picked up by the NDVI response.

3.3 Relationship between classification and IBRA

The relationship between IBRA regions and classes is illustrated in a matrix which shows the percentage contribution made by the classes to each IBRA region (Fig. 7). In some instances a very strong relationship exists between IBRA region and class. The Riverina IBRA, for instance, is dominated by single class 5 (81%), with minor contributions from related classes, mainly 3, 6 and 11, that have similar NDVI response. Likewise the Finke region is dominated by class 16 (71%) with minor contribution from class 21 (18%). At the other extreme, some IBRA regions are made up of numerous classes of quite diverse NDVI time traces, indicating that these regions contain considerable variability of vegetation response. The Mulga Lands region for instance consists of classes 3, 7, 13, 16 and 21.

In some instances the classes have distinct boundaries and close correspondence to the IBRA. For example class 12 has sharply defined borders which closely match the northern part of the Mitchell Grass Downs IBRA region, where contrasting soils and vegetation types are juxtaposed. The NDVI temporal analysis confirms that these adjoining land systems have quite different temporal vegetation responses and that the boundary between them is indeed quite distinct. In many areas gradients occur where there is a continuum of classes that show a transition of vegetation temporal response but where the IBRA regionalization suggests distinct boundaries, such as the transition between the Coolgardie and the Murchison regions in Western Australia (class 1, 3 and 6).

Insert Table 2 approx. here

Some IBRA regions comprise several classes, which although showing some similarity in NDVI plot, behave quite differently over time. For instance of the three classes that dominate the Gibson Desert, class 20 shows moderate amplitude and an irregular pattern. Class 16 shows extreme peaks in NDVI, usually in winter, in 1982, 1983 and from 1988 to 1991. Class 18 on the other hand shows such peaks from 1992 to 2006.

It is clear that the designated large desert IBRA regions are not as internally homogenous as one might expect of low rainfall sparsely vegetated areas. Factors of erratic rainfall and unpredictable wildfires influence the vegetation response, which cannot be seen in the traditional stratification, but appears borne out by the NDVI time traces of the relevant classes in this study.

4. Conclusions

The Australian arid zone is an extremely large region with mean rainfall below 400 mm in the north and 250 mm in the south, but which contains a great diversity of land types and vegetation responses. The analysis in this paper has identified the major patterns of vegetation growth response throughout this region. The dominant factors are variation in a) total vegetation growth over long periods; b) seasonality of vegetation growth with contrasts between summer and winter, autumn and spring; c) magnitude of seasonal variability in growth with contrast between high and very little variation; and d) regularity of variation in growth. In addition to these dominant factors, around 15% of the variation in NDVI response, over the 25 year sequence analysed, resulted from episodic vegetation growth of limited spatial extent and duration, emphasising the considerable unpredictability of rainfall and vegetation growth in the Australian arid zone.

Using NDVI data that accounted for 85% of the variation in long-term vegetation growth, the Australian arid zone has been classified into 24 classes. These classes are based on similarity and differences in the temporal vegetation growth response described above. This classification considerably adds to our understanding of Australian arid vegetation dynamics and its driving forces. The NDVI temporal classification is based on inherent vegetation change and variation over 25 years of bi-monthly, spatially comprehensive observations of the continent, an approach quite different from the criteria used to delineate the IBRA classes. The classification provides new information about vegetation and landscape function: cycles and pulses or episodes of vegetation growth, the relative magnitude of primary production and standing biomass, and the distribution of regions of similar functional response.

This information can be used to enhance the current IBRA regionalisation and add a new dimension to definition and characterisation of the regions. It provides new information about the temporal dynamics of vegetation response in the IBRA regions, substantially adding to their current characterization in terms of climate, geology, geomorphology, vegetation composition and fauna. It also provides an independent and objective basis for re-evaluation of the IBRA regions and sub-regions. It highlights areas where IBRA vegetation response is highly variable, and may provide a basis for sub-regionalisation, where environmental boundaries between regions may be questioned or further explored.

The study also demonstrates a methodology that has wider potential for classification of broad regional landscapes. Whereas traditional approaches to mapping natural environments have relied on interpretation of landscape associations and patterns in photography or satellite imagery, using field survey to characterize the mapping units, our classification is based on the response of vegetation recorded over long periods of time. Regions with similar long-term vegetation dynamics are aggregated, providing a functional basis for landscape stratification. The resultant classes provide a new and valuable basis for ecological survey, biodiversity conservation and environmental management: each unit has a unique association of climate, topography, soil and vegetation, but also a distinctive history and temporal pattern of vegetation response. The growing global archive and ready availability of long-term sequences of NDVI imagery, at resolutions suitable for regional analysis, make this a valuable resource for environmental characterization.

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*Research Highlights

Research highlights

- Long term satellite imagery revealed vegetation dynamics of the Australian arid zone.
- Total vegetation response, seasonality and episodic events were the main factors of variability.
- A new zonation was created through unsupervised classification of the main factors of variability.
- Investigation of this new zonation increased understanding of arid zone vegetation dynamics

Figure 1

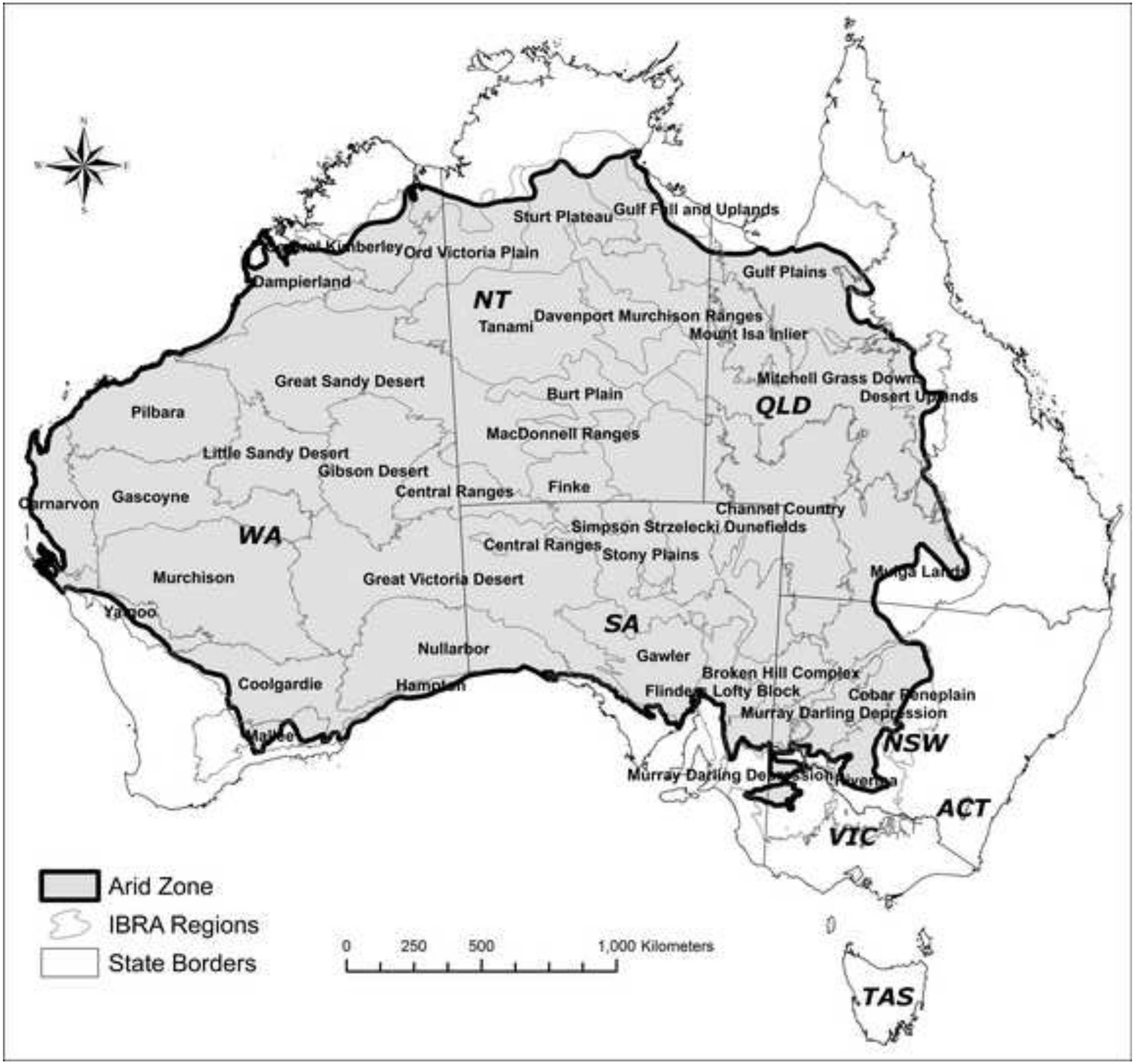

Sturt Plateau
Ord Victoria Plain
Dampierland
NT
Tanami
Davenport Murchison Ranges
Mount Isa Inlier
Gulf Plains
Great Sandy Desert
Burt Plain
QLD
Pilbara
MacDonnell Ranges
Little Sandy Desert
Gibson Desert
Central Ranges
Finke
Gascoyne
Channel Country
Simpson Strzelecki Dunefields
WA
Central Ranges
Stony Plains
Murchison
Great Victoria Desert
SA
Nullarbor
Gawler
Broken Hill Complex
Coolgardie
NSW
ACT
VIC
TAS
Arid Zone
IBRA Regions
State Borders
0
250
500
1,000 Kilometers

Figure 2

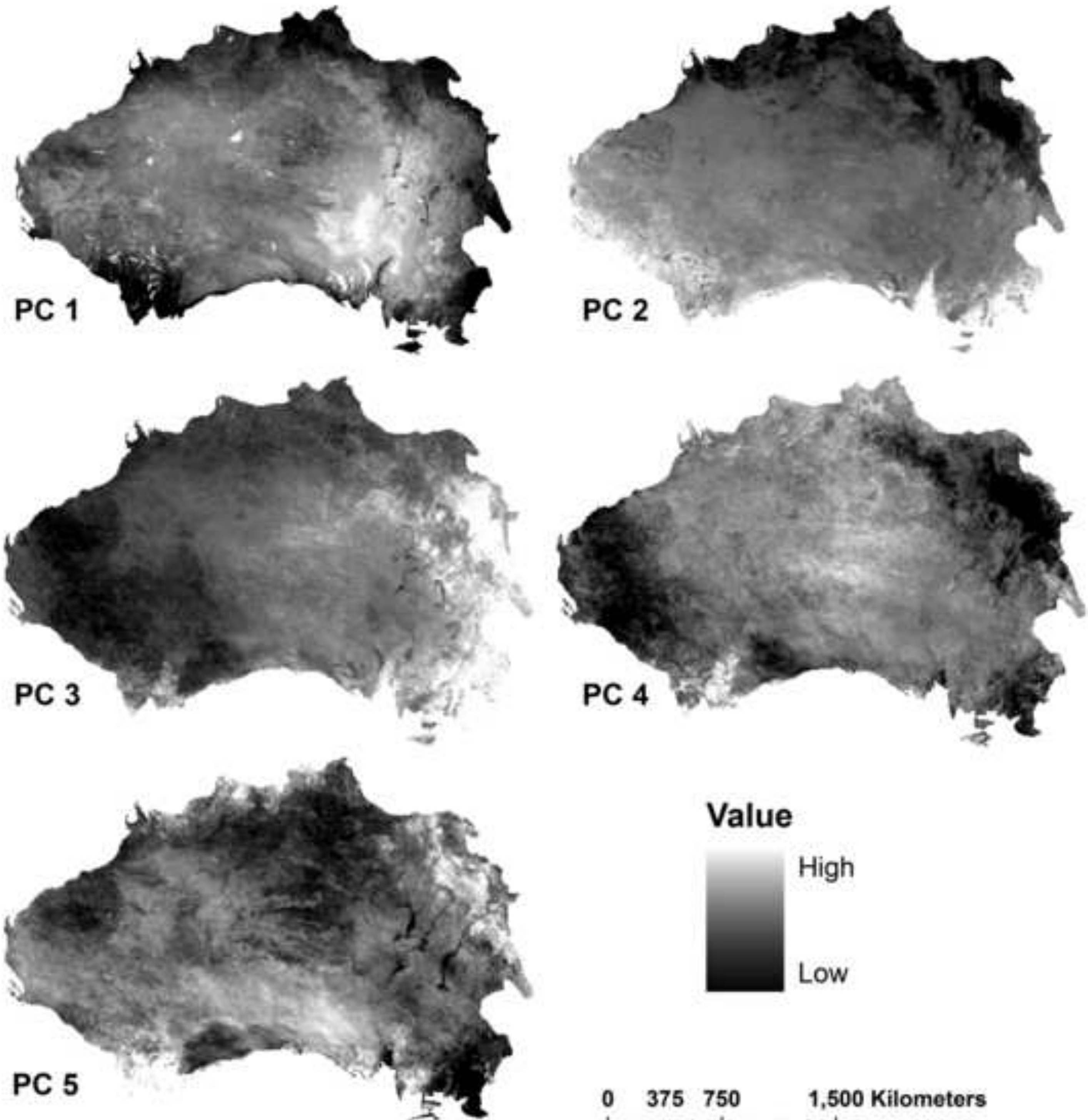


Figure 3

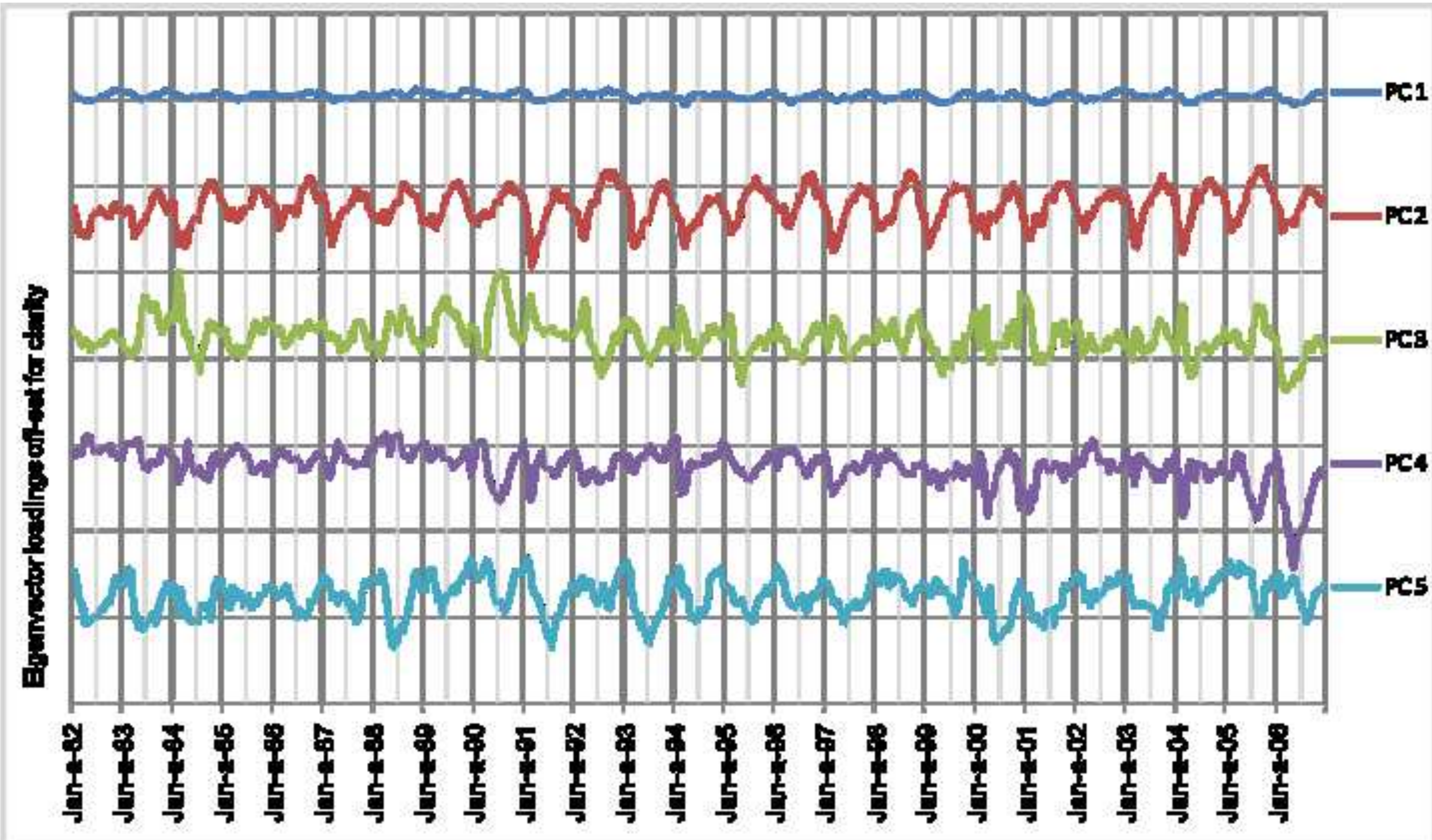
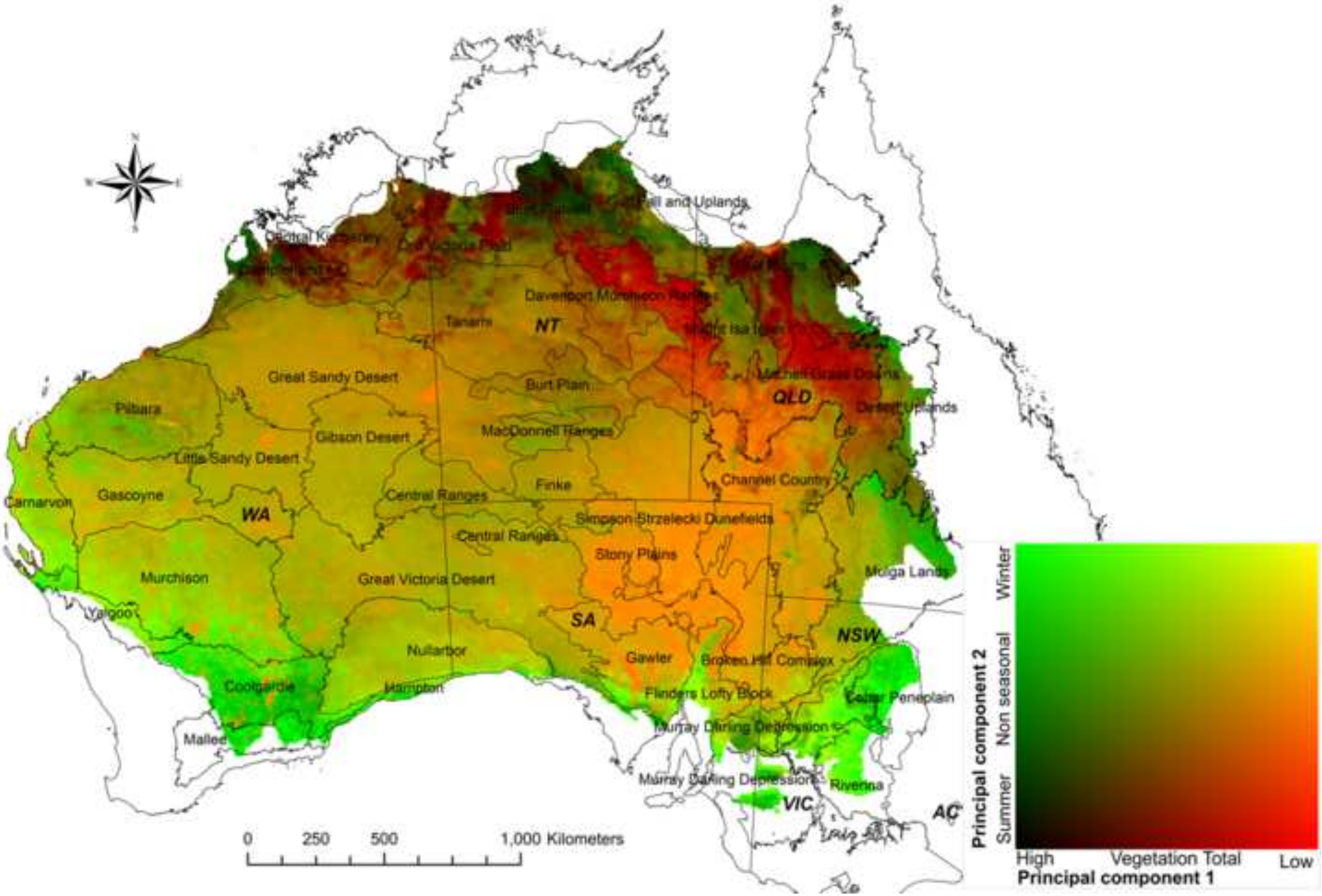

Eigenvector loadings off-set for clarity
PC1
PC2
PC3
PC4
PC5

Figure 4



WA
NT
QLD
SA
NSW
VIC
Pilbara
Great Sandy Desert
Gibson Desert
Little Sandy Desert
Carnarvon
Gascoyne
Murchison
Yalgoo
Coolgardie
Mallee
Hampton
Nullarbor
Great Victoria Desert
Central Ranges
Tanami
Davenport Murchison Ranges
Burt Plain
MacDonnell Ranges
Finke
Simpson Strzelecki Dunefields
Stony Plains
Gawler
Broken Hill Complex
Flinders Lofty Block
Murray Darling Depression
Riverina
Cobar Peneplain
Mulga Lands
Channel Country
Desert Uplands
Mitchell Grass Downs
0 250 500 1,000 Kilometers
Principal component 2
Summer
Non seasonal
Winter
High
Vegetation Total
Low
Principal component 1

Figure 5

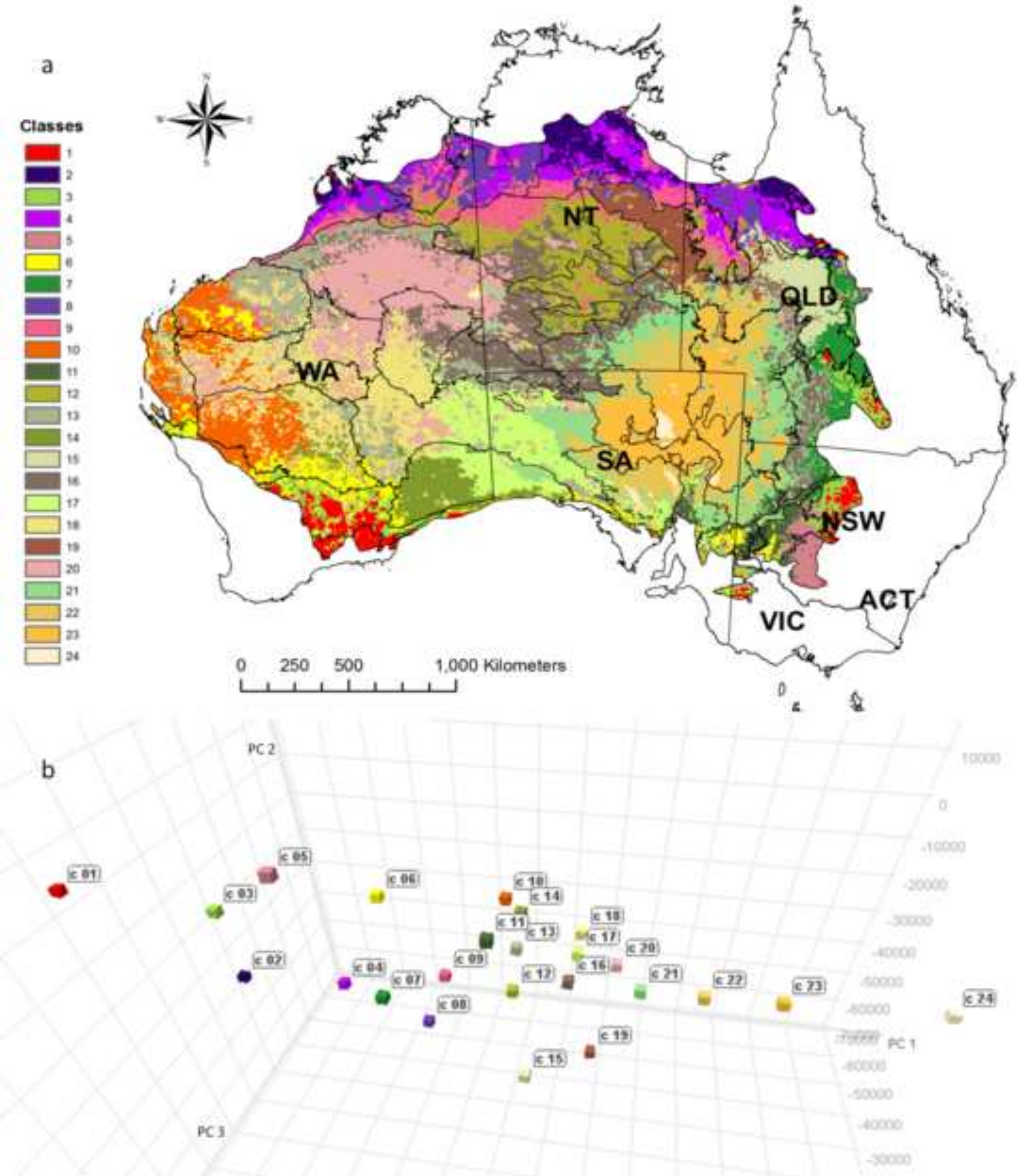
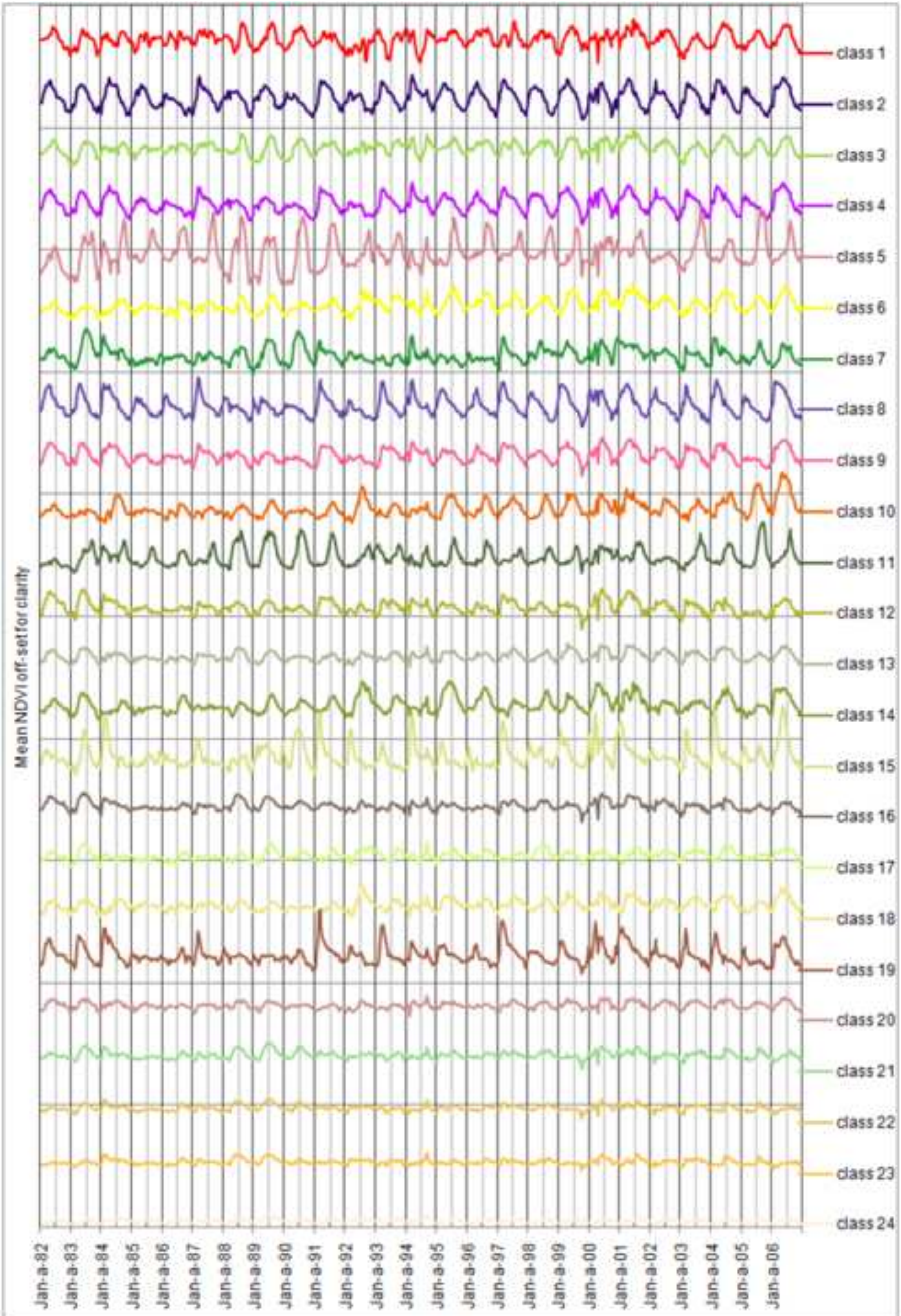

a
Classes
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
NT
QLD
WA
SA
NSW
ACT
VIC
0 250 500 1,000 Kilometers
b
PC 2
PC 1
PC 3
c 01
c 02
c 03
c 04
c 05
c 06
c 07
c 08
c 09
c 10
c 11
c 12
c 13
c 14
c 15
c 16
c 17
c 18
c 19
c 20
c 21
c 22
c 23
c 24

Figure 6


class 1
class 2
class 3
class 4
class 5
class 6
class 7
class 8
class 9
class 10
class 11
class 12
class 13
class 14
class 15
class 16
class 17
class 18
class 19
class 20
class 21
class 22
class 23
class 24
Mean NDVI off-set for clarity
Jan-a-82
Jan-a-83
Jan-a-84
Jan-a-85
Jan-a-86
Jan-a-87
Jan-a-88
Jan-a-89
Jan-a-90
Jan-a-91
Jan-a-92
Jan-a-93
Jan-a-94
Jan-a-95
Jan-a-96
Jan-a-97
Jan-a-98
Jan-a-99
Jan-a-00
Jan-a-01
Jan-a-02
Jan-a-03
Jan-a-04
Jan-a-05
Jan-a-06

Captions for figures and tables

Figure 1. The study area comprising the Australian arid zone excluding cultivated areas. Biogeographical regions defined by IBRA vs 6.1 are shown.

Figure 2. Principal components 1 to 5.

Figure 3. Plot of eigenvector band loadings of the first 5 principal components

Figure. 4. Colour composite of PC1 (red) and PC2 (green) with IBRA regions overlaid to indicate approximate locations. Legend block shows colour interpretation.

Figure 5. a. Geographic distribution of 24 classes resulting from unsupervised classification of the first 14 PCs of 25 year NDVI, with overlay of IBRA vs 6.1 regions; b. 3-D plot of class scores for PC 1, 2 and 3.

Figure 6. The variation in NDVI response over 25 years for each class.

Table 1. Percentage of variance captured by some of the 600 principal components.

Table 2. IBRA regions in the arid zone showing percentage of IBRA occupied by each class.

Table

Table 1. The percentage of variance captured by several of the 600 principal components.

	PC 1	*PC 2*	*PC 3*	*PC 4*	*PC 5*	*PC 6*	*PC 7*	*PC 14*
Percentage of variance	65.05	7.15	2.97	2.10	1.45	1.12	1.05	0.50
Cumulative percentage of variance	65.05	72.20	75.17	77.27	78.72	79.84	80.89	85.37

Table

IBRA region	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***
Mallee	**76**		17			6								1										
Coolgardie	**35**		**35**			23							1	2				1		1		1		
Cobar Penepln	**37**		**45**		11		6				1													
Desert Uplnds	3	1	19	9			**52**					6	2		4	4								
Sturt Plateau		**49**		**28**				4	17			2												
Gulf Fall n Up		19		**49**				2	**28**			2												
Gulf Plains	1	16		**37**				23	5			2			10	1			3			1		
Dampierland	1	17		**35**				19	22			1	3							1		1		1
Riverina	1		2		**81**	2					13													
Central Kimber				17				**31**	**40**			11												
Mount Isa Inlr				17				2	**41**			20	5		1	6			5	1	1			
Ord Vict Plain		1		17				**43**	**26**			12												
Yalgoo	1		16			**40**				**39**	1							1		1			1	
Murchison			1			13				**34**			5	10				**31**		5		1	1	
Carnarvon						9				**50**			11					18		6		2	2	2
Pilbara						10			6	**29**			**38**			1		13		2			1	
Murray Darl Dn	5		17	1	18	15	2				**34**		2				4				3			
Darling Riverin			1			2	4				**52**	1	1			10	2				24	1	1	2
Davenport Mu								1	13			**73**				10			2					
Tanami									18			**42**	1			**31**				7	1			
Burt Plain									7			**66**				**25**					1			
MacDonnell Rg							6		4			**53**	4			**33**					1			
Hampton	14		11			20				1				**54**										
Nullarbor			1			5							2	**47**			**34**	4		2	5	1		
Finke												2	5			**71**				3	18	1		
Central Ranges													21			**66**	7	1		4	1			
Grt Victoria Ds						3							15	2		3	**38**	18		9	9	3		
Mitchell GrsDn				1			11	3	2			3	1		**28**	4			**29**	1	5	10	3	
Little Sandy Ds													14			4		**31**		**49**		1	1	1
Gascoyne						1				16			7	1				**49**		23		3		
Gibson Desert													3			17	4	**36**		**38**	1			
Great Sandy Ds									2			2	12			23		1		**56**	2	1	1	1
Mulga Lands	4		15				23				3	1	14			22					15	2		
Flinders Lfty B			1		3	5					21		2			1	6				**29**	19	12	
Gawler			2			4					5		3				14			1	15	**39**	11	6
Channel Cntry							1					2	2			12			2	2	**28**	**27**	23	
Broken Hill Cm						1					14					2	1				**45**	**35**	3	
Simpson Strzel												1				9					21	**36**	**29**	5
Stony Plains																1				1	10	24	**63**	1