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# A remote sensing spatio-temporal framework for interpreting sparse indicators in highly variable arid landscapes

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ABSTRACT

The world's extensive and often remote arid landscapes are receiving increasing attention to maintain their ecological and productive values. Monitoring and management of these lands requires indicators and evidence of ecosystem condition and trend, generally derived from widely distributed and infrequently repeated site-based records. However adequate geographic representation and frequent site revisits are difficult to achieve because of the remoteness and vast extent of these landscapes. Interpreting such sparse ecological indicators is difficult, particularly within landscapes that are highly variable in space and time. To interpret ecological indicator data collected in such environments long-term patterns of natural landscape variability need to be understood.

This paper presents a framework of landscape spatio-temporal variability within which to interpret ecological indicator data. This framework is based on long-term patterns of vegetation growth across the Australian arid zone, derived from twenty-five years of high temporal resolution National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) satellite imagery. We present a case study of the extensive Alinytjara Wilurara (AW) Natural Resource Management (NRM) region in far western South Australia to illustrate new insights about landscape function gained from this approach, and their implications for collection and interpretation of ecological indicator data. We illustrate how variability in vegetation response is expressed across the region, and how stratification based on active vegetation response differs from more commonly used biogeographic stratifications in this region. Lastly we demonstrate the unique patterns of long-term vegetation response for the major vegetation response classes. Average amount, seasonality, magnitude, timing and variability of vegetation response over time are used to characterise the natural "envelope" of variability of the new landscape classes.

The study region showed low vegetation response in summer and higher response in winter. Onset of growth was earlier in the north and in ecosystems dominated by mallee vegetation. Cyclonic influence from the west was evident at the southern margin of the study region. The study demonstrates the landscape functional response of the study region, and presents a method whereby remote sensing reveals the landscape context within which to better interpret ecological indicator data collected in a highly variable landscape.

## 1. Introduction

Monitoring change in vegetation cover and interpreting the significance of such change is vital for arid zone environmental management. Arid regions encompass about 33% of the global land mass, and include a wide range of land utilisation and management regimes. Plant cover in grazed rangelands provides livestock fodder, erosion control and biodiversity benefits. The less disturbed regions are of high conservation value because they can provide information on ecosystem structure and function in unmodified landscapes and have potential for monitoring the effects of climate change (Driscoll et al., 2012; Pettorelli et al., 2012; Suppiah et al., 2006). They contain indigenous and endemic flora and fauna and are critical for the reduction of further biodiversity loss (de Groot et al., 2002; Fisher et al., 2009). Arid lands are under pressure from the impacts of expanding human settlements and increasing resource exploitation, resulting in reduction of arid ecosystem extent and quality.

Monitoring and management of arid lands requires indicators and evidence of ecosystem condition and trend. The most common

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approaches for assessing ecosystem condition rely on site-based observations and records repeated at intervals (DWLBC, 2002; USDA, 2014; Warburton, 2011; White et al., 2012). Selection of suitable indicators can be very complex (Smyth et al., 2009) with different indicators and methodologies for biodiversity, (Landsberg and Crowley, 2004) landscape function (Ludwig et al., 2000, 2004) and rangeland assessments (Ludwig and Bastin, 2008; Pyke et al., 2002).

Finding spatially and temporally representative indicators that can be used to develop management strategies for these systems remains a challenge (Ostendorf, 2011). Ideally, conditions need to be assessed at spatio-temporal scales that recognise landscape variation and key processes.

In reality, samples are often very sparsely distributed and site revisits remain infrequent, owing to the complex logistics and high cost of field campaigns in these vast remote regions. This poses major problems for trend analysis and limits the use of the information for management decisions. Land condition and vegetation growth in this zone are affected by the short and long term effects of drought, erratic rainfall and fire, which are distributed over a diversity of landforms. It is impossible to elicit meaning from change in indicator values in such highly variable landscapes when data are collected years apart and often at different times of the year. In addition, separating the effects of human-induced and natural spatial and temporal variability is difficult, even with spatially comprehensive land cover indicators derived from remote sensing (Kilpatrick et al., 2011).

A well accepted approach to assist interpretation of environmental indicators across variable landscapes is spatial stratification, dividing the landscape into regions within which homogeneity of response may be expected (Hutchinson et al., 2005; Pesch et al., 2011). The most used stratification in Australia is the Interim Biogeographic Regionalisation for Australia (IBRA), a national ecosystem classification that stratifies and describes the landscape in terms of climate, geology, topography, soils, vegetation, and where available, flora and fauna information (Thackway and Cresswell, 1997). Vegetation in the bioregions is characterised by the perennial species: trees, shrubs, and tussock and hummock grasses. This provides a static framework representing landscape structure and composition, the slow variables in the landscape. By its nature IBRA does not represent landscape function or variability over time, such as seasonal and inter-annual changes, the rapid growth of ephemeral vegetation after rain, nor the reduction and resprouting of perennial vegetation after fire. To evaluate change over time in ecological indicators it would be preferable to stratify the landscape on the basis of the spatio-temporal characteristics of the indicators, rather than their spatial distribution alone.

Satellite-based remote sensing is now providing the means for spatially comprehensive assessment of ecosystems. In addition, growing archives of image time-series provide new, objective evidence of landscape variability and trend over time (Guerschman et al., 2009; Okin et al., 2013), and are increasingly being used to support natural resource management (Thackway et al., 2013). Remote sensing time series may provide primary indicators of environmental condition and change (e.g. Broich et al., 2014; Petus et al., 2013). Alternatively, time series can be used to stratify land cover into regions of similar temporal response. Such stratification has been carried out through comparison of temporal trend in neighbouring pixels of satellite images, or by comparison to reference pixels (Ivits et al., 2013; Reeves and Baggett, 2014) or regions (Bastin et al., 2014). In addition, new classifications of broad-scale vegetation types have been derived from remote sensing time series at global, continental and regional scales (Hansen et al., 2000; Lymburner et al., 2011; Thenkabail et al., 2005; Turcotte et al., 1993; Xiao et al., 2005). Such classifications differ from more traditional vegetation mapping (e.g. AUSLIG, 1990) or the IBRA in that they are based on intra and inter-annual vegetation response over years or decades, rather than distribution at a single reference time.

This paper uses the Australian arid zone vegetation classification of Lawley et al. (2011) as a framework of landscape spatio-temporal variability within which to interpret ecological indicator data. This framework is based on long-term patterns of vegetation growth across the Australian arid zone, derived from satellite remote sensing. Lawley et al. (2011) stratified the Australian arid landscape based on variability in long-term vegetation response, as detected in high temporal frequency AVHRR Normalised Difference Vegetation Index (NDVI) images. They used principal component analysis (PCA) of these images to determine the key components that define vegetation dynamics. These were used to stratify arid Australia into separate zones of unique long-term variability in vegetation response. These are “envelopes” of variability, within which change in ecological indicator data can be interpreted.

We present a case study of the extensive AWNRM region in South Australia to illustrate the new insights about landscape function to be gained from this approach, and its implications for collection and interpretation of ecological indicator data. For the case study area we

a. investigate how the variability in vegetation response is expressed across the study region, in order to better understand the functional response of this landscape;
b. compare the new variability-based classification with static IBRA stratifications, in order to interpret the distribution of observed vegetation response in relation to landscape structure and composition;
c. characterise the main vegetation variability-based classes of the AW region in regard to location, landform, soils, vegetation type and rainfall, and
d. analyse the temporal vegetation response for each of these classes to define the framework of variability within which to interpret indicator data.

## 2. Materials and methods

### 2.1. Study region

The AWNRM region in the far west of South Australia covers 261,180 km$^2$, approximately 5.4% of the entire Australian arid zone, which was delimited by Lawley et al. (2011) as the modified Koeppen arid zone classification, but with the dryland cultivated areas masked out. The climate is hot and dry. Annual average daily maximum temperatures range from 23.6 °C at the Nullarbor coast, to 26 °C at Cook situated centrally within the region, and 29.3 °C at Giles (Western Australia), which is located northwest of the study zone (Fig. 1) (BOM, 2012). Rainfall is low, varying considerably from year to year and is deemed aseasonal (Greenslade et al., 1986). Mean annual rainfall at Cook was 153 mm over the 25 year study period (BOM, 2012). Evaporation potential is extremely high, from an annual mean of 2400 mm in the south to 4000 mm inland (Government of South Australia, 2007).

Livestock grazing has modified the landscape in the northeastern and southern areas of the AW region, which has likely altered native vegetation community structure, composition and regenerative capability (Thackway and Lesslie, 2006). At least 70% of the landscape has remained largely unmodified, and is loosely referred to as wilderness (AWNRM Board, 2011; Klein et al., 2009). The AW region contains seven terrestrial conservation reserves, covering almost 90,000 km$^2$ (Fig. 1). These include several destocked grazing properties dedicated to conservation between 1979 (Nullarbor Conservation Park) and 1991 (Tallaringa Conservation Park), an indication that the ecological value of these remote regions is increasingly recognised.

Wildfires are common in this landscape, with average fire size in the Great Victoria Desert estimated at 28 km$^2$, and the Central Ranges burning more frequently than surrounding regions (Haydon et al., 2000; Turner et al., 2008). Burnt or charred vegetation and regrowth after fire are integral parts of the natural vegetation variability of the AW landscape.

The region is of high conservation value as it holds information on ecosystem structure and function in unmodified landscapes and has potential for monitoring the effects of climate change (Driscoll et al., 2012; Pettorelli et al., 2012; Suppiah et al., 2006). It provides, because of its large extent, important ecosystem services (de Groot et al., 2002; Fisher et al., 2009), contains indigenous and endemic flora and fauna, and is the homeland to Aboriginal traditional owners, who have a keen interest in monitoring landscape health.

The region is under increasing pressure from the impact of mining and tourism, proliferation of feral grazers (Pitt et al., 2007) and weed invasion (Marshall et al., 2012). The sparsely vegetated arid landscape is very resilient and is adapted to prolonged periods of heat and drought. It is also fragile; biological soil crust is easily destroyed (Belnap and Gillette, 1998), and loss of the slow growing perennial vegetation is difficult to reverse (Eldridge and Ferris, 1999; Friedel et al., 2003; Lawley et al., 2013). Management authorities seek to detect change and trend in this landscape, so appropriate management action can be applied.

### 2.2. Data

The components and classes of the zonation created by Lawley et al. (2011) are here used to show the distribution of variability across the AW landscape. That zonation was based on principal component analysis (PCA) of 25 years (1982–2006) of twice-monthly maximum value composite (MVC) AVHRR data, which had been calculated, at 8 km spatial resolution to the NDVI. The NDVI is a well-established index using the near infra-red (NIR) and red (R) spectral reflectance, (NIR − R)/(NIR + R), to represent all photosynthetically active vegetation in the landscape (Rouse et al., 1974; Tucker, 1979). PCA revealed three main components underlying Australian arid zone long-term vegetation variability. Greatest variability (65%) was found in the spatial distribution of temporally aggregated vegetation response across the arid zone (low to high). The second component (7% of remaining variability) represented seasonality; it contrasted northern Australian monsoonal summer growth with southern Australian winter growth and defined the arid zone interior as aseasonal. The third component (3% of further variability) was defined by vegetation growth resulting from erratic rainfall, at times linked to coastal cyclone-related rain events on Australia's east or west coast.

The Lawley et al. (2011) zonation consists of twenty-four classes created by unsupervised iso-classification of the first 14 principal components (85% of variability). These new classes represent areas of distinct variability in vegetation response across the Australian arid zone. Here we use both the key principal

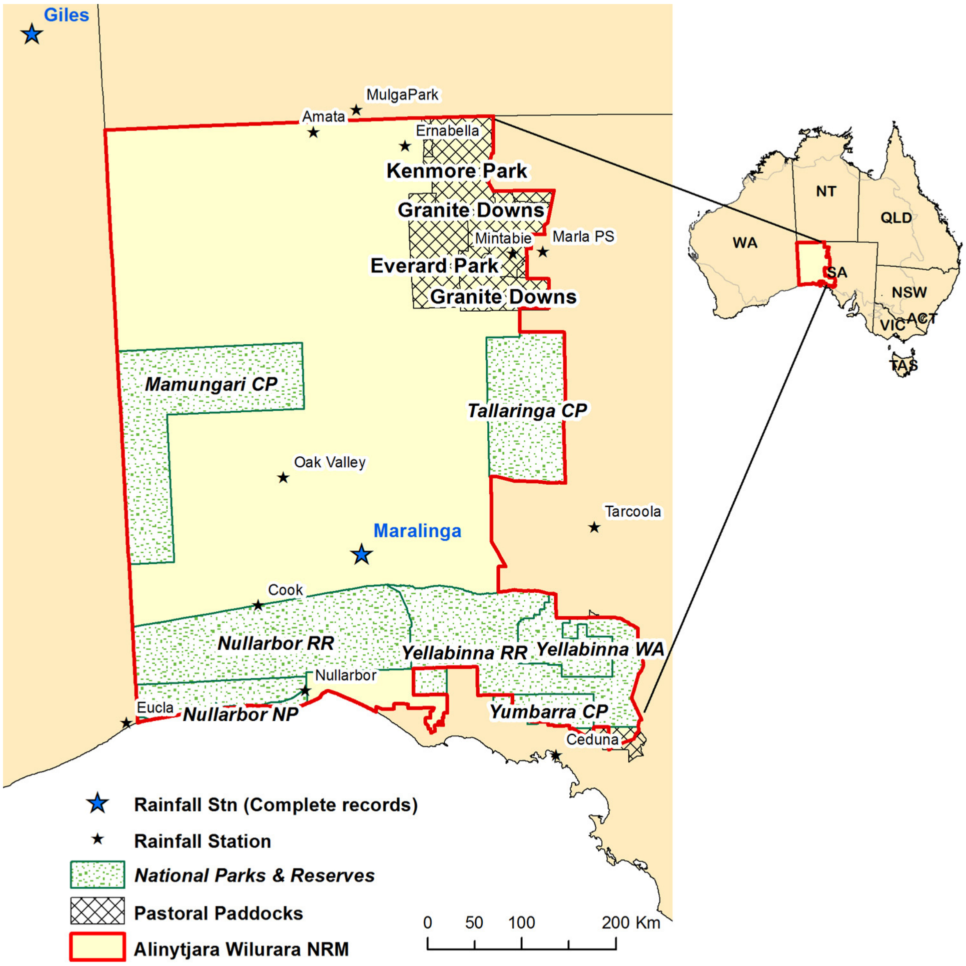

**Fig. 1.** The AW study region showing pastoral paddocks and conservation reserves. CP = Conservation Park, RR = Regional Reserve, WA = Wilderness Area, NP = National Park. Rain recording stations highlighted in blue are used in the analysis, as they have near complete records for the entire 1982–2006 study period.

**Fig. 2.** The distribution of IBRA (vs 6.1) regions across non-cultivated arid Australia.

components and the classes from that analysis, with their 25 year NDVI time series, to show how variability in vegetation response is distributed spatially and temporally across the AW region.

## 2.3. Analysis

### 2.3.1. Interpretation of factors governing vegetation variability in the AW region

We display the relative distribution and influence of the three key components of arid zone variability in a red–green–blue composite image to show how these dynamic elements (the distribution of total vegetation response, the seasonal response, and the erratic or east-west response) are expressed within the AW region, and in the context of the wider arid zone patterns.

Seasonality statistics for the Australian arid zone extracted from PCA eigenvector loadings (Lawley et al., 2011) were used to detect the frequency with which annual growth maxima occurred for every calendar month over the 25 years of investigation.

### 2.3.2. Comparison of dynamics classes and IBRA stratifications

The IBRA divides arid Australia, as defined by the Koeppen category but with cultivated regions excluded, into some 39 regions (Fig. 2) (Lawley et al., 2011; Thackway and Cresswell, 1997). Four of these regions form the main coverage in the study area. Finer-scaled stratification defines 18 sub-IBRAs that partly or entirely occur within the AW region, and further division shows 40 IBRA-associations, which form a detailed South Australian regionalisation. The main IBRA in the AW region are Central Ranges, Finke, Great Victoria Desert (GVD) and Nullarbor (Fig. 2). We compared the vegetation variability-based classes with the IBRA regions, IBRA sub-regions and IBRA associations to detect whether variability in vegetation response corresponds to the IBRA or sub-regional landscape stratifications.

### 2.3.3. Analysis of vegetation variability classes in the AW region

We focus on the classes with the greatest geographic extent in the AW region, and describe their geographical distribution, dominant vegetation cover, landform, and soils. Vegetation descriptions were derived from the South Australian Vegetation Information System Database (SAVEG). This database, in line with the National

Vegetation Information System (NVIS) framework, defines vegetation communities in the Australian landscape by their uniform structure and floristic composition, and names them by their dominant species in major vegetation groups (MVGs) and subgroups (MVSs) (NVIS, 2012). Landform and soil descriptions were extracted from the South Australian IBRA-associations (Government of South Australia, 2007).

To further characterise the classes in relation to timing, magnitude and variability in growth over the course of the year, we calculated the 25-year inter-annual mean NDVI for each twice-monthly date for the classes of interest. Coefficients of variance were calculated at each date to show how inter-annual variability for each class changes over the course of a year.

We also analysed the 25-year bi-monthly AVHRR NDVI time series (600 images) for each class to identify intra and inter-annual trends and possible climatic drivers. We did this by means of STL plots (Seasonal Decomposition of Time Series by Loess using the R-function plot.stl) (Cleveland et al., 1990). This involves locally weighted regression function (Loess) smoothing of the raw NDVI time series, after which the seasonality was extracted at frequency 24; the number of twice monthly observations per year. Removing the seasonality from the Loess smoothed data reveals the trend, which is the non-repeating signal over the observation period. The remainder represents the high frequency variability removed by the smoothing, and shows the information not explained by the model. The decomposition summary was interpreted to detect the strength of seasonality, which we deduced from the percentage of data represented within the interquartile range of the seasonality summary in R.

We compared class long-term vegetation responses with rainfall using data from two rainfall stations with the most comprehensive monthly recordings over the 1982–2006 period (Fig. 1); records from other stations with long gaps in records over the 25-year study period were excluded (BOM, 2012). Seasonality of rainfall was tested through STL decomposition of the monthly rain data (1982–2006, frequency = 12) at the two relevant rainfall stations. Strength of seasonality was deduced from the decomposition summary.

To further illustrate analysis of temporal trends we applied iterative break detection to the time series for largest class. This identifies abrupt changes in the STL decomposition trend signal. Abrupt changes flag periods of increasing and decreasing vegetation response and times of marked change in trend (Verbesselt et al., 2010).

## 3. Results and interpretation

### 3.1. AW regional variability in continental context

The geographic distribution and influence of the three main components that underlie variability in Australian arid vegetation response: the spatial distribution of temporally aggregated vegetation response (red), the seasonality (green), and the east-west erratic effects (blue) are shown for the entire Australian arid zone and for the AW region (Fig. 3).

Total vegetation response in the AW region is moderate in the wider arid zone context, but variability in vegetation response is low relative to the extreme contrasts evident in northern and eastern arid Australia (Fig. 3). Vegetation clearly showed greater response within the AW than in areas under grazing leases to the east of the region, such as the Stony Plains, Simpson and Strzelecki dune fields, and Channel country (Fig. 3); (for locations see Fig. 2). Difference in biomass production is generally ascribed to difference in rainfall (e.g. Pickett-Heaps et al., 2014), but rain distribution maps indicate that the central AW region receives similar annual rainfall to Stony Plains, Simpson and Strzelecki dune fields, and Channel country (BOM, 2012). This suggests that although rainfall distribution (Greenslade et al., 1986), and soil type will likely play a role, a further reason may be that a large proportion of the AW region has never been grazed by domestic stock. It has not suffered the historical soil surface damage from hard hooved stock, nor long-term degradation and loss of production resulting from past drought related overstocking, which has occurred in many areas under grazing lease. Vegetation in the natural AW region is relatively intact and delivers a moderately strong NDVI response.

**Table 1**
Seasonality across arid Australia shown by the number of years in which the component 2 eigenvector extremes occurred in this month.

| Seasonality | Component 2, 7% of 25 years of variability | |
|---|---|---|
| | Australian North maxima | Australian South maxima |
| January | 3 | – |
| February | 6 | – |
| March | 9 | – |
| April | 7 | – |
| May, June, July | – | – |
| August | – | 5 |
| September | – | 10 |
| October | – | 7 |
| November | – | 3 |
| December | – | – |

Seasonality (green), and erratic events (blue) are not strongly expressed in the AW region, in the continental context, but some of the northern coastal influence appears to have extended inland towards the north of the AW region and some of the western influence has affected growth over the Western Australian portion of the Nullarbor (Fig. 3).

### 3.2. Variability within the AW region

Although the magnitude of variability in vegetation growth in the AW region is confined within a relatively narrow range and at the lower end of the scale in the continental context, considerable spatial heterogeneity is evident across the AW region; the underlying factors exert varying degrees of influence. A broadly distributed pattern of variability can be seen in wide bands from the south east across the region north westwards (Fig. 3).

Temporally aggregated vegetation growth is the main defining factor in the eastern Great Victoria Desert area and from there within a narrowing band towards the northwest across the region. The north eastern part of the Nullarbor also shows this as the main dynamic. Temporally aggregated vegetation growth over 25 years is lowest in the Tallaringa region, an area estimated to be in good condition by regional management (AWNRM Board, 2011). Salt lakes such as Lake Maurice and the Serpentine Lakes in Mamungari Conservation Park naturally show close to nil vegetation response (deeper red), even where some lake edge vegetation is included due to the 8 km ground sampling resolution of the NDVI imagery (Fig. 3). Greater total vegetation growth (less red) is apparent in the southern Yellabinna, Yumbara area, Mamungari Conservation Park (for location see Fig. 1) along the Western Australian border, and the area west of Walalkara (Fig. 3).

Analysis of the eigenvectors of the seasonality factor revealed that continental annual southern vegetation growth peaked during the Austral winter and spring months of August to November (Table 1). Although the AW region lies geographically in the aseasonal vegetation growth area, the coastal margin revealed higher late winter and spring seasonal growth. The greatest effect of this is visible in the areas along the Hampton and Yalata coast (Fig. 3).

The east-west factor (blue) was interpreted at continental scale as vegetative growth resulting from major cyclone driven rain

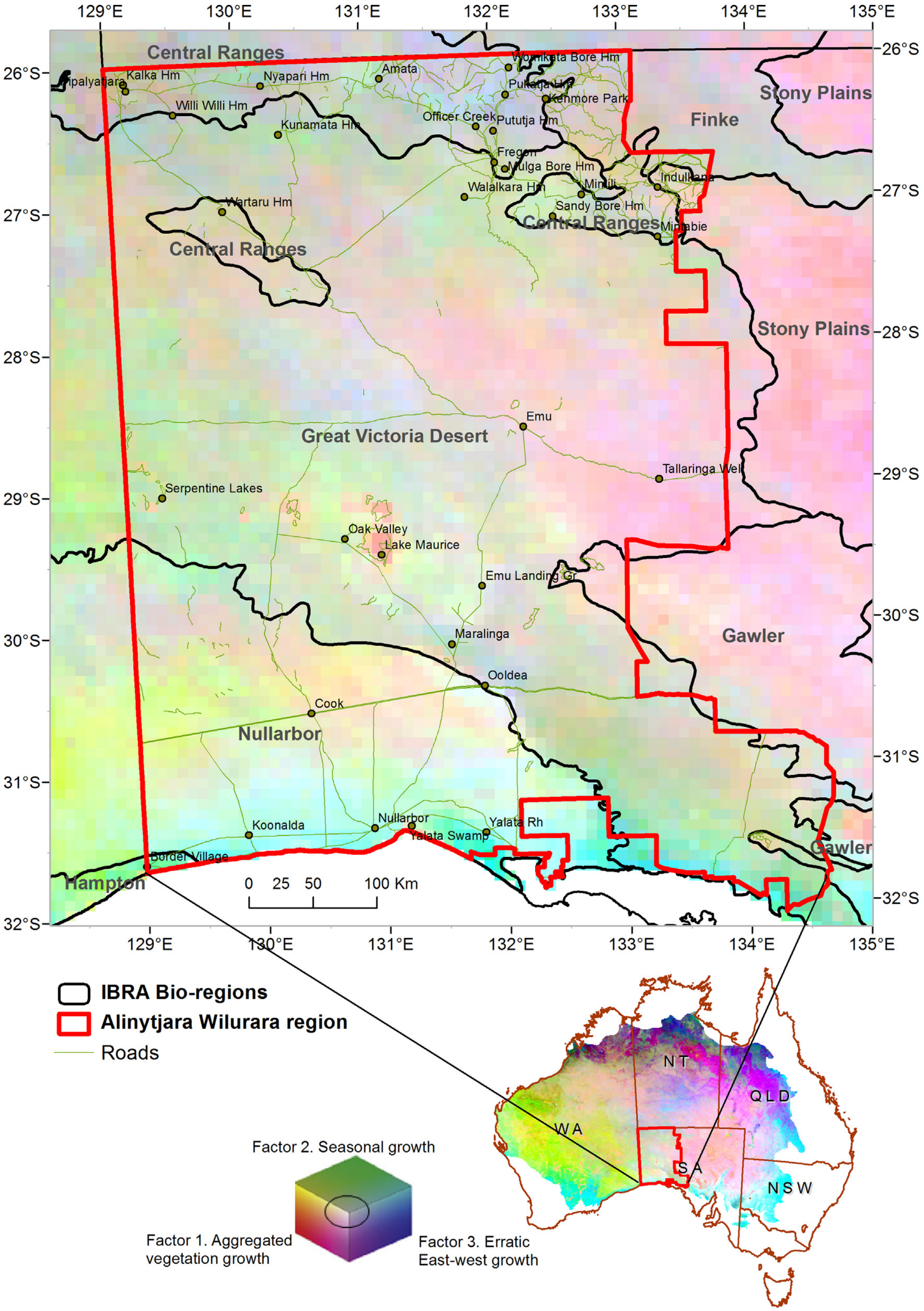

**Fig. 3.** Colour composite of the three main components that define vegetation variability across the Australian arid zone, and as expressed in the AW region. The area within the oval shape on the legend cube shows the AW response: the vegetation 25-year aggregate is moderate to low (red), vegetation response is aseasonal to winter active (green), and not strongly affected by extreme east-west erratic events (blue).

events (Lawley et al., 2011). The extreme effect seen at the continental margins is not apparent in the AW region but nevertheless some monsoonal or cyclonic influence appears to have entered into the AW region from the north and from the west, affecting the Central Ranges and southern Nullarbor (Fig. 3).

Cyclones crossing the Western Australian coast result in rain reaching the Nullarbor on average two or three times per decade (Gillieson et al., 1994). Australian Bureau of Meteorology data[1] shows that eight cyclone paths entered the Western Australian portion of the Nullarbor during the 25-year study period, but none extended into South Australia. The only cyclone path entering the AW region within the study period was tropical cyclone Gertie which crossed the Central Ranges from west to east in December 1995. No rainfall associated with specific cyclone dates appeared to be recorded across the wider AW region (BOM, 2012), but some of the long term effects of these erratic events, which are strongly expressed as growth in the Western Australian part of the Nullarbor, appear to have extended along the coast into South Australia (Fig. 3).

Elsewhere in the AW region erratic effects (blue) appear attributable to localised and short term effects, rather than cyclonic activity. In those locations strongest growth may occur in seasons other than winter/spring, and vegetation response is relatively high (absence of red) (Fig. 3). Such erratic response can be seen, for example, near Ooldea, at the northern edge of the Nullarbor (Fig. 3) where the dominant vegetation is mallee (*Eucalyptus* spp.), a vegetation type which typically grows and flowers in summer.

### 3.3. *Classified vegetation variability within the AWNRM region*

Lawley et al. (2011) mapped twenty-four spatio-temporal classes of vegetation response across arid Australia. Thirteen of these classes occur at least in part in the AW region, the four most dominant of which (classes 17, 21, 16 and 13) cover areas ranging from 29,000 km$^2$ to 135,800 km$^2$ within this region (Fig. 4). Each class maps the distribution of a particular set of unique long-term vegetation dynamics. We coined names for the classes in the AW region, for ease of discussion (Fig. 4 legend).

#### 3.3.1. *Vegetation response classes in relation to IBRA stratification*

IBRA regions show less internal homogeneity in vegetation response than expected. The GVD is for instance a large IBRA and our analysis reveals that it is internally quite variable with all four main vegetation response classes present within its boundary (Fig. 4a). Conversely, similar variability in vegetation response can occur in different IBRAs, such as the long-term response of the Desert class which occurs in the GVD IBRA but also in a large portion of the adjacent Nullarbor IBRA. Areas of like response may also occur in geographically widely separate locations. For example the Yellabinna class (13) occurs in the far southern part of the GVD IBRA and in the northern part of the GVD, where it occurs intermingled with the Ranges class. Although class and IBRA boundaries generally show little coincidence, an exception is the boundary between the GVD IBRA and the north eastern edge of the Nullarbor IBRA, which aligns with the boundary between classes 17 and 21 (Fig. 4a).

A large IBRA region may include a variety of landforms. Division of the IBRA into sub-regions and IBRA associations deals with some of this diversity. At this finer-grained stratification of the region, there was only slightly stronger correspondence with the distribution of the vegetation variability classes (Fig. 4b and c).

#### 3.3.2. *Class characteristics*

To better understand how spatio-temporal variability differs across the AW landscape we summarise the landforms, soils and vegetation (Table 2), the average, variability, seasonality and trends of vegetation response, as shown by NDVI time series (Figs. 5 and 6, Table 3) and, where relevant, rainfall (Figs. 6 and 8) for each class.

The Desert class (17) is most typical of the study region (Fig. 4); widespread, and with greater extent within than beyond the AW boundaries. Its most dominant features are sand dunes and spinifex (*Triodia* spp.) although chenopod plains dominate in the south (Table 2).

The 25-year average NDVI plot for the Desert class shows that on average growth peaks in late August, with low inter-annual variability in growth (coefficient of variation less than 17%). Greatest inter-annual variability over 25 years occurs in June (Fig. 5). These annual patterns are further confirmed in the STL plot Fig. 6, which shows that the Desert class (17) vegetation annual growth patterns show some cyclic nature (Fig. 6) but this is not strong, with 68.9% of the data in the interquartile range (IQR) of the seasonal decomposition plot. This cycle shows its lowest value relatively late in January, and highest value in late August (Table 3; Fig. 5), which is early in the context of the southern winter/spring maxima of Australia-wide seasonality (Table 1). The Loess function, in the decomposition process, smooths out minor artefacts in the imagery, while a larger image anomaly (June 1994) can be seen as relegated to the remainder plot.

The trend for the Desert class (Fig. 6) shows considerable fluctuations over the study period with very low values in 1985–1986 and three separate large peaks in late 1989, late 1992 and early 1998. The averaged trend was upward. The positive residuals in the remainder plot are slightly higher than the negative as result of the June 1994 artefact, but overall they are evenly distributed, which retains confidence in the observed trend. Each of the classes under investigation shows great variability in trend (Fig. 6).

The iterative break analysis applied to the trend of the Desert class (17) shows four distinct breaks, where an abrupt change in vegetation response flagged a time of marked change in trend (Fig. 7). It shows that the pattern of vegetation response for the Desert class is extremely variable, with declining trends punctuated by sudden increase.

Vegetation growth (raw NDVI) of the Desert class shows on occasions a clear relationship to Maralinga rainfall records, but at other times no correspondence is apparent (Fig. 8). Lagged vegetation response to major rainfall events occurred in March 1983, March 1989, February 2003 and February 2004. Lags of two months or more between effective rain and vegetation growth peaks are common in the Australian arid landscape dominated by perennial plants (Nightingale and Phinn, 2003; Pickup and Bastin, 1997).

STL analysis of Maralinga monthly rainfall (Fig. 6) indicates that a mere 6.4% of rainfall data was captured within the IQR of the seasonal cycle, confirming the interpretation that rain in the Great Victoria Desert is aseasonal (Greenslade et al., 1986).

Rainfall clearly does not drive the cycles in vegetation growth so strongly demonstrated in the STL NDVI decomposition (Fig. 6). Nightingale and Phinn (2003) also note the lack of correspondence between precipitation and AVHRR NDVI for many arid southern Australian vegetation types. Factors suggested as responsible for this periodicity in greening are temperature, with shoot growth reduced to zero when the temperature rises above a certain threshold during the hottest part of summer (Specht and Specht, 2002), or day length and sun angle, with vegetation able to utilise dew till later in the day in winter. Added to this is the finding that even good summer rain may not result in the level of vegetation response that can be expected in the cooler months, because the extreme heat and high evaporation curtail ephemeral growth. This

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[1] http://www.bom.gov.au/cyclone/climatology/wa.shtml.

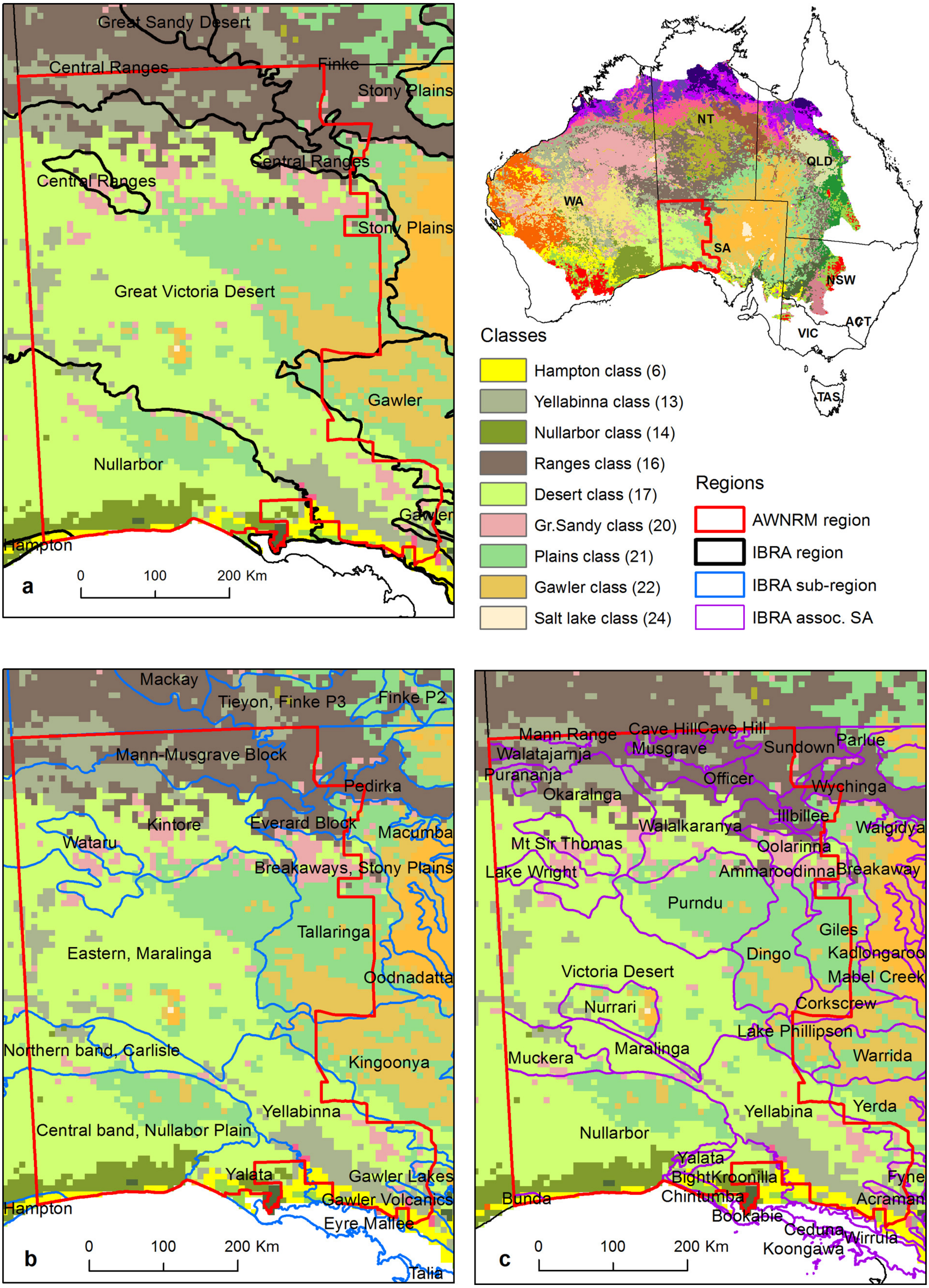


**Fig. 4.** The study site showing the classes represented within the AW region, with main classes named in the legend. Biogeographic regions mapped are, a. IBRA regions, b. IBRA sub-regions, c. South Australian IBRA associations.

**Table 2**
Description of the main classes of variability in vegetation response across the AW region.

| | Extent in Australian arid zone Extent within AW | % of AW | Dominant vegetation cover | Dominant landform | Soil |
|---|---|---|---|---|---|
| Desert class Class 17 | 264,320 km$^2$<br>135,808 km$^2$ | 51.4% | Low eucalypt woodland, open acacia scrubland and tall mallee shrubland and spinifex (*Triodia* spp.) grasslands. Low open shrubland of mulga, hakea, grevillea, senna, emubush and spinifex. In the south eastern open scrub of Mallee scrub and spinifex especially in the south eastern region. In the Nullarbor region, chenopod shrubland of saltbush, bluebush and samphire. | Extensive dunefields with occasional silcrete rises and shallow depressions. Plains with closely spaced easterly trending dunes and occasional rock outcrops in the south eastern region. On the Nullarbor, Limestone plain with occasional sinkholes and caves. Traces of surface drainage occasionally form elongated chains of dry lakes. | Red earthy sands, red siliceous sands, crusty red duplex soils and reddish dense loams and on the Nullarbor, powdery red calcareous loams and reddish calcareous earths. |
| Plains class Class 21 | 348,096 km$^2$<br>48,064 km$^2$ | 13.8% | Low open woodland of marble gum, mulga and spinifex, Shrublands of mulga, tussock grass, senna and emubush, with some hakea and grevillea. Chenopod shrubland of bluebush, saltbush samphire and sea heath. In the Nullarbor region, chenopod shrubland of saltbush, bluebush and samphire. Open scrub of mallee. | Undulating plain with dunes, low gibber covered rises and shallow sandy depressions associated with a relict drainage system. On the Nullarbor, Limestone plain with some sinkholes and caves. Occasional elongated chains of dry lakes. | Red massive earths, red earthy sands, red siliceous sands and crusty red duplex soils. Red calcareous loams, reddish calcareous earths and earthy sands. |
| Ranges class Class 16 | 501,632 km$^2$<br>31,360 km$^2$ | 6.3% | Hummock grassland of spinifex and wanderrie grass, low woodland of mulga and witchetty bush, low open woodland of mulga, hakea and witchetty bush, low shrubland of senna, emubush and witchetty bush and low woodland of river red gum and ironwood. Further east, Low open woodland of mulga and grasses. Open hummock grassland of spinifex. Low shrubland of witchetty bush, senna and emubush. Chenopod shrubland of bluebush, senna and emubush and low woodland of river red gum and umbrella grass. | Rugged ranges. Steep talus fans extending into the surrounding alluvial plains which carry isolated dunes and hills. Towards the east limestone and silcrete gravel plains occur, also gently undulating plains with parallel dunes. Some granitic inselbergs and silcrete capped mesas. | Red massive earths, red earthy sands and red siliceous sands. In the western area reddish loams and brown self-mulching cracking clays. Further east, Red earthy sands, red siliceous sands and crusty red duplex soils. |
| Yellabinna classClass 13 | 322,496 km$^2$<br>29,056 km$^2$ | 9.0% | In the north and west: Low open woodland of mulga, tall shrubland of mallee, spinifex, mulga and wire-grass or desert oak. Grassland of spinifex and wire-grass. Low shrubland of witchetty bush, senna and emubush. In the south: Open scrub of mallee and spinifex. | Extensive dunefields with easterly trending dunes, extensive sand plains, occasional inselbergs or calcrete rises. In the south plains with closely spaced dunes and occasional rock outcrops. | Red massive earths, red siliceous sands, reddish powdery calcareous loams. Red calcareous earths, crusty red duplex soils, reddish siliceous sands. |
| Nullarbor class Class 14 | 137,728 km$^2$<br>7168 km$^2$ | 5.2% | Chenopod shrubland of saltbush, bluebush and samphire, and open scrub of mallee and dryland teatree. | Featureless limestone plain with occasional sinkholes and caves and prominent cliffs along the coast. Traces of surface drainage occasionally form elongated chains of dry lakes. | Powdery red calcareous loams, reddish calcareous earths and reddish earthy sands |

can be seen when only limited growth followed by rapid decline was evident after heavy rain recorded at Maralinga in December 1982 and December 1988. The very high mid-summer evaporation and consequent surface drying may have halted ephemeral growth.

A cautious approach is needed when linking vegetation greening over a vast landscape to potentially patchy rainfall at a single rain recording station, as exemplified in 1992, when very little mid-year rain was recorded, yet NDVI levels rose, clearly as results of rain that fell elsewhere but failed to register at Maralinga (Fig. 8).

**Table 3**
STL results summarised. Low and peak timing, as calculated by STL, are also evident in Fig. 5.

| Decomposition seasonal values | Relative amount | Seasonal IQR | Overall trend | Low | Peak |
|---|---|---|---|---|---|
| Desert class (17) | Moderate | 68.9% | Upward | Late January | Late August |
| Plains class (21) | Low | 75.9% | Level | Late January | Early August |
| Ranges class (16) | Moderate | 91.9% | Downward | Early December | Late July |
| Yellabinna class (13) | High | 95.1% | Upward | Early January | Late July |
| Rain Giles | NA | 18.8% | NA | August | December |
| Rain Maralinga | NA | 6.4% | NA | NA | NA |

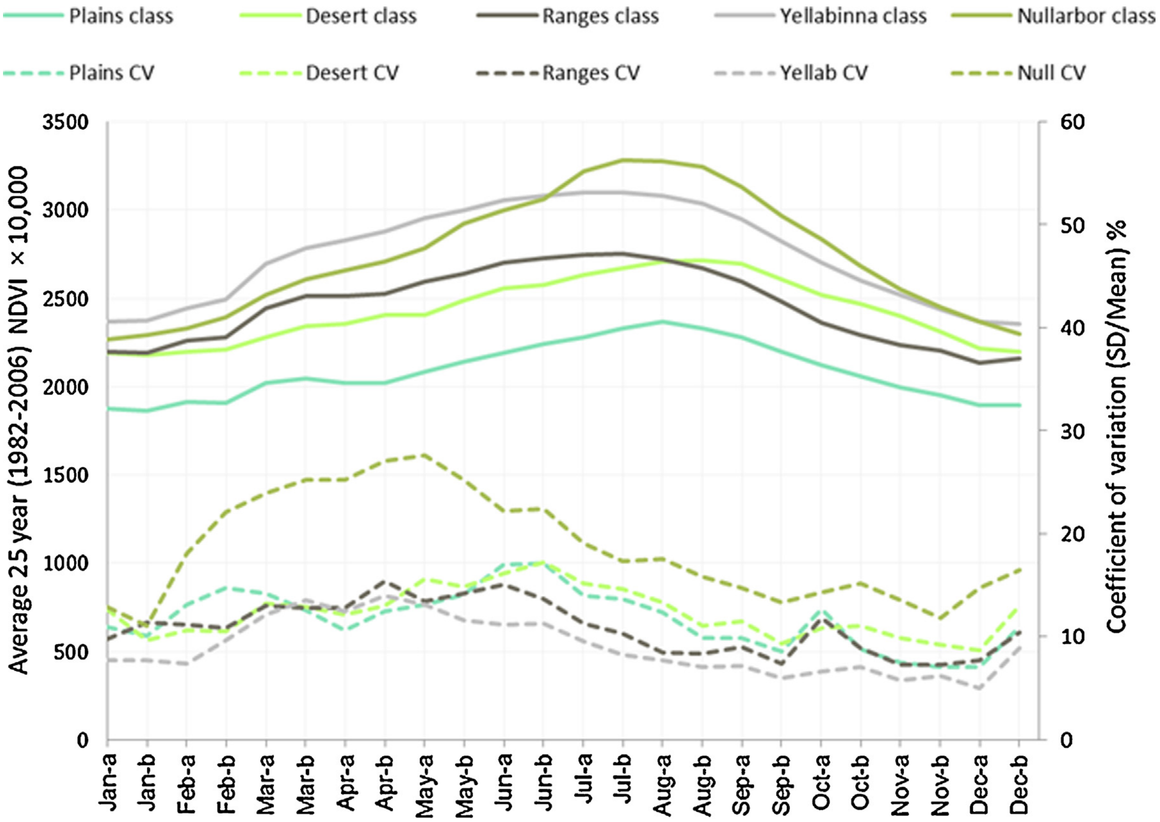


**Fig. 5.** NVDI for each class averaged over 25 years at twice monthly intervals. Variability for each date is shown by the coefficient of variation (CV, dashed lines).

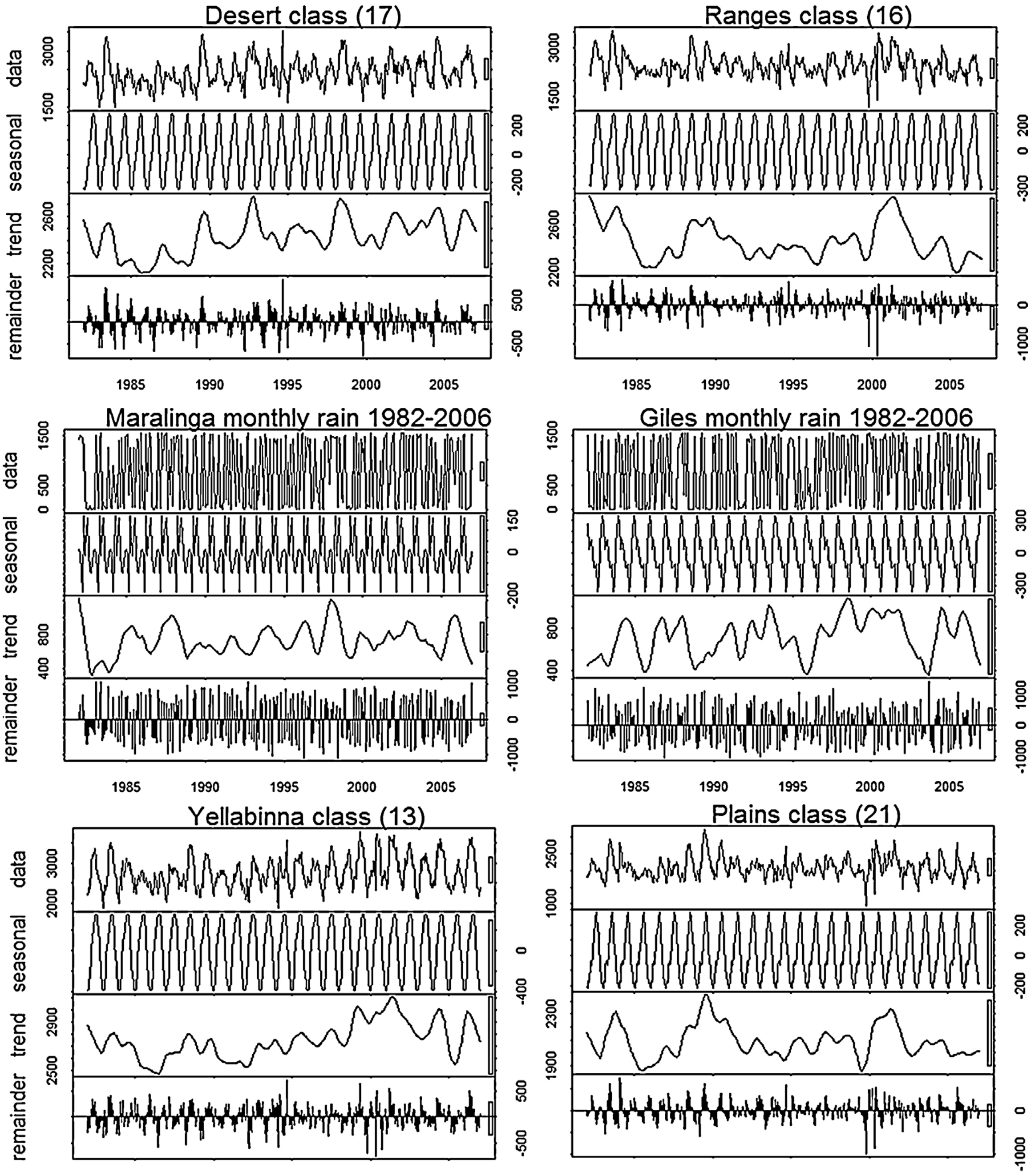
The Plains class (21) has by far the lowest average long-term vegetation response of all classes. Its inter-annual variation over the course of a year is very similar to that of the Desert class, but greater inter-annual variability is shown in late February (Fig. 5). Vegetation growth shows stronger seasonality in the Plains class than in the Desert class. The decomposition captures 75.9% of data within the IQR of the seasonal cycle. The lowest point of the Plains cycle occurs in late January, as in the Desert class, but the highest point occurs in early, rather than late, August. This pattern is supported by the 25-year average growth plot (Fig. 6).

The Ranges class (16) is largely associated with the Central Ranges and geographically confined to the north of the AW region. The vegetation components unique to this class appear to be the spinifex covered slopes and the tree and tall-shrub lined gullies and drainage lines (Table 2). In this zone growth commences earlier in the year than elsewhere in the AW region (Fig. 5) and it exhibits low inter-annual variation. The Ranges class and Desert class show the same average NDVI, but the Ranges class average exceeds that of the Desert class in the early part of the year (summer–autumn), whereas the Desert class NDVI average is the greater later in the year (late winter–spring) (Fig. 5).

The Ranges class vegetation shows relatively strong seasonal growth (Fig. 5; Table 3). Peak NDVI in the cycle occurs in late July and the minimum in early December, indicating that the growth cycle commences and finishes much earlier than that of other classes. The rainfall station associated with the Ranges class is Giles Meteorological Station, where average monthly rainfall at times exceeds 300 mm. By comparison Maralinga average monthly rain remained below 150 mm over the entire 1982–2006 period. STL decomposition of Giles rain records showed a slight tendency towards seasonality in rainfall with 18.8% of data in the IQR of the seasonal cycle, with peaks over the 25 year period occurring in December and lowest values in August (Fig. 6). This seasonality is likely related to the summer monsoonal rains to the north. The Ranges class trend over 25 years showed decline in vegetation growth. This corroborates with information from local Aboriginal managers, who suggest they observed a decline in landscape health as quoted in the AWNRM Management Plan. That trend was however estimated over a shorter, 10 year period (AWNRM Board, 2011).

The Yellabinna class (13) is an example of a class occurring in two widely divergent regions in the AW. In addition to its patchy occurrence in the west in Mamungari Conservation Park, a large portion of this class occurs in the Yellabinna area in the south, but also in the far north of the GVD where it grades into margins of the Central Ranges. Although these Yellabinna class regions appear quite diverse, the iso-classification had detected a similar long term pattern of variability in vegetation response in these separate regions.

Vegetation in the Yellabinna class showed the highest NDVI of any of the dominant classes, but also the least inter-annual variation (Fig. 5). This may be attributable to the relatively dense vegetation and higher foliage cover in mallee regions, where woody perennials dominate, rather than herbaceous (ephemeral) or grassy vegetation. The 25-year trend in vegetation growth for the Yellabinna class shows low response in the earlier part of the period, increasing after 1999, resulting in an overall increase. Strong seasonal periodicity is evident with 95.9% of the Loess smoothed data fitting within the IQR of the seasonal decomposition plot (Fig. 6). Comparison between the Yellabinna and the Ranges class reveals very similar responses, both showing relatively strong cyclic patterns, and near-coincidence in timing. Summer rain could explain the strong and early response in growth for the Ranges class and the northern portion of the Yellabinna class, but the southern portion of the Yellabinna class does not experience such rainfall patterns. The similar cyclic response in the south could be explained by the phenology of mallee, a summer



Desert class (17)

Ranges class (16)

Maralinga monthly rain 1982-2006

Giles monthly rain 1982-2006

Yellabinna class (13)

Plains class (21)

**Fig. 6.** Trend analysis for each of the major classes. STL plot showing for each class the raw twice monthly NDVI values over 25 years in the top panel; below this are the seasonality after Loess smoothing, the trend panel and the residual panel.

growing species. This showed that quite different drivers may produce similar growth patterns.

The Nullarbor class (14) is a relatively minor class in the AW region, occurring only at the southern margin of the Nullarbor, although in Western Australia this class occupies the greater part of the Nullarbor region. This class is of special interest because it exhibits growth patterns and variability very different from the main AW classes, with greater magnitude and amplitude and stronger Austral-winter response. Nullarbor class (14) peak-growth on average culminates in winter, and mean magnitude of growth is greater than that of the four main classes, but the coefficient of variation revealed that vegetation growth differs substantially from year to year in the early part of the year only.

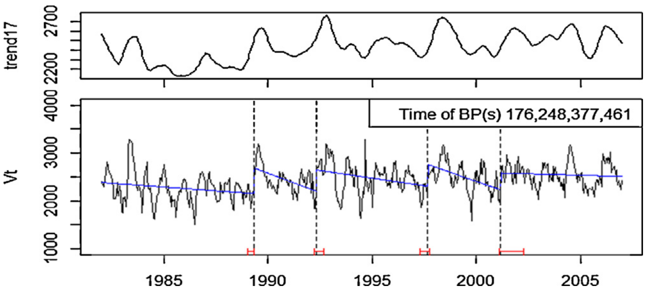


**Fig. 7.** Trend in NDVI time series and iterative breakplot for Desert class (17).

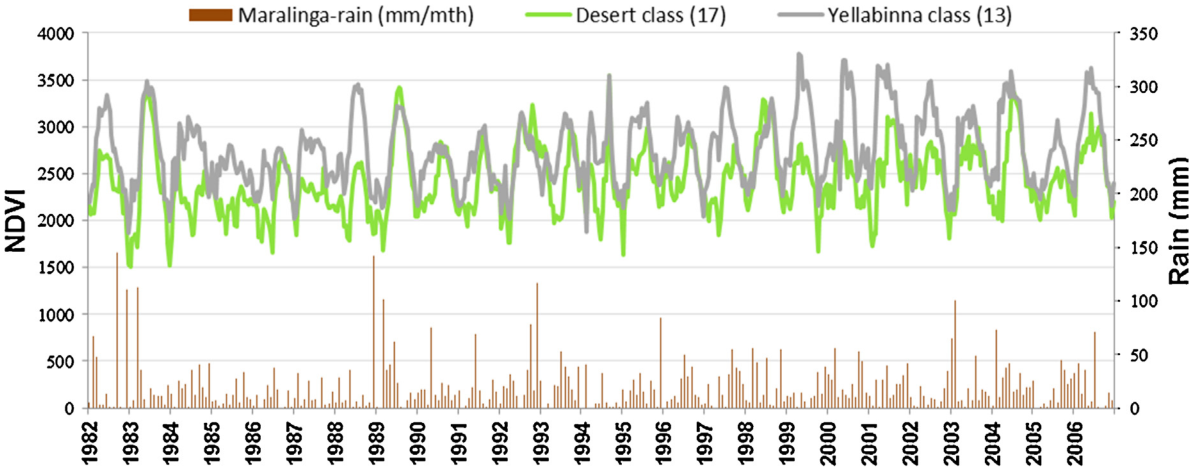


**Fig. 8.** Desert class (17) and Yellabinna class (13) NDVI time series showing vegetation response over 25 years. Rainfall shown was recorded at Maralinga, the most relevant station with comprehensive records for the 1982–2006 period.

This inter-annual variation appears to be linked to seasonality plus rainfall associated with the east-west erratic factor, as shown in the colour composite (Fig. 3). Lawley et al. (2011) suggested that these strong fluctuations in vegetation response, which are not evident in the adjacent Desert class, may be indicative of grazing regimes that have led to a reduction in chenopod cover and increase in annual forbs and grasses. Here we propose that an additional, or alternate, explanation is the third defining factor of arid zone variability, the erratic east-west response. Vegetation greening occurs as result of cyclone triggered rain, which appears to strongly affect vegetation growth in the Western Australian part of the Nullarbor (Fig. 3). This interpretation is supported by the fact that eight cyclonic paths traversed the Western Australian section of the Nullarbor in the 25-year study period – always in the early part of the year but not every year (BOM, 2012), which explains the greater inter-annual variability in vegetation response shown for this class in the early part of the year (Fig. 5).

## 4. Discussion

In highly variable landscapes change and trends in sparse ecological indicator data are very difficult to interpret. This study shows that remote sensing can provide the spatial and temporal context and framework needed to improve interpretation of ecological indicator data.

We have presented a detailed analysis of the spatio-temporal patterns that represent variability in vegetation growth across the AW wilderness region of South Australia. The geographic distribution and relative effect of the main components that govern long term variability in vegetation response in this arid region are presented. Iso-classification of the combined key components and NDVI time series for the main variability-based classes in the AW region revealed key differences between these classes. This information indicates where in the region certain vegetation responses may be expected and the strength and variability of such response.

The new stratification based on the distribution of the vegetation functional response clearly differs markedly from the stratifications based on biogeographical properties of climate, geology, soil and landform and vegetation composition and structure. The new classification is not intended to replace the IBRA but rather adds information about the vegetation functional response to enhance the IBRA stratifications and potentially enable better interpretation of ecological indicator data. This zonation based on active vegetation growth patterns may be more effective for monitoring of vegetation-growth related flora and fauna phenomena.

The considerable difference between distribution of the vegetation response-based classes and the traditional IBRA stratifications is important for data interpretation. Areas with the same observed growth pattern, although they are geographically located in different IBRA, may point to currently undocumented phenological and physiological similarities in vegetation. Conversely areas of different vegetation dynamics classes, even though they occur in the same IBRA region, need to be interpreted differently. IBRA stratifications are often used in the design of on-ground ecological sampling programmes (Foulkes et al., 2011), or to aggregate site records for broad-scale interpretation. The new stratification presents an alternative basis for field sample location, based on broad scale observation of vegetation function over time.

Several ecological condition assessment protocols have been established in Australia and elsewhere, collecting on-ground vegetation and soils data intended for use as ecosystem indicators. Some of these include repeat samples at various intervals. Examples of such field survey programmes in Australia are the Biological Surveys of South Australia (Heard and Channon, 1997; Kenny and Thompson, 2008), the AusPlots field monitoring programme of the Terrestrial Ecosystems Research Network (TERN) (Foulkes et al., 2011; White et al., 2012) and the detection and mapping of woody vegetation change for the Queensland Statewide Landcover and Trees Study (SLATS), which developed a field measurements method also used for Australia-wide fractional ground cover monitoring (Muir et al., 2011). Monitoring protocols may include assessment, in the arid zone usually in one hectare sites, of an array of ecological indicators such as vegetation species presence, soil characteristics and metagenomics, vegetation cover, tree biomass and leaf area index (LAI). The collected data are intended to reflect the condition of the site's ecosystem.

However, detecting trends in land condition is difficult if data has limited temporal frequency, sometimes as little as two or three assessments. To interpret such site data it is essential to understand the natural long-term patterns and cycles that operate at the site. Only when this natural variability is understood can judgement be made on whether the condition is truly improving or declining beyond the normal 'envelope' of variability. Furthermore to interpret values collected at a point in time we need to understand when in the natural temporal cycles and patterns of variability the data were collected. Currently anomalies in data values may be explained anecdotally by reference to known events such as a fire or heavy rain, but these factors are not always known for remote sites, and if known cannot be quantified. There is clearly a need to interpret site data in the measurable context of natural spatio-temporal patterns and cycles, especially when attempting to separate natural from management effects (Ostendorf, 2011).

The decomposition of the greenness signal (NDVI) of 25 years of NOAA AVHRR data showed considerable variation in the trend for each class across the 25 years. Extracting a definitive trend can be elusive, even when using the persistent, frequent and objective records of a long time-series of satellite data, covering a large part of the landscape. It emphasizes the complexity and episodic nature of arid landscapes. The study shows how interpretation of site based data without knowing the variability is apt to lead to misinterpretation of change detected in ecological indicator values and erroneous trend evaluations. The breakpoint analysis also draws attention to the likelihood of misinterpretation when using shorter time series for trend analysis.

This study used satellite data which offers spatially comprehensive high temporal frequency information over large spatial and temporal extent. This allowed us to gain greater understanding of landscape functioning which is impossible to obtain from field data alone. Our analysis has provided geographic patterns at 8 × 8 km ground resolution and temporal cycles at 16-day resolution. This does not reveal the condition or cycle at hectare-scale field sites, but it does reveal the envelope within which the sample site functions and by supplying this framework it can vastly improve the interpretation of data collected at the site.

The research demonstrates that each zone has a unique set of conditions, an envelope of variability rather than a “base line” of condition, within which we can place the field observations at specific times. We have used readily available satellite data for 1982–2006 but the temporal signal for each class can be extended with contemporary AVHRR-NDVI or higher resolution MODIS remotely sensed data. As future field data are collected, their timing in the response cycle can be determined and compared with those for previous observations from that site.

The findings in this research have, beyond improving data interpretation, also implications for ecological sampling protocols and site selection for comparative monitoring points, and for biodiversity management purposes. This study has not only given a new perspective on the regional AW landscape, it has also presented an approach to improve interpretation of indicator data that is applicable for arid zone management worldwide.

## References

AUSLIG, 1990. Vegetation Atlas of Australian Resources, vol. 6. Australian Surveying and Land Information Group, Canberra Australia.

AWNRM Board, 2011. Alinytjara Wilurara Regional Natural Resources Management Plan. Government of South Australia, Adelaide.

Bastin, G., Denham, R., Scarth, P., Sparrow, A., Chewings, V., 2014. Remotely-sensed analysis of ground-cover change in Queensland's rangelands, 1988–2005. Rangeland J. 36, 191–204.

Belnap, J., Gillette, D.A., 1998. Vulnerability of desert biological soil crusts to wind erosion: the influences of crust development, soil texture, and disturbance. J. Arid. Environ. 39, 133–142.

BOM, 2012. Australian Bureau of Meteorology.

Broich, M., Huete, A., Tulbure, M.G., Ma, X., Xin, Q., Paget, M., Restrepo-Coupe, N., Davies, K., Devadas, R., Held, A., 2014. Land surface phenological response to decadal climate variability across Australia using satellite remote sensing. Biogeosciences 11, 5181–5198.

Cleveland, R.B., Cleveland, W.S., McRae, J.E., Terpenning, I., 1990. STL: a seasonal-trend decomposition procedure based on loess. J. Off. Stat. 6, 3–73.

de Groot, R.S., Wilson, M.A., Boumans, R.M.J., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecol. Econ. 41, 393–408.

Driscoll, D.A., Felton, A., Gibbons, P., Felton, A.M., Munro, N.T., Lindenmayer, D.B., 2012. Priorities in policy and management when existing biodiversity stressors interact with climate-change. Climatic Change 111, 533–557.

DWLBC, 2002. Pastoral Lease Assessment, Technical Manual for Assessing Land Condition on Pastoral Leases in South Australia, 1990–2000. Department of Water, Land and Biodiversity Conservation, Pastoral Program, Sustainable Resources, Adelaide.

Eldridge, D.J., Ferris, J.M., 1999. Recovery of populations of the soil lichen Psora crenata after disturbance in arid South Australia. Rangeland J. 21, 194–198.

Fisher, B., Turner, R.K., Morling, P., 2009. Defining and classifying ecosystem services for decision making. Ecol. Econ. 68, 643–653.

Foulkes, J.N., White, I.A., Sparrow, B.D., Lowe, A.J., 2011. Discussion Paper, AusPlots-Rangelands Monitoring Site Stratification and Survey Methods Within TERN (Terrestrial Ecosystem Research Network). School of Earth and Environmental Sciences. The University of Adelaide, South Australia.

Friedel, M.H., Sparrow, A.D., Kinloch, J.E., Tongway, D.J., 2003. Degradation and recovery processes in and grazing lands of Central Australia. Part 2: Vegetation. J. Arid. Environ. 55, 327–348.

Gillieson, D.S., Cochrane, J.A., Murray, A., 1994. Surface hydrology and soil movement in an Arid Karst – the Nullarbor Plain Australia. Environ. Geol. 23, 125–133.

Government of South Australia, 2007. Atlas of South Australia.

Greenslade, P., Joseph, L., Barley, R., 1986. The Great Victoria Desert. Nature Conservation Society of South Australia Inc, Adelaide, 136 pp.

Guerschman, J.P., Hill, M.J., Renzullo, L.J., Barrett, D.J., Marks, A.S., Botha, E.J., 2009. Estimating fractional cover of photosynthetic vegetation, non-photosynthetic vegetation and bare soil in the Australian tropical savanna region upscaling the EO-1 Hyperion and MODIS sensors. Remote Sens. Environ. 113, 928–945.

Hansen, M.C., Defries, R.S., Townshend, J.R.G., Sohlberg, R., 2000. Global land cover classification at 1 km spatial resolution using a classification tree approach. Int. J. Remote Sens. 21, 1331–1364.

Haydon, D.T., Friar, J.K., Pianka, E.R., 2000. Fire-driven dynamic mosaics in the Great Victoria Desert Australia – I. Fire geometry. Landsc. Ecol. 15, 373–382.

Heard, L.M.B., Channon, B., 1997. Guide to A Native Vegetation Survey Using the Biological Survey of South Australia Methodology. DENR, Adelaide.

Hutchinson, M.F., McIntyre, S., Hobbs, R.J., Stein, J.L., Garnett, S., Kinloch, J., 2005. Integrating a global agro-climatic classification with bioregional boundaries in Australia. Global Ecol. Biogeogr. 14, 197–212.

Ivits, E., Cherlet, M., Sommer, S., Mehl, W., 2013. Addressing the complexity in non-linear evolution of vegetation phenological change with time-series of remote sensing images. Ecol. Indic. 26, 49–60.

Kenny, S.D., Thompson, D.S., 2008. A Vegetation Map for the Nullarbor Bioregion, South Australia. Department for Environment and Heritage, Adelaide, pp. 108.

Kilpatrick, A.D., Warren-Smith, S.C., Read, J.L., Lewis, M.M., Ostendorf, B., 2011. Cross-fence comparisons: theory for spatially comprehensive, controlled variable assessment of treatment effects in managed landscapes. Ecol. Inf. 6, 170–176.

Klein, C.J., Wilson, K.A., Watts, M., Stein, J., Carwardine, J., Mackey, B., Possingham, H.P., 2009. Spatial conservation prioritization inclusive of wilderness quality: a case study of Australia's biodiversity. Biol. Conserv. 142, 1282–1290.

Landsberg, J., Crowley, G., 2004. Monitoring rangeland biodiversity: plants as indicators. Aust. Ecol. 29, 59–77.

Lawley, E.F., Lewis, M.M., Ostendorf, B., 2011. Environmental zonation across the Australian arid region based on long-term vegetation dynamics. J. Arid. Environ. 75, 576–585.

Lawley, V., Parrott, L., Lewis, M., Sinclair, R., Ostendorf, B., 2013. Self-organization and complex dynamics of regenerating vegetation in an arid ecosystem: 82 years of recovery after grazing. J. Arid. Environ. 88, 156–164.

Ludwig, J.A., Bastin, G.N., 2008. Rangeland condition: its meaning and use. A Discussion Paper prepared for the Australian Collaborative Rangelands Information System (ACRIS) Management Committee.

Ludwig, J.A., Bastin, G.N., Eager, R.W., Karfs, R., Ketner, P., Pearce, G., 2000. Monitoring Australian rangeland sites using landscape function indicators and ground- and remote-based techniques. Environ. Monit. Assess. 64, 167–178.

Ludwig, J.A., Tongway, D.J., Bastin, G.N., James, C.D., 2004. Monitoring ecological indicators of rangeland functional integrity and their relation to biodiversity at local to regional scales. Austral Ecology 29, 108–120.

Lymburner, L., Tan, P., Mueller, N., Thackway, R., Thankappan, M., Islam, A., Lewis, A., Randall, L., Senarath, U., 2011. The National Dynamic Landcover Dataset – Technical Report. National Earth Observation Group, Geoscience Australia, Symonston, ACT.

Marshall, V.M., Lewis, M.M., Ostendorf, B., 2012. Buffel grass (*Cenchrus ciliaris*) as an invader and threat to biodiversity in arid environments: a review. J. Arid. Environ. 78, 1–12.

Muir, J., Schmidt, M., Tindall, D., Trevithick, R., Scarth, P., Stewart, J.B., 2011. Field Measurement of Fractional Ground Cover: A Technical Handbook Supporting Ground Cover Monitoring for Australia. Prepared by the Queensland Department of Environment and Resource Management Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra.

Nightingale, J.M., Phinn, S.R., 2003. Assessment of Relationships Between Precipitation and Satellite Derived Vegetation Condition Within South Australia. Aust. Geogr. Stud. 41, 180–195.

NVIS, 2012. Major Vegetation Groups and Major Vegetation Subgroups 4.1. Department of the Environment.

Okin, G.S., Clarke, K.D., Lewis, M.M., 2013. Comparison of methods for estimation of absolute vegetation and soil fractional cover using MODIS normalized BRDF-adjusted reflectance data. Remote Sens. Environ. 130, 266–279.

Ostendorf, B., 2011. Overview: spatial information and indicators for sustainable management of natural resources. Ecol. Indic. 11, 97–102.

Pesch, R., Schmidt, G., Schroeder, W., Weustermann, I., 2011. Application of CART in ecological landscape mapping: two case studies. Ecol. Indic. 11, 115–122.

Pettorelli, N., Chauvenet, A.L.M., Duffy, J.P., Cornforth, W.A., Meillere, A., Baillie, J.E.M., 2012. Tracking the effect of climate change on ecosystem functioning using protected areas: Africa as a case study. Ecol. Indic. 20, 269–276.

Petus, C., Lewis, M., White, D., 2013. Monitoring temporal dynamics of Great Artesian Basin wetland vegetation Australia, using MODIS NDVI. Ecol. Indic. 34, 41–52.

Pickett-Heaps, C.A., Canadell, J.G., Briggs, P.R., Gobron, N., Haverd, V., Paget, M.J., Pinty, B., Raupach, M.R., 2014. Evaluation of six satellite-derived Fraction of Absorbed Photosynthetic Active Radiation (FAPAR) products across the Australian continent. Remote Sens. Environ. 140, 241–256.

Pickup, G., Bastin, G.N., 1997. Spatial distribution of cattle in arid rangelands as detected by patterns of change in vegetation cover. J. Appl. Ecol. 34, 657–667.

Pitt, J., Feuerherdt, L., Carmody, M., 2007. 2006–2011 Alinytjara Wilurara Natural Resources Management Region Pest Management Strategy. Alinytjara Wilurara NRM Board, Adelaide.

Pyke, D.A., Herrick, J.E., Shaver, P., Pellant, M., 2002. Rangeland health attributes and indicators for qualitative assessment. J. Range Manage. 55, 584–597.

Reeves, M.C., Baggett, L.S., 2014. A remote sensing protocol for identifying rangelands with degraded productive capacity. Ecol. Indic. 43, 172–182.

Rouse, J.W., Haas, R.H., Schell, J.A., Deering, D.W., Harlan, J.C., 1974. Monitoring the Vernal Advancement and Retrogradation (Greenwave Effect) of Natural Vegetation. Remote Sensing Center, Texas A&M University, College Station, TX, pp. 77843.

Smyth, A., Brandle, R., Brook, A., Chewings, V., Fleming, M., Read, J., 2009. Methods for Identifying, Selecting and Interpreting Indicators for Assessing Biodiversity Condition in Desert Australia, Using the Stony Plains Bioregion as a Case Study. Desert Knowledge Cooperative Research Centre, Alice Springs.

Specht, R.L., Specht, A., 2002. Australian Plant Communities: Dynamics of Structure, Growth and Biodiversity. Oxford University Press, South Melbourne.

Suppiah, R., Preston, B.L., Whetton, P.H., McInnes, K.L., Jones, R.N., Macadam, I., Bathols, J.M., Kirono, D.G.C., 2006. Climate Change Under Enhanced Greenhouse Conditions in South Australia Climate Impacts and Risk Group. CSIRO Marine and Atmospheric Research, Aspendale.

Thackway, R., Cresswell, I.D., 1997. A bioregional framework for planning the national system of protected areas in Australia. Nat. Areas J. 17, 241–247.

Thackway, R., Lesslie, R., 2006. Reporting vegetation condition using the Vegetation Assets States and Transitions (VAST) framework. Ecol. Manage. Restoration 7, S53–S62.

Thackway, R., Lymburner, L., Guerschman, J.P., 2013. Dynamic land cover information: bridging the gap between remote sensing and natural resource management. Ecol. Soc. 18, 14.

Thenkabail, P.S., Schull, M., Turral, H., 2005. Ganges and Indus river basin land use/land cover (LULC) and irrigated area mapping using continuous streams of MODIS data. Remote Sens. Environ. 95, 317–341.

Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8, 127–150.

Turcotte, K.M., Lulla, K., Venugopal, G., 1993. Mapping small-scale vegetation changes of Mexico. Geocarto Int. 8, 73–85.

Turner, D., Ostendorf, B., Lewis, M., 2008. An introduction to patterns of fire in arid and semi-arid Australia, 1998–2004. Rangeland J. 30, 95–107.

USDA, 2014. National Resources Inventory Rangeland Resource Assessment Natural Resources Conservation Service. USDA, Washington, DC.

Verbesselt, J., Hyndman, R., Newnham, G., Culvenor, D., 2010. Detecting trend and seasonal changes in satellite image time series. Remote Sens. Environ. 114, 106–115.

Warburton, D., 2011. Rangeland Condition Monitoring – A Guide for Pastoral Lessees. Department of Agriculture and Food Perth.

White, A., Sparrow, B., Leitch, E., Foulkes, J., Flitton, R., Lowe, A.J., Caddy-Retalic, S., 2012. AusPlots Rangelands Survey Protocols Manual. Terrestrial Ecosystem Research Network (TERN), The University of Adelaide, Adelaide.

Xiao, X.M., Boles, S., Liu, J.Y., Zhuang, D.F., Frolking, S., Li, C.S., Salas, W., Moore, B., 2005. Mapping paddy rice agriculture in southern China using multi-temporal MODIS images. Remote Sens. Environ. 95, 480–492.