



# **Satellite remote sensing to monitor land condition and dynamics in arid Australia**

Letting the landscape speak for itself



**Thesis submitted for the degree of**

**Doctor of Philosophy**

by

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Title page image: Landscape in the northwestern Alinytjara Wilurara Natural Resources Management region near Pipalytjara. Photo by E F Lawley, February 15, 2012.

## ABSTRACT

The natural arid regions of Australia hold special value because their ecosystems are relatively intact. They play an important role in carbon cycling, provide ecosystem services, deliver benchmark information about ecosystem structure and function in unmodified landscapes, and are often the last stronghold of threatened species. Many of these regions are also homelands for Aboriginal traditional owners. These regions are under increasing external pressures from mining, tourism, localised grazing and invasive species. Careful management is needed to maintain their ecological values.

Monitoring land condition is vital for management, but in extensive remote regions collecting field data to adequately represent land systems and processes is time consuming and costly. The high spatio-temporal variability of the arid landscape further confounds data interpretation. Long-term patterns of variability in vegetation response need to be understood to interpret management effects as distinct from natural variability. These long-term patterns cannot be understood from field data alone. In contrast, satellite-based monitoring offers potential monitoring solutions, with spatially comprehensive and consistent coverage over wide regions at relatively low cost.

This overall aim of the research was to improve arid land condition monitoring through use of satellite remote sensing. Vegetation cover and soil exposure were used as indicators of land condition throughout the study.

The study focused on the Alinytjara Wilurara (AW) Natural Resources Management (NRM) region in the far west of South Australia. This region is 261,180 km<sup>2</sup> in extent, much of it in near-pristine or wilderness condition, and is co-managed by the South Australian Government and the Aboriginal traditional owners. The landscape is extremely varied, incorporating calcarenite cliffs and dunes along the southern coast, the flat limestone Nullarbor Plain, red dune fields of the Great Victoria Desert, and the granitic Central Ranges and associated alluvial fans and plains in the north.

The research comprised three components to address the overall aim. Specific objectives were to characterize and better understand the patterns of long term spatio-temporal variability in vegetation growth over the Australian arid zone; to interpret these patterns, their significance and implications for monitoring and management across the AW study region; and to evaluate the potential of high-temporal frequency

low-spatial resolution fractional cover imagery for rapid land condition monitoring in the region. To address the difficulties of field validation, a further objective was to develop the use of high-spatial resolution satellite data as a tool for evaluation of low-spatial resolution fractional cover products.

To detect long-term patterns of variability in vegetation growth, 25 years of twice-monthly AVHRR NDVI data were analysed with principal components analysis. The main components that underlie Australia-wide arid zone variability were revealed as total vegetation growth, seasonal response, and erratic east-west response driven by cyclonic activity. These factors were used as the basis to classify the Australian arid region into 24 classes. The new spatio-temporal classes, which represent long-term vegetation function, were compared to the existing Interim Biogeographic Regionalisation for Australia (IBRA), which describes vegetation in terms of structure and composition. Some classes showed close correspondence with IBRA regions, but in other areas the classes revealed variation in functional response within and between IBRA regions.

Subsequently, focusing on the AW region, the four dominant classes in this region showed distinct characteristics in relation to average amount and temporal variability of vegetation growth, timing of growth cycles, and vegetation type. These distinctions can improve interpretation of on-ground data and have important implications for site selection and monitoring protocols such as timing and frequency of monitoring.

Lastly, a MODIS fractional cover product, designated for Australia-wide usage, was tested for suitability over the AW region for ongoing monitoring of land condition. In the absence of field data, remotely-sensed surrogates were created, which classified high-spatial resolution (2.5m) ALOS PRISM data into fractions of bare soil and vegetation cover. These were up-scaled to MODIS resolution. Weak correlation was found between the surrogate and the MODIS fractional cover product, implying that the MODIS product is not suitable in its current form for use in the AW region. The finding of a slightly stronger correlation with increased vegetation cover suggests that the lack of relationship may be due to the generally low NDVI response of the arid perennial vegetation in this region. The novel method employed to create the soil exposure surrogate for this evaluation warrants further development and application for validating low spatial resolution image products in arid regions worldwide.

This research shows how remote sensing can be used to define the high spatio-temporal variability of the Australian arid zone and provide new spatio-temporal information to improve regional environmental monitoring and management. We recommend that satellite remote sensing, because of its temporal capacity and comprehensive nature, be included as an essential component for monitoring remote arid environments.



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## DECLARATION

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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**DEDICATION**

FOR STEVEN

29-12-1975 – 29-03-1995



## ACKNOWLEDGEMENTS

Well here we are, and what a journey it has been. There seems to be a certain madness in going to university after 30 years of filling in “occupation – home duties” on the census forms. When asked why I am studying, with the “at your age?” implied, my reply has been: curiosity drove me! But truth-be-told, the wish to write a scientific report on our findings as environmental volunteers, and my inability to do so, was the driver.

This adventure would however never have happened without the encouragement of many people along the way. From Ben Pavy, who infected me with the joy of recognising plants, to Sue Kenny and Lee Heard who showed how to preserve and record the information, and most of all to Brad Page and Annelise Wiebkin, who on distant islands, under starry skies while waiting silently for Little penguins to come home, swayed my mind into believing that studying for a university degree was a realistic option; I may have surprised them as much as myself, when it became a PhD. Thanks goes to Dr. Scoresby Shepherd, whose example I admire, not spending time on obstacles, but navigating around them and keeping on course. He showed me, in his role as editor, how to “omit needless words”, though I confess that has remained a struggle. To these and many others I owe gratitude for their belief in me that set me on this journey.

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## LIST OF PUBLICATIONS

### **Publications included in this thesis**

Lawley, E.F., Lewis, M.M., & Ostendorf, B. (2011). Environmental zonation across the Australian arid region based on long-term vegetation dynamics. *Journal of Arid Environments*, 75, 576-585

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## ACRONYMS

ALOS	Advanced Land Observing Satellite
AW region	Alinytjara Wilurara region
AWNRM	Alinytjara Wilurara Natural Resources Management
AVHRR	Advanced Very High Resolution Radiometer
BRDF	Bidirectional Reflectance Distribution Function
IBRA	Interim Biogeographic Regionalisation for Australia
MODIS	MODerate resolution Imaging Spectroradiometer
MODIS Fract-G	The MODIS Fractional cover product created by Guerschman et al (2009) – abbreviation coined for this thesis.
NBAR	Nadir BRDF-Adjusted Reflectance
NOAA	National Oceanic and Atmospheric Administration
PRISM	Panchromatic Remote-sensing Instrument Stereo Mapping
GVD	Great Victoria Desert



# CHAPTER 1

## INTRODUCTION



## 1.1 Background

Monitoring land condition is critical for effective environmental management, and for reporting on land condition trends, states and transitions which are affected by land management (Bastin et al., 2009; Thackway and Lesslie, 2006). Collecting adequate environmental monitoring information and interpreting it can however be extremely challenging. Landscape heterogeneity, variability over time and the difficulty of collecting enough data for meaningful analysis all contribute to these challenges. This is particularly so for the arid zone of Australia.

The Australian arid and semi-arid zone, defined as the Desert and Grassland category in the Köppen world climate classification, occupies over 70% of the Australian continent. It is the region where evaporation exceeds precipitation (BOM, 2012; Stern et al., 2000) (Appendix A). The arid zone landscape is extremely variable, showing both short and long-term vegetation responses to erratic rainfall and fire events.

This sparsely vegetated landscape is very resilient, with vegetation adapted to persist through prolonged periods of heat and drought and to recover after wildfire. It is however also fragile; soil crust is easily destroyed (Eldridge and Ferris, 1999) and loss of the slow growing perennial vegetation is difficult to reverse (Friedel et al., 2003). Close monitoring of such landscapes is important to detect degradation early and initiate remedial action.

Present land condition over this vast region is very much a product of past management. For instance a large proportion of the Australian arid zone, where reliable surface or subterranean water was available, was managed as rangeland from late 19<sup>th</sup> - early 20<sup>th</sup> century onwards. The fragility of the arid country was initially not understood and much overgrazing and subsequent degradation occurred when domestic stock was first introduced into the arid region (Buckley, 1982; Letnic, 2000; Morton et al., 1995; Purvis, 1986).

The land largely remained in its natural condition where water for stock was unavailable. Those remarkable natural regions have very high conservation value. They are often the last stronghold of threatened species. These regions have relatively intact native vegetation and soil structure and many indigenous and endemic flora and fauna species are present (Klein et al., 2009; Thackway and Lesslie, 2008). Their large extent

ensures that they play a significant role in carbon cycling and provide important ecosystem services (de Groot et al., 2002; Fisher et al., 2009; Naidoo et al., 2008). They also deliver benchmark information about ecosystem structure and function in unmodified landscapes, and have the potential for monitoring and interpretation of the effects of climate change (Driscoll et al., 2012; Pettorelli et al., 2012). There is a need for improved monitoring of land condition in these high-value regions which are generally classed as pristine or wilderness (Lesslie, 1991; Thackway and Lesslie, 2006).

### 1.1.1 *Wilderness management*

To avoid ambiguity the term wilderness needs consideration here, as its meaning has changed over time and differs between cultures.

Wilderness was to the early European settlers in Australia undeveloped land and viewed as wastelands (Pressey and Tully, 1994). This view of wilderness as wastelands led in South Australia to some areas being used as nuclear testing sites from 1953 to 1963, causing depopulation of that region (Mattingley and Yatala and Oak Valley Communities, 2009). After cleanup operations these areas were, from the European perspective, left to return to wilderness condition (Eldridge and Ferris, 1999). This view of wilderness as wastelands has since changed and wilderness areas are now highly valued because of their ecological qualities.

The Australian Aboriginal perspective of wilderness is quite opposite to both the earlier and the more recent European-based views. To Aboriginal Australians wilderness is mismanaged land, such as that degraded through overgrazing and erosion (Rose, 1996). They have defined wilderness as land 'without its songs and ceremonies' - land that has lost its custodians and consequently is no longer maintained (Lawrence, 1996; Strelein, 1993). Aboriginal Australians refer to well-maintained land as healthy country and to those who live in these regions, maintaining "country" is core of cultural and ceremonial life. They do not regard the land on which they live as wilderness.

The author has chosen to use the term wilderness in this thesis in the more recent European sense, indicating land undisturbed by anthropogenic actions imposed for commercial use of the natural resources. The author however recognizes that anthropogenic actions from within the regions are an intrinsic part of the Australian natural ecosystems and have over thousands of years shaped this wilderness.

In the wilderness areas of South Australia Aboriginal traditional owners and government agencies now find common ground for management. For example monitoring of fauna is taking place in the Anangu Pitjantjatjara Yakuntjatjara (APY) lands in the north-west of South Australia as part of the “Kuka kanyini” program; literally: “keeping the meat”, but in western terms: “lose no species” (Wilson and Woodrow, 2009). Land condition monitoring is an important part of the Natural Resource Management Plan which has been developed for the AW region through cooperation between State government and Aboriginal management (AWNRM Board, 2011).

Fire played a significant role in pre-European Aboriginal land management. Clearing the country of old vegetation to enable fresh growth was common management practice. Lighting small fires when foraging for prey, such as monitor lizards, which is still performed by Aboriginal women, leads to greater diversity of successional stages (Bird et al., 2008). Suppressing fire was initially viewed as desirable from the European perspective, although it is now recognised that fire mosaics were part of the pre-European land management practice, referred to as fire stick farming (Bird et al., 2008). Fire, although resulting in short term reduction of vegetation cover and exposure of bare soil, can be viewed as natural when followed by regeneration (Buckley, 1982). Fires are accepted as part of the wilderness ecosystems and add further spatio-temporal variability to a landscape where vegetation growth is strongly influenced by patchy and erratic rainfall.

Monitoring land condition in such highly variable environments is challenging, but of increasing importance because of growing threats to landscape health of the natural regions.

#### 1.1.2 *Threats to land condition*

Land condition in the wilderness regions was until recently mainly affected by traditional Australian Aboriginal usage and the natural forces of climate and fire, but increasingly these pristine remote regions are encroached upon. Tourism, local vehicular traffic, and mining exploration and development, are increasingly accessing these regions, thereby risking soil and vegetation damage and the introduction of weed species, all of which have negative effects on land condition.

High fuel-load buffel grass (*Cenchrus ciliaris*) has invaded some of the wilderness regions, in particular in northern South Australia (Marshall et al., 2012; Miller et al., 2010; Pitt et al., 2007; Smyth et al., 2009). Weed invasions change fire regimes and cause loss of perennial native plant species (Schlesinger et al., 2013). This in turn changes soil exposure and has long-term effect on land condition.

Feral grazers and browsers have proliferated and affect vegetation and soil in the arid zone. These are the descendants of deliberately introduced, escaped or abandoned domestic animals, such as rabbits, goats, donkeys, horses and camels (Pitt et al., 2007). They compete for food with native species, cause damage to vegetation and natural waterholes, and may affect land condition by breaking up soil crusts. Camel numbers in particular have increased in arid Australia and their browsing on shrubs and trees can have severe impact on this type of vegetation (Edwards et al., 2004; Fensham and Fairfax, 2008). These threats to landscape “health” create the strong need for monitoring land condition of these unique regions, so management can take appropriate action in order to ensure that the irreplaceable natural values are maintained.

### 1.1.3 *Land condition indicators*

To monitor land condition it is important to decide on appropriate land condition indicators. Ecologists and Aboriginal managers are interested in flora and fauna management and ecosystem health, while managers of grazing properties are interested in fodder production. These at times competing interests need to be considered to ensure that land condition indicators are relevant, meaningful and understood by all interested parties. In addition, with increasing interest in remote monitoring, it is important that these indicators can be recognized and quantified by remote means.

Vegetation cover and soil exposure are widely used as indicators of land condition for rangeland management (Bastin et al., 1993; Bastin et al., 1998; Foran and Pickup, 1984; Friedel, 1997; Friedel et al., 2003; Graetz et al., 1976; Pickup and Nelson, 1984). Maintaining vegetation cover and soil stability and preventing degradation are important for long-term pasture production. Land condition in commercially grazed areas has been measured as differences between potential and actual vegetation response in years with high rainfall (Pickup and Chewings, 1994) and by rain use efficiency (Pickup, 1996). Measurements are often based on features directly related to domestic grazing. Water points and distance from these are used to assess grazing



impacts (Bastin et al., 2012; Bastin et al., 1993) - a grazing artifact also referred to as piosphere (Lange, 1969; Washington-Allen et al., 2004). Paddock fence lines have been used in cross-fence comparisons of land condition (Kilpatrick et al., 2011).

In the wilderness regions such pastoral features do not exist and consequently a different approach is needed to monitor land condition. However, in these regions vegetation cover and soil exposure are just as important, because wind and water erosion here too result in reduced production of vegetation biomass. While this affects potential stocking rates in pastoral areas, it likewise affects wildlife breeding success in wilderness areas (Bilton and Croft, 2004).

Relative levels of soil exposure and vegetation cover can be seen as an important condition indicator in arid land management, irrespective of the focus of interest. In this thesis the proportion of vegetation cover relative to exposed soil is used as key indicator of land condition.

## **1.2 Research motivation and approach**

Motivation for this study was the desire of the Alinytjara Wilurara Natural Resources Management Board (AWNRM Board, 2011) to use remote sensing to better assess and monitor land condition in the Alinytjara Wilurara (AW) Natural Resources Management (NRM) region in the far west of South Australia. This vast arid region is managed by the traditional owners, in cooperation with the South Australian Government. The AWNRM Board consists entirely of Aboriginal members most of whom live in homeland communities on country that has traditionally been in their care. They have a strong desire to monitor the “health” of this country of which they are the cultural custodians, while at the same time fulfilling the governmental responsibilities of monitoring and reporting on land condition. This research set out to investigate ways to address this need, and in particular the use of remote sensing to achieve this.

Regional vegetation response does not occur in spatial isolation, but is irrevocably bound to climatic events that extend well beyond the region. To interpret change in regional vegetation cover, and detect whether this change is atypical, it is necessary to understand the wider long-term patterns and cycles of vegetation growth and the factors that govern these; the wider context needs to be understood. This is especially so for landscapes with high spatio-temporal variability such as the AW region where erratic

rain and fire affect vegetation growth. However the patterns, cycles and trends that define the long-term broad scale variability of vegetation growth in arid Australia are unknown. This severely hampers interpretation of monitoring data.

When long-term broad-scale patterns of vegetation growth are known, these can form the background against which to interpret regional monitoring data. An expectation can be formed as to how various zones within the study region might respond over time. It is therefore important to analyse and define the long-term response patterns that are typical for various areas within the AW region, in order to improve monitoring within this region.

With improved understanding of long-term vegetation response across the AW landscape it should be feasible to monitor the region using high-temporal frequency satellite imagery, because this will now be easier to interpret. Such satellite imagery would need to be evaluated over the regions of interest prior to use which is challenging because field data to carry out such evaluation are difficult to obtain. A method needs to be developed to test high temporal frequency imagery.

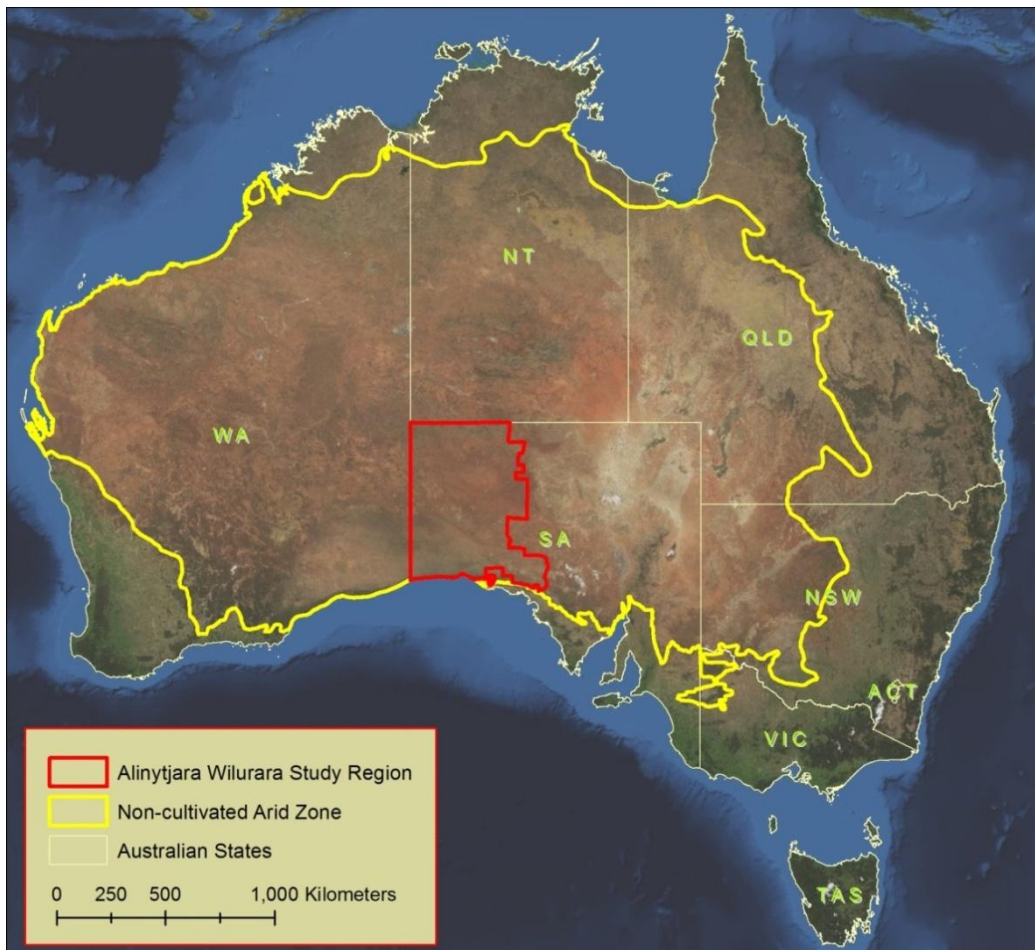
To address these needs this research aimed to develop an understanding of patterns of vegetation growth in the Australian arid zone and the AW region, to evaluate high-temporal frequency satellite imagery for regional monitoring, and to develop an evaluation method that does not rely on field data.

### **1.3 Study areas**

The entire non-cultivated arid zone of Australia was chosen as the first study area in order to detect and map long-term variability in vegetation growth at continental scale. The arid zone of Australia is traditionally defined as the modified desert and grassland category in the Köppen climatic classification (Stern et al., 2000). This delineation was for the purpose of this research further modified to exclude areas of dryland agriculture, the response of which fell outside of the sphere of interest of this study. The region thus defined is approximately 5,250,000 km<sup>2</sup> in extent. It includes a great variety of vegetation and landforms, and shows some variation in climatic conditions within the arid response range.

The second study area was chosen in order to respond to the need of the AWNRM Board for improved monitoring of land condition in the AW region. This region is

nested south-centrally within the Australian arid zone and covers approximately 261,180 km<sup>2</sup>. It encompasses the entire far western area of South Australia. Its northern and western perimeters are formed by the State boundary, its southern margin is the Great Australian Bight and its eastern perimeter lies roughly to the west of the Stuart Highway which connects southern South Australia with the Northern Territory (Fig. 1.1).



**Fig. 1.1** The Australian arid zone and Alinytjara Wilurara study areas.

The AW region includes a great diversity of landscapes, broadly indicated as the Central Ranges and alluvial fans and plains in the north, the red dune fields of the Great Victoria Desert in the centre, the flat limestone regions of the Nullarbor Plain further south, and steep calcarenite cliffs and white sand dunes along the southern shores. The environment is relatively well vegetated, dominated by perennial tussock and hummock grasses, and shrubs and small trees and areas of extensive chenopod shrublands. After rain ephemeral vegetation rapidly emerges, reproduces and senesces.

Pastoral leases operate in the northeast of the region, but in the south a number of long established pastoral properties have been destocked and assigned protected reserve status with the view for these to revert to natural ecosystems. About 70% of the AW region is natural wilderness that has never been grazed by domestic stock.

Further detailed descriptions of the AW study region in regard to climate (Appendix A and B), land systems and vegetation are provided in the scientific papers that form chapters 3 and 4 of this thesis.

### 1.3.1 *Currently available quantitative data*

Recorded objective and quantitative monitoring information is scarce for the region. Remotely sensed soil surficial mapping has been conducted across Australia, but very few field samples were available from the AW region (Viscarra Rossel et al., 2011). Monitoring points exist on the pastoral properties in the northeast of the AW region, but site-based monitoring data from this region are not available.

The best environmental information to date about the region is embodied in the national classification of ecosystems, the Interim Biogeographic Regionalisation for Australia (IBRA), which broadly stratifies the landscape into zones on the basis of climate, geology, landform soils and associated vegetation (Thackway and Cresswell, 1995, 1997). Data for this were collected during the integrated land system survey, which informed the CSIRO Land Use Series (Christian and Stewart, 1953) and was later developed, by Laut et al. (1977), for environments of South Australia. Environmental units are defined by repeated landscape patterns deduced from broad scale imagery, such as aerial photography or multispectral satellite imagery. Field-survey information and broad scale biophysical data are combined with expert knowledge to describe the mapping units. IBRA stratifications are periodically updated when new information becomes available.

The IBRA divides arid Australia into some 39 regions. Four of these regions dominate the AW study area. Division into sub-regions, and in South Australia into IBRA associations, provides greater detail. Vegetation in the IBRA zones is characterised by the perennial species: trees, shrubs, and tussock and hummock grasses.

Vegetation surveys in South Australia provide detailed information on vegetation communities within the IBRA delineations. Several inventory-type surveys were carried

out between 1984 and 2007 in the AW region. These surveys focussed on the species likely to persist after prolonged dry periods and do not include ephemeral plant growth (Heard and Channon, 1997; Kenny, 2008; Kenny and Thompson, 2008; NVIS, 2012).

The IBRA stratifications and vegetation surveys provide considerable vegetation and landform information, but are a static representation of the landscape; they do not provide information on actual vegetation growth (of perennial and ephemeral species combined) which fluctuates in response to climatic conditions.

#### **1.4 Field-based monitoring of land condition**

Arid zone land condition monitoring is traditionally performed through field data collection, which is very time consuming and costly. Therefore long time periods may elapse between site visits and it is difficult to obtain statistically meaningful information, maintain consistency, and deal with the inevitable observer differences affecting the data (Friedel and Shaw, 1987a; Friedel and Shaw, 1987b; Trevithick et al., 2012).

In the Australian arid zone field conditions can vary markedly from year to year. Vegetation response is driven by unpredictable rainfall events, and stochastic fire events are followed by slow recovery of perennial plants. Point-based vegetation data, even when collected in the same month in successive years, may reflect the effects of preceding weather conditions, rather than management effects. Data collected on specific dates at discrete field locations need to be interpreted in the context of the wider temporal and spatial landscape dynamics for monitoring to be meaningful. Based on a relatively small amount of field data and few site revisits, it is difficult to determine whether changes in the landscape indicate a change in land condition or whether they are part of normal long-term dynamics (Bastin et al., 2012; Bastin et al., 1993).

The wider-context long-term dynamics cannot be understood or described using field-based data alone. This thesis sets out to show that remote sensing can provide this context.

#### **1.5 Remote sensing for monitoring land condition**

Remote sensing has much to offer for environmental monitoring. In particular satellite-based imaging delivers spatially comprehensive and frequently repeated coverage,

acquired over wide regions of interest, and archived over long periods of time. The value of remote sensing for environmental monitoring is increasingly recognized, especially that using high temporal frequency imagery. It has the potential to show trends and changes in the extent and condition of landscape features and can deliver dynamic land cover information, which in turn may inform natural resource management (Lymburner et al., 2011; Thackway et al., 2013). The digital format of the reflectance data, acquired by the sensors over distinct wavebands, lends itself to a variety of analyses that can reveal environmental information in a consistent and repeatable manner. While field sample data can give detailed information for a small region, remote sensing covers broad extents. In addition it can reveal the extent to which field point data may be extrapolated. Remote sensing is especially useful for dealing with landscape heterogeneity and therefore eminently suitable for use over the study region.

A plethora of satellite image data are available in various spatial, spectral, temporal and radiometric resolutions, but to use these data for environmental monitoring, which necessitates frequent assessments, it is important that they are cost effective and readily available. Selection of appropriate imagery requires consideration of the spatial, temporal and spectral expression of the environmental phenomena to be monitored, in relation to the image characteristics.

#### 1.5.1 *Long time series to investigate vegetation dynamics*

Investigating historical spatial and temporal patterns in vegetation growth over long periods and wide regions is possible with archival high-temporal frequency low-spatial resolution satellite imagery (Appendix C). This imagery is acquired daily by sensors on board polar-orbiting satellites. It was originally intended for meteorological purposes, but is made freely available for environmental analyses, for which it is widely used (Cracknell, 2001). The data are generally delivered in composited form, for example twice monthly maximum pixel value (MVC) composites. The compositing minimises atmospheric effects and cloud contamination (Cihlar, 2000), while relatively high temporal frequency is maintained.

The longest archive of low spatial resolution data is from the Advanced Very High Resolution Radiometers (AVHRR) on board the National Oceanic and Atmospheric Administration (NOAA) series of satellites. These data have been available since 1981.

Some twenty years later acquisition of a similar class of imagery commenced at the launch of the Earth Observation Systems (EOS) satellites Terra (1999) and Aqua (2002). These satellites carry Moderate Resolution Imaging Spectroradiometers (MODIS). AVHRR and MODIS radiometers, while collecting similar class of data, can provide quite different information, because of difference in archival depth and difference in spectral properties (Appendix C).

AVHRR imagery, although low spatial resolution (1.1 km), is very suited to monitoring actively growing vegetation because it is collected in two suitable optical bandwidths, band 4, red ( $0.58\mu - 0.68\mu$ ) and band 5, near infra-red (NIR) ( $0.73\mu - 1.00\mu$ ). These two spectral bands enable calculation of the normalized difference vegetation index (NDVI) which uses the formula  $(\text{NIR} - \text{red})/(\text{NIR} + \text{red})$ , a well-known index to represent actively growing vegetation (Rouse et al., 1974; Tucker, 1979).

AVHRR NDVI imagery has been used in vegetation studies ever since it became available (Gatlin et al., 1984; Norwine and Greigor, 1983). It has been used in many environmental studies linking vegetation growth to rain records (Martiny et al., 2006; Nicholson et al., 1990), and as substitute for rain records where rain recording stations are sparsely distributed (Oesterheld et al., 1998). AVHRR NDVI gives a good representation of active vegetation growth in situations of widely different growth patterns. In Australia AVHRR NDVI data have been used for assessing pasture growth in regions of highly seasonal grazing systems (Hill et al., 2004), but also in arid non-seasonal grazing situations where forage production was assessed related to rain or drought conditions over wide regions (Foran and Pearce, 1990).

AVHRR data are, because of their extensive collection period, ideal for long-term vegetation analysis. The great archival depth has enabled study of long term vegetation dynamics worldwide. For example over the Soudano-Sahel, dynamics were linked to change in rainfall and land use (Bégué et al., 2011), spatial heterogeneity and temporal dynamics were revealed for a large region in Brazil through extraction of monthly and annual vegetation growth patterns (Barbosa et al., 2006) and global assessments of seasonal cycles of vegetation response were made using AVHRR NDVI (McCloy and Lucht, 2004).

Understanding long-term vegetation growth patterns is essential for interpretation of monitoring data in highly variable landscapes. These patterns have not been defined for the Australian arid zone. The research described in this thesis sought to address this lack.

### 1.5.2 *Long time series to monitor fractional vegetation cover*

The NDVI has been by far the most widely used index with AVHRR data, but with MODIS data, because of the increased number of spectral bands and greater spectral resolution (Appendix C), a wider range of indices and approaches are being used. The MODIS sensors collect data useful for vegetation monitoring at 250 m ground resolution in bands 1 (0.62  $\mu$  - 0.67  $\mu$ ) and 2 (0.84  $\mu$  - 0.88  $\mu$ ), and at 500m within the lower range of 0.46  $\mu$  to 0.57  $\mu$  (bands 3 and 4), and the higher range of 1.2  $\mu$  to 2.2  $\mu$  (bands 5,6 and7).

MODIS imagery is delivered in the form of several land surface products, which deal with the effects of the wide view angle of the MODIS sensors (Morisette et al., 2003). The bidirectional reflectance distribution function (BRDF) (MOD43B1) and nadir BRDF-adjusted reflectance (NBAR) (MOD43B4) products were developed, where an apparent reflectance is created that is unaffected by the location of the sensor relative to the pixel at the time of acquisition (Schaaf et al., 2002). These products have been validated (Liang et al., 2002; Morisette et al., 2003) and form the basis for many further derived products and investigations.

MODIS-based investigations can detect green vegetation, using the NDVI and Enhanced Vegetation Index (EVI) (Huete et al., 2002), but in addition its spectral bands in the short wave infra-red (SWIR) region enable detection of various other landscape components such as soil, and plant litter (Asner and Lobell, 2000; Nagler et al., 2003). This adds valuable environmental information. For example, SWIR indices employed in time series have been used to monitor drying of fuel loads in relation to fire management (Cao et al., 2010). The MODIS combination of spectral, spatial and temporal resolution offers much scope for large scale long term land condition analysis.

The low spatial resolution of the satellite data under consideration combined with high landscape heterogeneity means that mixed pixels are inevitable (Cracknell, 1998). Mixed pixels combine the reflectance of a number of landscape components. Fractional



cover analyses have been developed, in various forms, to detect the per-pixel contribution made by the components of interest, and hence their proportion in the landscape. The proportional change of individual components is of interest for environmental monitoring, where these components are used as land condition indicators. Fractional cover analysis, when applied to high temporal resolution satellite data therefore shows great potential for rapid monitoring of land condition.

AVHRR NDVI data can be used to perform fractional cover analysis, but this needs auxiliary data. In a southern African study for example, AVHRR NDVI data in conjunction with information on seasonality, rain records, and phenology, were used to deliver three fractions: permanently bare soil, woody vegetation, and bare soil combined with herbaceous vegetation, (Scanlon et al., 2002). In the Australian arid zone such auxiliary data are not available; rain is aseasonal, rain recording stations are scarce (BOM, 2012), and phenology patterns tend to be erratic and difficult to predict (Friedel et al., 1994). AVHRR NDVI, although attractive because of its great archival depth, is therefore is not suited for fractional cover analysis over the Australian arid landscape. MODIS on the other hand, although of shorter archival length, offers through its wider spectral range greater scope for such sub-pixel analyses.

Several methods to estimate fractional cover have been developed, initially mostly for single date imagery in the form of spectral mixture analysis (SMA) (Huete, 1986; Settle and Drake, 1993; Smith et al., 1990). Multiple endmember spectral mixture analysis (MESMA) was developed to give greater discrimination than SMA by allowing endmembers to vary on a per-pixel basis (Roberts et al., 1997). More recently relative spectral mixture analysis (RSMA) was developed to separate green vegetation (GV), nonphotosynthetic vegetation/litter (NPV) and snow in high-temporal frequency data, relative to a reference time (Okin, 2007). RSMA over the agricultural zone of South Australia extracted the per-pixel proportions of photosynthesising vegetation (PV), non-photosynthesising vegetation (NPV) and bare soil (Okin et al., 2013).

In Australia a very promising high-temporal frequency fractional cover product has been developed for the tropical northern savanna regions (Guerschman et al., 2009). This uses MODIS NBAR (MOD43B4) imagery, and creates from this a 16-day, 500 m ground resolution product, separating the fractions PV, NPV and bare soil in three

dimensional data space. It is proposed that this product, which is continually produced, be used for Australia-wide fractional cover monitoring.

Bare soil and total vegetation cover fractions are used as key indicators of land condition in this thesis. Frequent monitoring of these fractions in the AW region would be a valuable advance for environmental management of this region. This suggests that the Australian MODIS fractional cover product offers a potential monitoring option. However validation of the product over the region of interest is needed prior to use (Thackway et al., 2013).

### 1.5.3 *Validating low spatial resolution satellite products*

Validation can be defined as “the process of assessing, by independent means, the quality of the data products derived from the system outputs” (Justice et al., 2000; Morisette et al., 2003). Product validation is critical prior to usage (Cihlar et al., 1997; Justice and Townshend, 1994; Morisette et al., 2003).

Validating low spatial resolution satellite data by field measurement is problematic because the area covered by field measurements is extremely small, relative to the size of the low spatial resolution satellite image pixels. Collecting enough field sample data to support a direct comparison of field measurements with low resolution satellite pixels is not possible (Morisette et al., 2003), and point data cannot be directly compared to low resolution pixels such as 500 m MODIS pixels. Some form of extrapolation is therefore often used prior to comparison (Liang et al., 2002). A commonly used method is to upscale field point data to moderate resolution satellite data, such as Landsat TM, which is then used for evaluation (Barnsley, 2000).

Where field data collection is not possible, or inadequate, this intermediary step cannot be created. In such instances evaluation has been approached through direct use of high resolution imagery. Morisette et al. (2003) used high resolution IKONOS data to evaluate percent bare ground, herbaceous, and tree cover in the MODIS Vegetation Continuous Fields product. He stressed that consideration needs to be given to the spatial structure and spectral values of the high resolution satellite data, because validation can only be accomplished if the component under investigation can be clearly detected in the high resolution imagery. Where the component of interest can be

correctly identified, and its extent estimated in the high spatial resolution imagery, this information can be used as field data substitute.

Research in this field has been very limited. Some form of classification is generally applied to the high-spatial resolution images and, because no field check is possible, it is critical that this classification is accurate, although errors in classification can be difficult to avoid (Barnsley 2000). An example of successful evaluation by visual detection of image features used tree crowns in high-spatial resolution Quickbird imagery and a grid overlay to evaluate a 500 m MODIS tree cover product over the circumpolar region. (Montesano et al., 2009). Although there is now considerable coverage of high-spatial resolution satellite imagery over Australian arid regions, it has not been used to evaluate low-spatial resolution land cover products. Indeed over the AW study region no form of evaluation, field-based or satellite-based, of such low-spatial resolution imagery has been attempted. This thesis presents the first attempt at such evaluation.

## **1.6 Aims and significance of the research**

The overall aim of this research is to address the needs of the AWNRM Board for improved regional land condition assessment and monitoring, and advance satellite remote sensing for this purpose. To achieve this, the research has several objectives.

- a. To better understand the patterns of long-term spatio-temporal variability in vegetation growth over the Australian arid zone, this research aims to analyse high-temporal frequency long-term satellite imagery to detect the key factors that govern long-term variability in vegetation response. It further aims to classify and map zones of similar response and variability.
- b. To show the significance and implications for regional management of the key factors that govern long-term patterns of vegetation response, the study seeks to interpret the factors and newly mapped zones at regional level in the AW study region.
- c. To investigate the potential of using available high-temporal frequency low-spatial resolution fractional cover imagery for rapid land condition monitoring in the region, the research seeks to evaluate such product for regional use.

d. To address the difficulties of field validation in the remote study region, the research aims to develop the use of high-spatial resolution satellite data as tool for evaluation of low-spatial resolution fractional cover products.

This research is particularly significant in that it progresses the use of remote sensing for the non-pastoral remote arid environments. While the pastoral arid regions, because of their commercial interest, have benefitted from a considerable amount of research into the use of remote sensing for monitoring land condition, there has been virtually no research to monitor the natural regions. Many of the parameters used in pastoral situations are irrelevant in the natural zone, where herbivores graze freely and are not confined within fence lines or near watering points. This study therefore focused on monitoring methods specifically suited to wilderness environments.

An important aspect of the research is that it deals with the temporal dynamics of the Australian arid zone, which often confound interpretation of local monitoring data. Gaining understanding of the long-term vegetation dynamics which form the background signal against which change can be assessed is an important step towards better monitoring at regional scale. Managers need to be aware of the significance of the broad long-term patterns, and how these manifest in the regional landscape, in order to interpret regional change against this background.

Adopting a high-temporal frequency fractional cover monitoring product suitable for continuous regional monitoring of vegetation cover is the next anticipated step. Application of such product is dependent on positive validation outcomes. Because evaluation through field data collection is not feasible in vast, remote and highly variable regions, the development of a satellite-based validation tool is an important advancement.

## **1.7 Thesis structure**

This thesis is divided into 5 chapters. Chapter 1 outlines the general background and focusses on remote sensing, with reference to some of the relevant literature. Chapters 2 to 4 cover the analysis, which has been presented in the form of published or submitted scientific papers. These are stand-alone chapters and therefore of necessity contain some repeated information. Chapter 5 delivers the discussion and conclusion. A brief summary of the content of each chapter is presented below.

## **Chapter 1**

This chapter introduces the research, and discusses the general question of monitoring land condition in the arid zone. It describes the landscape in relation to its conservation values and indigenous-Australian values. The threats to land condition are identified and the choice of land condition indicator is discussed. The chapter explains the motivation for the study and delineates and broadly describes the two geographic regions that are focus of the study. The options of field-based monitoring versus remotely sensed monitoring are explored and the benefits of remotely sensed monitoring are highlighted. Some satellite imagery and their usage for arid zone monitoring are discussed. Special focus is placed on long term fractional cover monitoring, and the use of high spatial resolution satellite imagery for evaluation of fractional cover products. The aim and objectives of the study, and the study significance are presented. The chapter finally outlines the thesis structure and gives a brief summary of the content of each chapter.

## **Chapter 2**

Lawley, E.F., Lewis, M.M., & Ostendorf, B. (2011). Environmental zonation across the Australian arid region based on long-term vegetation dynamics. *Journal of Arid Environments*, 75, 576-585

This chapter presents an Australia-wide study of arid zone vegetation dynamics. The aim of this study was to analyse long time series of high temporal frequency satellite data to discover the temporal and spatial sequences and patterns of vegetation response, and to detect the factors that govern these long-term patterns and cycles. Understanding the key factors is crucial to interpretation of regional scale vegetation response in the highly variable arid regions. This is important so atypical change may be distinguished from expected variations. This study created a zonation based on the key factors that underlie variability in vegetation response and compared this dynamic zonation with existing biogeographic stratifications, which are a static representation of the landscape, and in themselves cannot show variability over time.

### **Chapter 3**

Lawley, E.F., Lewis, M.M., & Ostendorf, B. (2014). Using spatio-temporal vegetation imagery for arid lands monitoring. *Ecological Indicators* (Submitted)

This chapter investigates how the Australia-wide patterns of vegetation dynamics manifest in the AW study region. It aims to show how the vegetation response patterns detected in the previous study can aid on-ground management. It set out to do this by characterising the previously determined classes in relation to regional vegetation, soil and landform, and rainfall information, examining these at the extent of the AW region. The zones resulting from the previous investigation are here compared at regional scale, and spatio-temporal variability across the AW region is explored. The study investigates trends over time, and compares the AW regional zones with existing environmental stratifications. It shows how Australia-wide spatio-temporal patterns are relevant for regional management.

### **Chapter 4**

Lawley, E.F., Lewis, M.M., & Ostendorf, B. (2014). Evaluating MODIS soil fractional cover for arid regions, using albedo from high-spatial resolution satellite imagery. *International Journal of Remote Sensing*, 35, 2028-2046

This study set out to evaluate a MODIS fractional cover product, over the AW study region. This evaluation is of significance because this MODIS fractional cover product, developed by Guerschman et al. (2009), is intended for Australia-wide use. To test how well the vegetation cover and bare soil proportions in the MODIS product represent these proportions in the AW landscape, twenty-two 850 km<sup>2</sup> sites were assessed covering 600 km from north to south and representing a wide variety of landforms. To carry out this evaluation it was necessary to create field data surrogates because suitable field data representing the AW region were not available. A novel method was employed to determine classification thresholds in high-spatial resolution ALOS Panchromatic Remote-sensing Instrument Stereo Mapping (PRISM) data. The classified data were upscaled to MODIS spatial resolution and used to evaluate the MODIS fractional cover product.

## **Chapter 5**

This chapter brings together the findings from chapters 2 to 4 and highlights the advances made by this research to improve land condition monitoring in the AW region. It discusses the significance of the findings for arid zone monitoring by remote sensing, and provides recommendations for ongoing research.





# CHAPTER 2

ENVIRONMENTAL ZONATION ACROSS THE  
AUSTRALIAN ARID REGION BASED ON LONG-TERM  
VEGETATION DYNAMICS



## STATEMENT OF AUTHORSHIP

### Authorship of chapter 2

<b>Title of Paper</b>	Environmental zonation across the Australian arid region based on long-term vegetation dynamics		
<b>Publication Status</b>	<input checked="" type="radio"/> Published, <input type="radio"/> Accepted for Publication, <input type="radio"/> Submitted for Publication, <input type="radio"/> Publication style		
<b>Publication Details</b>	Lawley, E.F., Lewis, M.M., & Ostendorf, B. (2011). Environmental zonation across the Australian arid region based on long-term vegetation dynamics. <i>Journal of Arid Environments</i> , 75(6), 576-585		
<b>Author Contributions</b>			
By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.			
<b>Name of Principal Author (Candidate)</b>	Evertje Frederika Lawley		
<b>Contribution to the Paper</b>	Development, conceptualisation and realisation of the research, wrote manuscript, corresponding author.		
<b>Signature</b>		<b>Date</b>	3/4/2014
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<b>Contribution to the Paper</b>	Supervised development, conceptualisation and realisation of the research and evaluated the manuscript.		
<b>Signature</b>		<b>Date</b>	3/4/2014
<b>Name of Co-Author</b>	Bertram Ostendorf		
<b>Contribution to the Paper</b>	Co-supervised development, conceptualisation and realisation of the research and evaluated the manuscript		
<b>Signature</b>		<b>Date</b>	3-4-14



Lawley, E.F., Lewis, M.M., & Ostendorf, B. (2011). Environmental zonation across the Australian arid region based on long-term vegetation dynamics. *Journal of Arid Environments*, 75, 576-585

### **Abstract**

Zonation of landscapes is generally based on broad scale biophysical data, field surveys, imagery and expert knowledge. Such zonation represents a static view of the environment and does not reflect dynamics and function. Arid environments are however often highly dynamic, and spatial and temporal patterns may be expressed over long periods of time. These dynamics need to be understood for management. Our aim is to understand the dynamics and functional response of vegetation in the Australian arid zone, and use this to inform and potentially improve the currently employed stratification. Principal component analysis of 25 years of satellite imagery identified underlying factors influencing patterns of arid vegetation growth, and regions of similar long-term response. Dominant factors of variation were identified as the spatial distribution of total vegetation growth, seasonality of growth, magnitude of seasonal variability in growth, and regularity of variation in growth. Additional variation resulted from episodic vegetation growth of limited spatial extent and duration. Classes expressing these functional components were compared with the existing biogeographical regions, revealing agreement in some instances, and in other cases adding information previously not available. The study demonstrates a new approach to Australian landscape zonation that has potential for much wider application.

### **2.1 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 Biogeographic Regionalisation 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., 2011).

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 the United States National Oceanographic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA AVHRR) and the Moderate-resolution Imaging Spectroradiometer (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 1980s. Initially based only on few dates within a single year to stratify vegetation using a climatic gradient (Norwine and Gregor, 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.

## **2.2 Methods**

### *2.2.1 Study area*

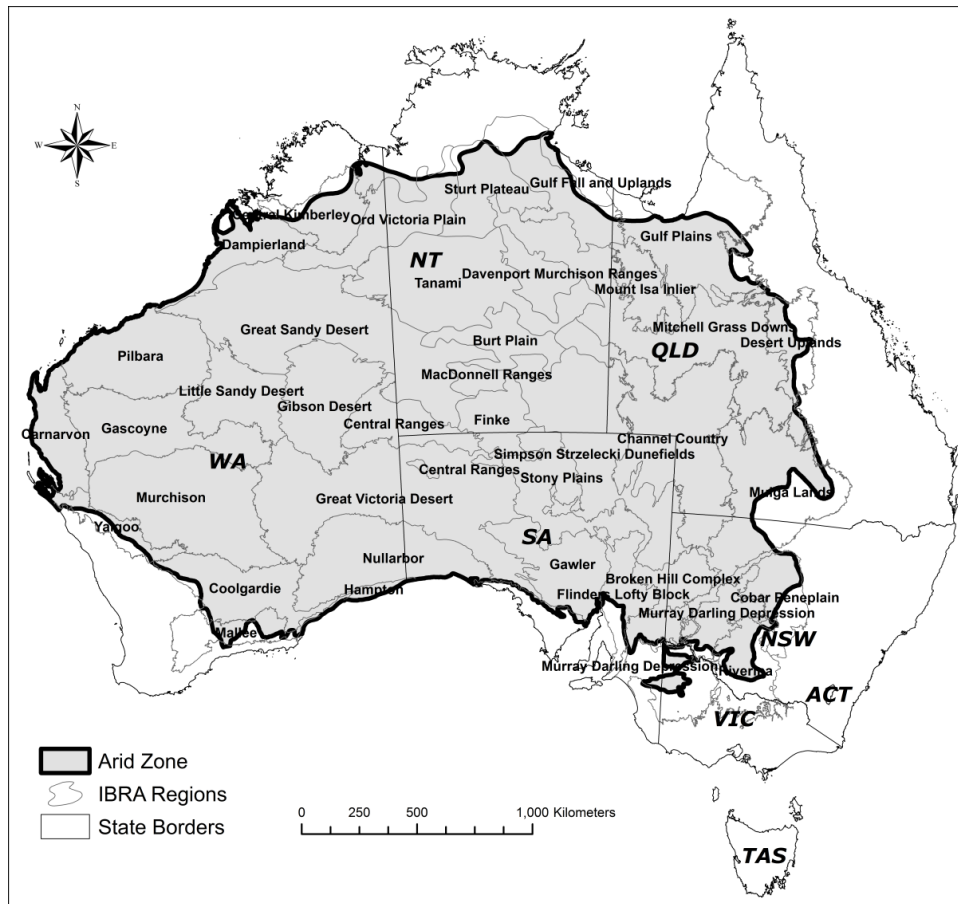
The limits of an arid zone are not rigid and can be defined according to the purpose of an investigation. The global agroclimatic classification for instance focuses on climate constraints on crop growth, and defines as arid the Australian region too dry to support field crops (Hutchinson et al., 1992, 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 dryland 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, 2002) were masked from the study area, resulting in the arid zone outline used for the current study (Fig. 2.1).

The approximately 5,250,000 km<sup>2</sup> 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.





**Fig. 2.1** The study area comprising the Australian arid zone excluding cultivated areas. Biogeographic regions defined by IBRA vs 6.1 are shown.

### 2.2.2 NDVI data

This study used a series of 600 NDVI images which were derived from data collected daily from 1982 to 2006, by the AVHRR aboard the 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 -10,000 to 10,000, water pixels had been assigned the value of -10,000, 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:  $NDVI = \text{float}(\text{raw}/10,000)$  (GLCF 2008). The data were obtained as continental files, Albers projection, and were for this study reprojected to South Australian Lambert 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.

### 2.2.3 *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.

#### 2.2.4 *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 principal components 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.

### 2.3 **Results**

#### 2.3.1 *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 2.1), 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. 2.2).

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. 2.1). 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.

**Table 2.1 Percentage of variance explained by some of the 600 principal components.**

	<b>PC 1</b>	<b>PC 2</b>	<b>PC 3</b>	<b>PC 4</b>	<b>PC 5</b>	<b>PC 6</b>	<b>PC 7</b>	<b>PC 14</b>
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

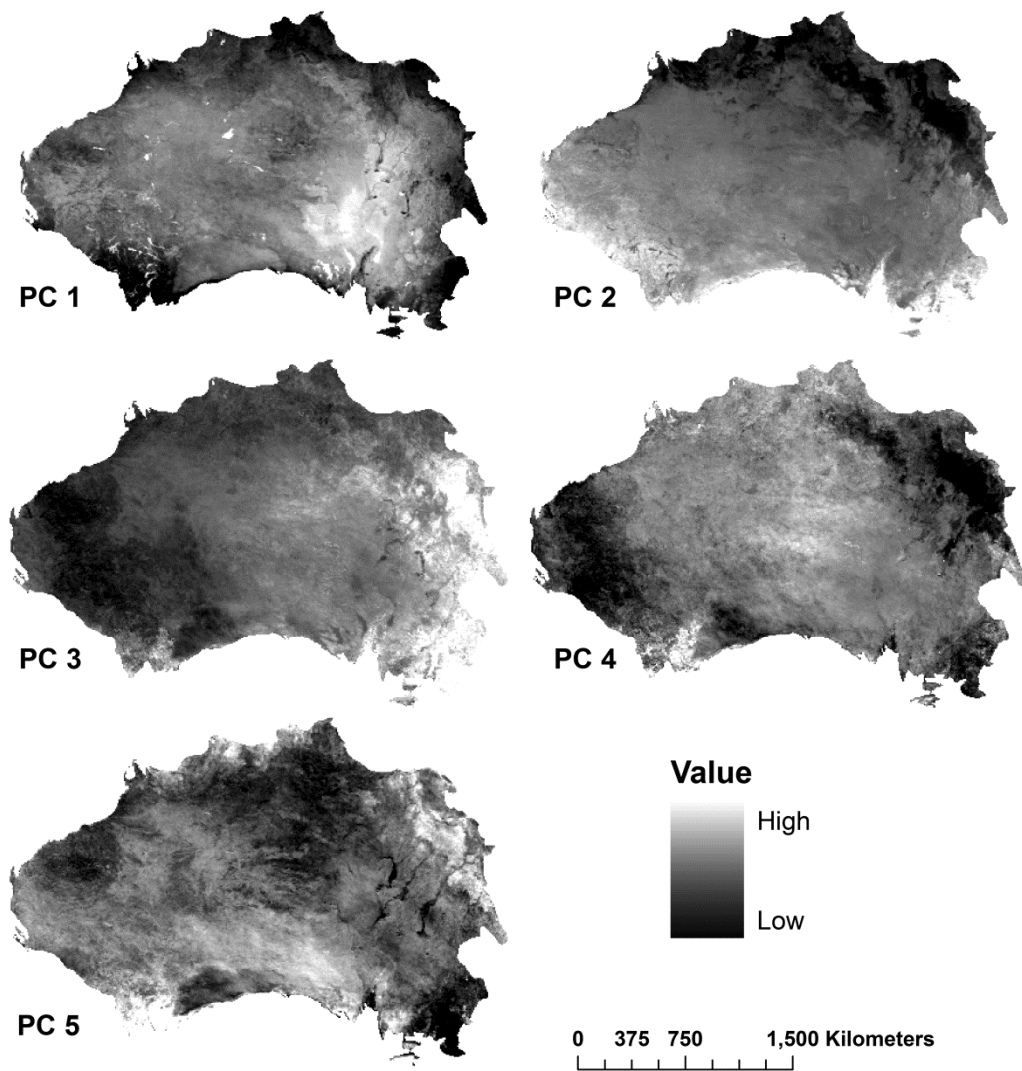


Fig. 2.2 Principal components 1 to 5.

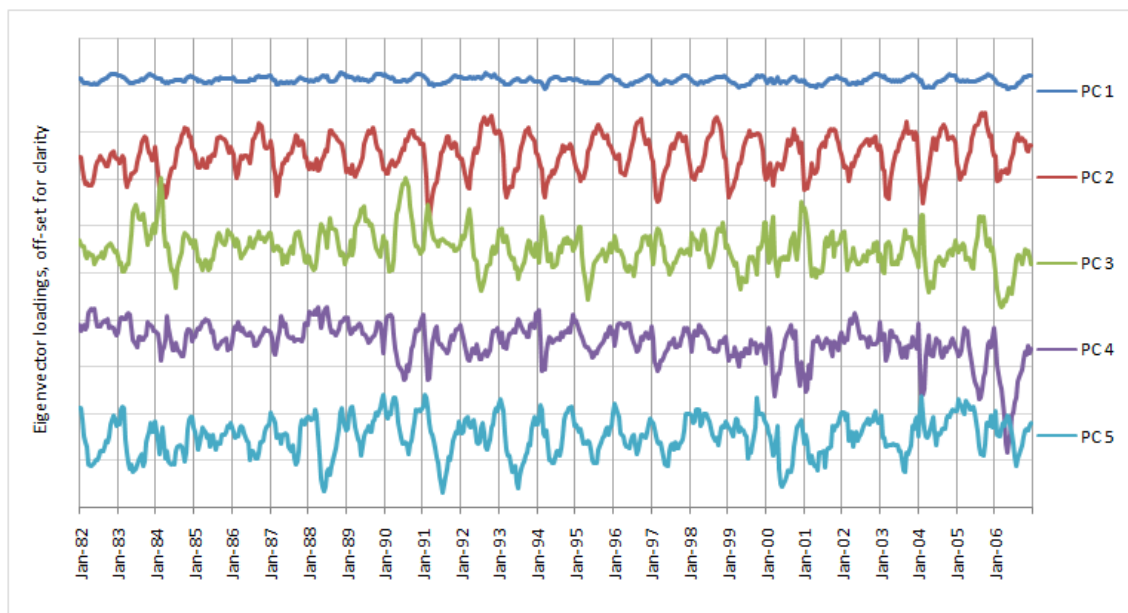
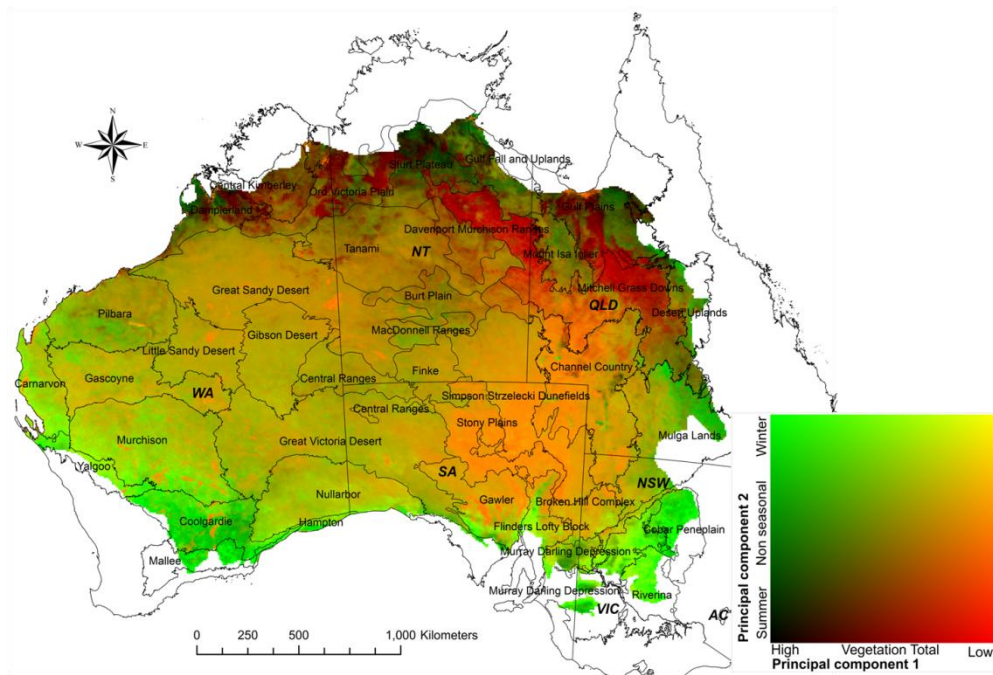


Fig. 2.3 Plot of eigenvector band loadings of the first 5 principal components.

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. 2.3).

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. 2.3). 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. 2.2). 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. 2.4). 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. 2.4).



**Fig. 2.4 Colour composite of PC1 (red) and PC2 (green) with IBRA regions overlaid to indicate approximate locations**

PC 3 explained 2.97% of the remaining variance, showing an irregular east-summer versus west-winter growth contrast (PC 3 in Fig. 2.2) apparently perturbed by erratically occurring climatic events as shown in the eigenvector plot (Fig. 2.3). 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. 2.2). An exceptionally high loading in July 1990 followed widespread flooding in eastern Australia (Fig. 2.3). 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 (Sahukar et al., 2003). 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. 2.3). 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. 2.2).

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. 2.3). The PC image shows clear contrast between various regions (PC 5 in Fig. 2.2), 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.

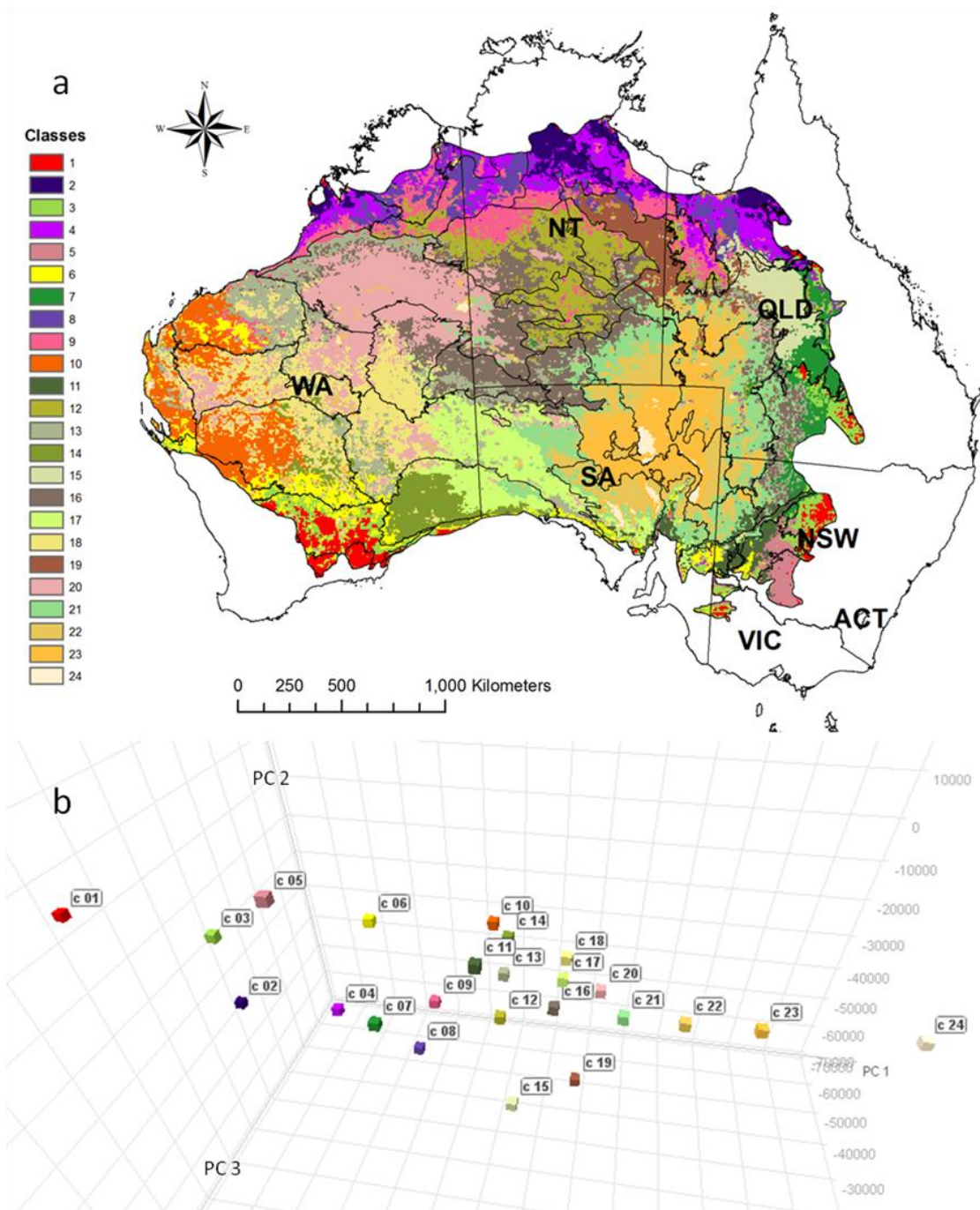
The first 14 components captured over 85% of the variation within the total data, as revealed in mean eigenvalues (Table 2.1). Although components from PC 7 to PC 14 explained a very small percentage of the remaining variation, from 1% incrementally down to 0.5 %, they are likely to hold information 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.

### 2.3.2 *Classification of vegetation temporal response*

The geographic distribution of classes resulting from the unsupervised classification is shown in Fig. 2.5 a, 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. 2.5 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).





**Fig. 2.5 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.**

Mean NDVI temporal traces for the dominant classes indicate how NDVI varies over 25 years (Fig. 2.6). 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. 2.1). 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. 2.6). 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 (Sahukar et al., 2003).

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. 2.6). 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. 2.5), 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. 2.5 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.

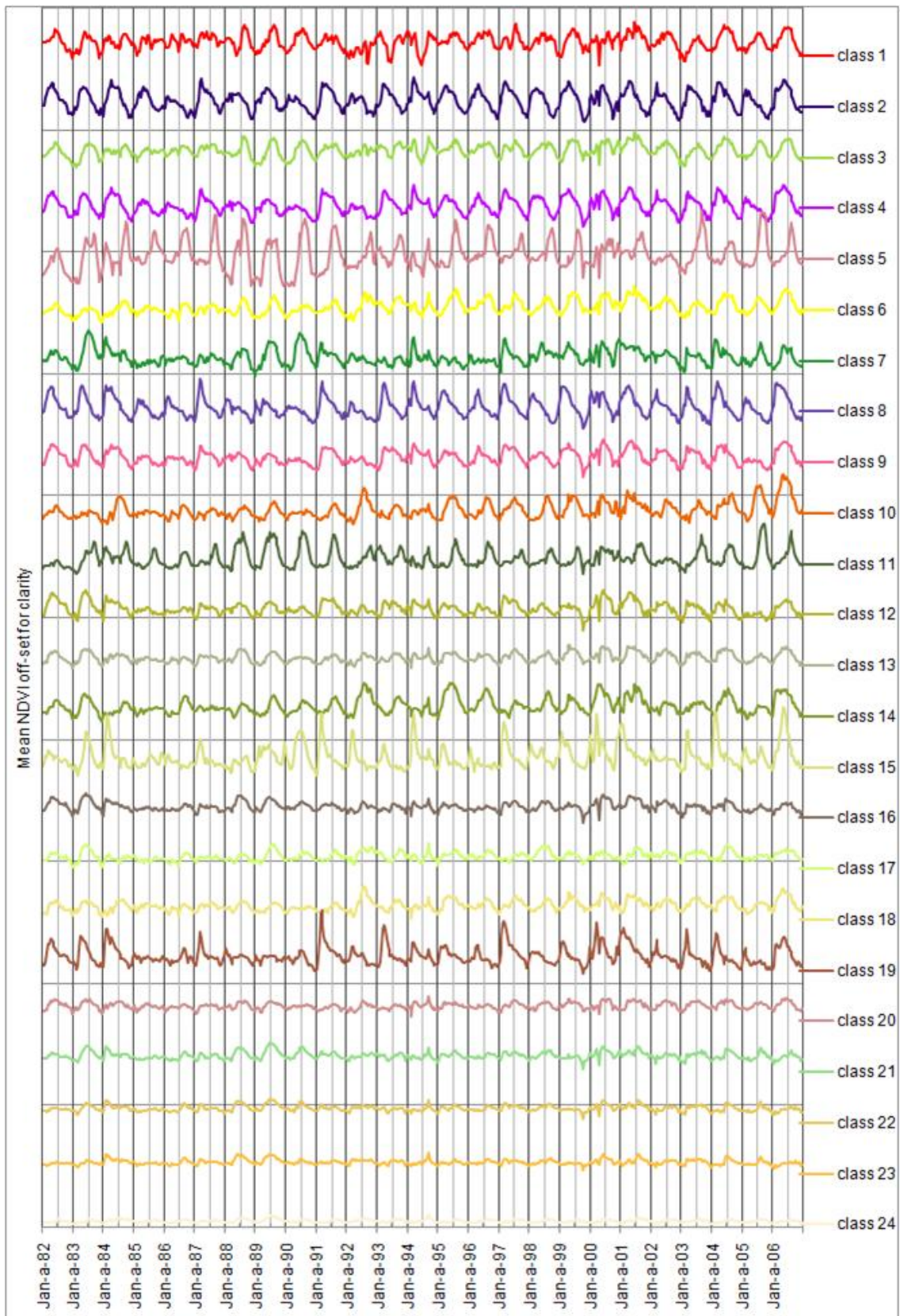


Fig. 2.6 The variation in NDVI response over 25 years for each class.

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. 2.6).

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 1 and 3, 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. 2.6), are characterized by low vegetation response, and appear to be part of the desert continuum reaching north-east to 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.

### 2.3.3 *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 (Table 2.2). 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.

Table 2.2 IBRA regions in the arid zone showing percentage of IBRA occupied by each class.

IBRA region	class																								Area (sq km)	
	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											27,328	
Coolgardie	35		35			23							1	2				1		1		1			121,856	
Cobar Peneplain	37		45		11		6				1														40,768	
Desert Uplands	3	1	19	9			52					6	2		4	4									35,840	
Sturt Plateau		49		28				4	17			2													97,472	
Gulf Fall and Up		19		49				2	28			2													90,176	
Gulf Plains	1	16		37				23	5			2			10	1			3			1			133,504	
Dampierland	1	17		35				19	22			1	3							1		1	1	1	77,568	
Riverina	1		2		81	2					13														35,264	
Central Kimberle				17				31	40			11													59,968	
Mount Isa Inlier				17				2	41			20	5		1	6				5	1	1			68,800	
Ord Victoria Pla		1		17				43	26			12													123,136	
Yalgoo	1		16			40				39	1								1		1		1		33,408	
Murchison			1			13				34			5	10				31		5		1	1		281,536	
Carnarvon						9				50			11					18		6		2	2	2	82,880	
Pilbara						10			6	29			38			1		13		2			1		180,352	
Murray Darling D	5		17	1	18	15	2				34	2					4					3			105,024	
Darling Riverine			1			2	4				52	1	1			10	2					24	1	1	2	16,256
Davenport Murchi								1	13			73				10				2					60,096	
Tanami								18			42	1				31					7	1			269,760	
Burt Plain								7			66					25						1			75,712	
MacDonnell Range							6		4			53	4			33						1			39,936	
Hampton	14		11			20				1				54											10,944	
Nullarbor			1			5							2	47			34	4			2	5	1		195,328	
Finke												2	5			71					3	18	1		74,112	
Central Ranges												21				66	7	1			4	1			102,016	
Great Victoria D						3						15	2		3	38	18				9	9	3		418,432	
Mitchell Grass D				1			11	3	2			3	1		28	4				29	1	5	10	3	343,808	
Little Sandy Des													14			4		31		49		1	1	1	112,320	
Gascoyne						1				16			7	1			49		23		3				183,040	
Gibson Desert													3			17	4	36		38	1				158,400	
Great Sandy Dese									2			2	12			23		1		56	2	1	1	1	406,400	
Mulga Lands	4		15				23				3	1	14			22					15	2			174,976	
Flinders Lofty B			1		3	5					21		2			1	6				29	19	12		53,312	
Gawler			2			4					5		3			14					1	15	39	11	6	123,328
Channel Country							1					2	2			12				2	2	28	27	23	308,032	
Broken Hill Comp						1					14					2	1				45	35	3		56,704	
Simpson Strzelec												1				9					21	36	29	5	274,944	
Stony Plains																1					1	10	24	63	1	133,440
																									Total area	5,186,176

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)

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.

## **2.4 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 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 characterisation.





# CHAPTER 3

USING SPATIO-TEMPORAL VEGETATION IMAGERY  
FOR ARID LANDS MONITORING



## STATEMENT OF AUTHORSHIP

### Authorship of chapter 3

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<b>Name of Principal Author (Candidate)</b>	Evertje Frederika Lawley		
<b>Contribution to the Paper</b>	Development, conceptualisation and realisation of the research, wrote manuscript, corresponding author.		
<b>Signature</b>		<b>Date</b>	3/4/2014
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<b>Contribution to the Paper</b>	Supervised development, conceptualisation and realisation of the research and evaluated manuscript		
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<b>Contribution to the Paper</b>	Co-supervised development, conceptualisation and realisation of the research and evaluated manuscript		
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### **Abstract**

Monitoring of land condition indicators is critical for environmental management, but collecting adequate land condition indicator data in remote arid environments is problematic. These regions are vast and challenging to access which makes data collecting highly time consuming and costly. Interpreting the meaning of change in infrequently collected data is difficult in particular for monitoring highly variable landscapes. This difficulty was dealt with in a study that used historical satellite data to determine the factors that underlie long-term variability in Australian arid zone vegetation growth, which were mapped into spatio-temporal patterns. These patterns, representing long term variability of vegetation growth, may enable managers to distinguish management induced change from natural variability in ecological indicators.

For managers it is important to know what these patterns signify at the scale and extent of their management regions. The current study aims to detect the meaning of these patterns within the South Australian Alinytjara Wilurara (AW) Natural Resources Management (NRM) region. This region is 261,180 km<sup>2</sup> in extent, largely unmodified and comprises a large variety of land types and vegetation communities.

The four main, and some minor, spatio-temporal classes dominant in the AW management region were investigated in detail in regard to their vegetation type, average amount and temporal variability of vegetation growth, timing of growth cycles, and relationship to rainfall. Trends were investigated and comparisons were made with commonly used landscape stratifications. This indicated new ways of interpreting the landscape. Distinctions could be made between low vegetation growth areas, areas with stronger seasonal effects, areas where vegetation growth was high and temporal variability low, and in the case of cyclonic influence, areas where vegetation response was high in some years only. The importance of the findings for monitoring various areas of the AW region was discussed.

This research, based on satellite remote sensing, reveals the vegetation functional response of the landscape, and thereby presents new information for management. Such information can be used to improve interpretation of monitoring data as well as improve monitoring protocols in regard to timing and frequency of ecological monitoring and site selection.

### **3.1 Introduction**

Monitoring change in vegetation cover and interpreting the significance of such change is vital for arid zone environmental management. Arid Australia encompasses both commercially grazed and relatively undisturbed environments. 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 testing 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 provide, because of their large extent, important ecosystem services (de Groot et al., 2002; Fisher et al., 2009). Monitoring change in such systems is therefore important.

The need for monitoring has become more urgent because these regions are 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 maintain itself throughout prolonged periods of heat and drought. It is also fragile; soil crust is easily destroyed, and loss of the slow growing perennial vegetation is difficult to reverse (Eldridge and Ferris, 1999; Friedel et al., 2003).

Monitoring data are used by managers to detect change in environmental indicators, identify degradation, and determine management action. Collecting monitoring data to adequately represent the arid landscape patterns is challenging because these lands are extensive, remote, and difficult to access. As a consequence representative field monitoring data on which to base management decisions are notoriously scarce.

Interpreting the meaning of these sparse indicator data is even more challenging, because of the high spatial and temporal variability of these environments (Ostendorf, 2011). The vast regions include many landforms and vegetation types, and the vegetation response to erratic rainfall and fire, which are typical for these regions, is

expressed over long periods of time. It is very difficult to determine whether change in indicator values has occurred as a result of inadequate management or whether it is part of the natural variability (Bastin et al., 2012; Bastin et al., 1993). Environmental managers need to understand the long-term spatio-temporal patterns of response in their particular land management regions in order to make these distinctions, and to better interpret monitoring data.

Traditionally monitoring data are interpreted in the context of established landscape stratifications. In Australia the Interim Biogeographic Regionalisation for Australia (IBRA) is a national ecosystem classification that stratifies and describes the landscape in terms of climate, geology, soils, topography, vegetation and where available information on flora and fauna (Thackway and Cresswell, 1995). Vegetation descriptions in the bioregions are characterised by the perennial species; trees, shrubs, and tussock and hummock grasses. The IBRA stratifications are thereby static representations of the landscape, with the vegetation component based on structure and composition, and not including the vegetation functional response.

A different approach to stratification was taken by Lawley et al. (2011) who devised a zonation, at the extent of the Australian arid zone, based on variability in long-term vegetation response detected in high temporal frequency satellite images. The key factors that govern greatest variability in 25 years of vegetation growth were used for this stratification and the zonation was thus based on the response from all actively growing ephemeral and perennial vegetation and, where present, activated microphytic crust and lichen. This mapped zones of similar variability in long-term vegetation response across the Australian continent.

The spatio-temporal patterns of that zonation have great potential to enhance understanding of vegetation functional response and to improve interpretation of monitoring data across the Australian continent, but they need to be examined in greater detail and over smaller regions to extract information relevant to on-ground management.

The overall aim of this research is to improve land condition monitoring and management at a scale and extent relevant to regional management authorities. We propose to achieve this by using the Australia-wide factors and classes that were

mapped by Lawley et al. (2011) and determine their significance at regional management level.

The objectives of this paper are to

- a. analyse the spatio-temporal patterns of vegetation growth at regional management extent, and relate these to geographic location, landform, vegetation type and rainfall;
- b. compare the distribution of vegetation classes based on long-term growth patterns with the current IBRA stratifications for the region; and.
- c. determine how this new source of information about landscape-scale vegetation response can improve interpretation of change, whenever this is detected in regional environmental indicator values.

## **3.2 Materials and method**

### *3.2.1 Study region*

The research focusses on the Alinytjara Wilurara Natural Resources Management (AWNRM) region, hereafter referred to as the AW region, a vast wilderness region in the far west of South Australia. This region covers 261,180 km<sup>2</sup>, which is approximately 5.4% of the entire Australian arid zone. 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 but is the station with most comprehensive and quality-checked meteorological records in that region (Fig. 3.1) (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). Recording stations are few and widely dispersed at distances from 120 km to 640 km (Fig. 3.1). 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, altering native vegetation community structure, composition and



regenerative capability (Thackway and Lesslie, 2006). At least 70% of the landscape has remained largely unmodified, and is referred to as wilderness (AWNRM Board, 2011; Klein et al., 2009). The AW region contains seven terrestrial conservation reserves, covering almost 90,000 km<sup>2</sup> (Fig. 3.1). 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 recognized.

Fires are common in this landscape, with average fire size in the Great Victoria Desert estimated at 28 km<sup>2</sup>, and the Central Ranges burning more frequently than surrounding regions (Haydon et al., 2000; Turner et al., 2008).



Fig. 3.1 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.

### 3.2.2 *Data*

This study uses the factors and classes of the Australia-wide zonation, created by Lawley et al. (2011), for analysis at regional scale. This zonation was based on principal component analysis (PCA) of 25 years of twice-monthly maximum value composite (MVC) Advanced Very High Resolution Radiometer (AVHRR) data. These data had been calculated, at 8 km spatial resolution, to the normalised difference vegetation index (NDVI), a well-established index  $(\text{near-infrared} - \text{red}) / (\text{near-infrared} + \text{red})$  to represent all actively growing vegetation in the landscape (Rouse et al., 1974; Tucker, 1979). PCA revealed three main factors that underlie 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 factor (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 factor (3% of further variability) was defined by vegetation growth resulting from erratic rain events, at times linked to coastal cyclone rain events.

Lawley et al. (2011) created twenty-four classes by unsupervised iso-classification of 14 of the PCA factors (85% of variability). These classes represent areas of distinct variability in vegetation growth across the Australian arid zone, which was displayed in NDVI time series graphs for each class. Here we use both the factors and classes from that study in order to interpret their significance in the AW region.

### 3.2.3 *Analysis*

#### **Interpretation of factors governing variability in the AW region**

We display the relative distribution and influence of the main three factors of arid zone variability in a red-green-blue composite image to show how these factors (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 extracted from PCA eigenvector loadings were used to detect the frequency with which annual growth maxima occurred Australia-wide in a particular month over the 25 years of investigation.

### **Analysis of classes of variability in the AW region**

We focus analysis and interpretation on the classes with the greatest geographic extent in the AW region. Geographical distribution, dominant landform, and vegetation types of these classes are described. 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). Land type and soil descriptions were extracted from the South Australian IBRA-associations (Government of South Australia, 2007).

The NDVI data on which the analysis was based consisted of 600 images (25 years, twice monthly) a small number of which were partly affected by sensor artifacts. PCA, in the transformation process, relegated these images to lesser components and thereby excluded them from the classification process (Lawley et al. 2011). However when plotting the temporal NDVI values for each class here, all images are considered. The images with sensor artifacts were retained to not exclude valid information which forms the larger portion of those images, and their dates were noted.

To further characterise each of the classes and thereby detect how long term vegetation growth varies across the AW landscape in regard to timing, magnitude and variability in growth over the course of the year, we calculated and plotted 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 analysed trends in the NDVI time series 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 most comprehensive monthly recordings over the 1982 - 2006 period (Fig. 3.1); rain data from other stations, which exhibited 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.

### **Comparison with IBRA stratifications**

The IBRA divides arid Australia into some 39 regions (Fig. 3.2) (Thackway and Cresswell, 1997). Four of these regions form the main coverage in the study area. Finer scaled fragmentation defines 18 sub-IBRAs that partly or entirely occur within the AW region, and further division shows 40 IBRA-associations, which are a detailed South Australian regionalisation. These IBRA stratifications all form static representations of the landscape as they are defined on the basis of climate, geology, soil and landform, and include information on vegetation structure and composition but do not incorporate temporal vegetation response.

The four main IBRA which occur in the AW region are Central Ranges, Finke, Great Victoria Desert and Nullarbor (Fig. 3.2). Here we assess the homogeneity of these IBRA within the AW study region in relation to the number and distribution of the spatio-temporal vegetation response classes and the extent to which class and IBRA boundaries coincide. Similar comparisons are also made with the sub-IBRAs and with the IBRA-associations within the AW region, interpreting the spatio-temporal vegetation response classes in greater detail.

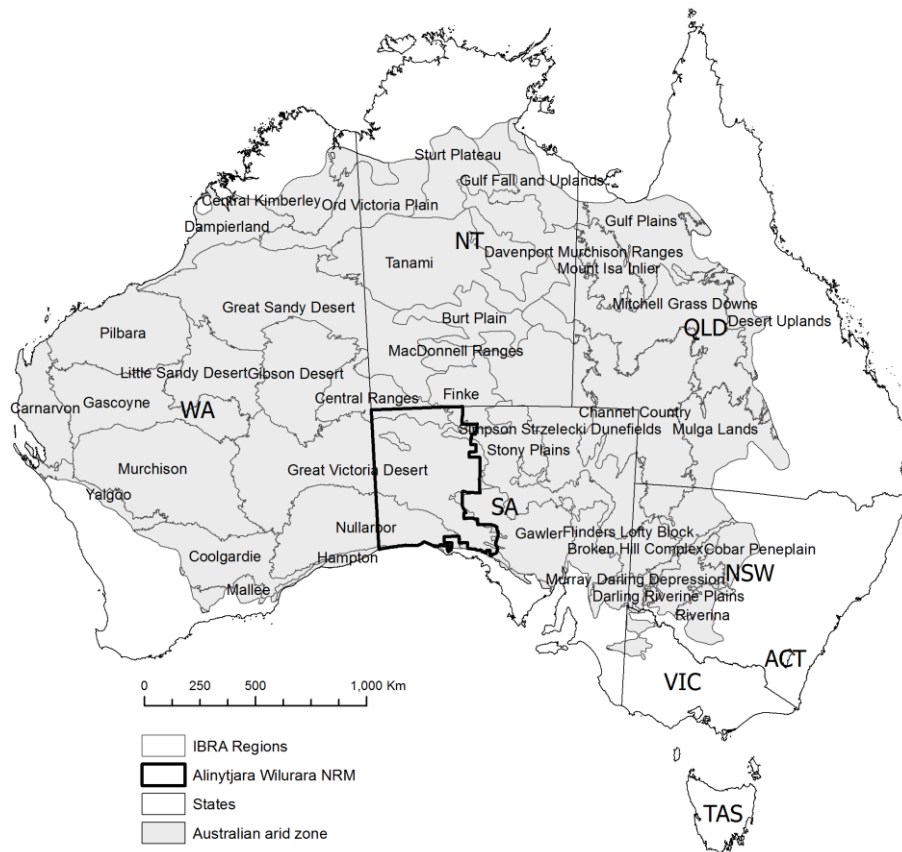


Fig. 3.2 The distribution of IBRA (vs 6.1) regions across non-cultivated arid Australia.

### 3.3 Results and interpretation

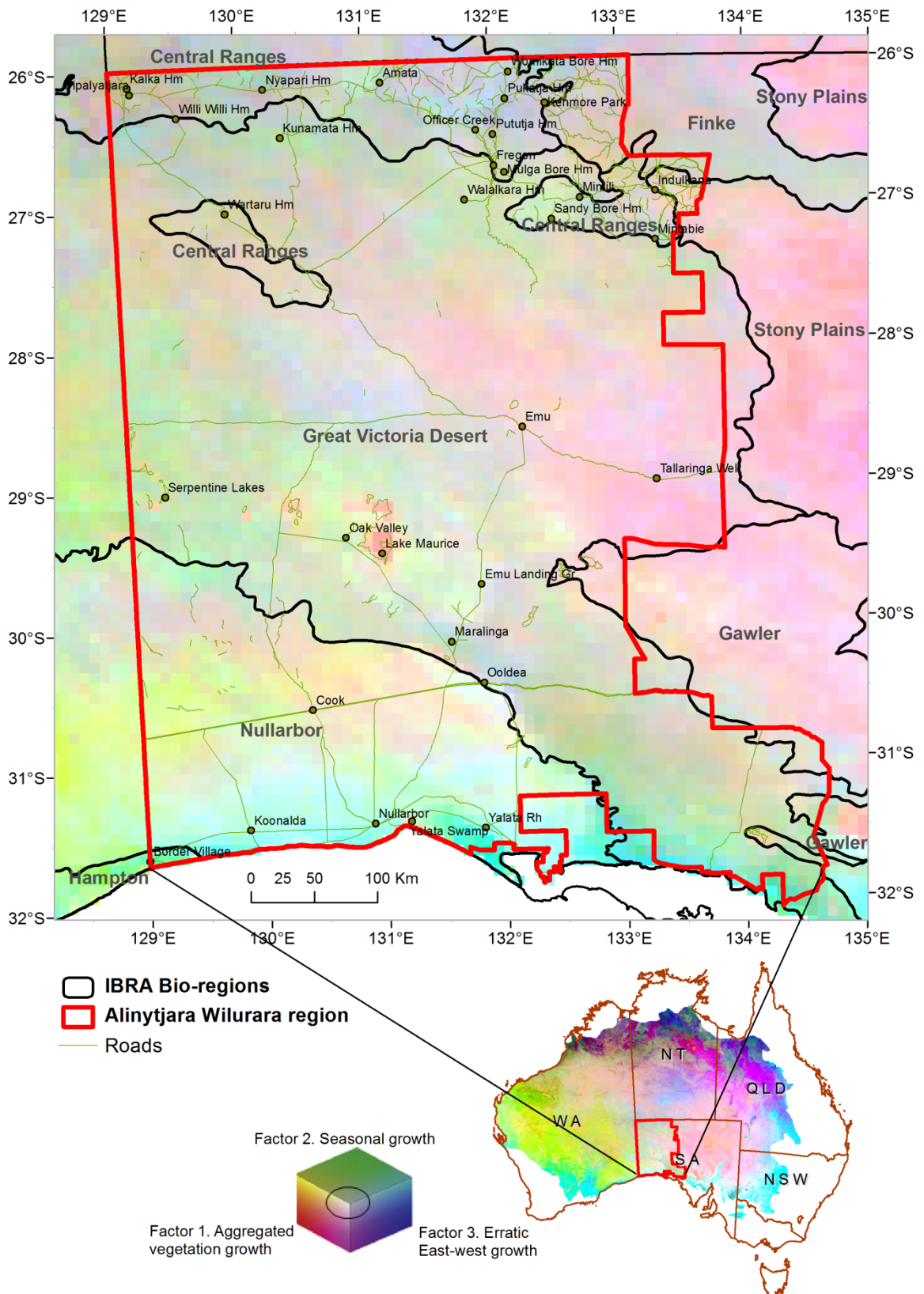
#### 3.3.1 AW regional variability in continental context

The geographic distribution and influence of the three main factors that underlie variability in Australian arid vegetation growth: the spatial distribution of temporally aggregated vegetation response (red), the seasonality (green), and the east-west erratic effects (blue) are shown for the AW region (Fig. 3.3).

Variability in vegetation response in the AW region is low relative to the extreme contrasts evident in northern and eastern arid Australia (Fig. 3.3), but total vegetation response is moderate in the wider arid zone context. However, vegetation clearly showed greater response within, than in the areas under grazing leases to the east of the AW region, such as the Stony Plains, Simpson and Strzelecki dune fields, and Channel country (Fig. 3.2, Fig. 3.3). 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 very similar annual rainfall to Stony Plains, Simpson and Strzelecki dune fields, and Channel country (BOM, 2012). This suggests that although rainfall distribution may play some role (Greenslade et al., 1986), 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. This finding highlights that the AW wilderness regions may be used as comprehensive benchmarks to inform restoration efforts in grazed regions, where benchmarks are limited to stock-proof enclosures and areas remote from water (Bastin, 2005; Bastin et al., 2012).

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).



**Fig. 3.3** Colour composite of the three main factors 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).

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 broad distribution pattern of variability can be seen in wide bands from the south east across the region north westwards (Fig. 3.3).

Temporally aggregated vegetation growth is the main factor of influence 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. 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, even where some lake edge vegetation is included due to the 8 km ground sampling resolution of the NDVI imagery (Fig. 3.3). Absence of vegetation means that the seasonality or erratic response factors cannot be expressed leaving total vegetation as governing factor. Greater total vegetation growth (less red) was shown in the southern Yellabinna, Yumbera area, Mamungari Conservation Park along the Western Australian border, and the area west of Walalkara (Fig. 3.3).

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 3.1). 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. 3.3).

The East - west factor (blue) was interpreted at continental scale as vegetative growth resulting from major cyclone driven rain 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. 3.3).

**Table 3.1 Seasonality across arid Australia shown by the number of years in which the factor 2 eigenvector extremes occurred in this month.**

<i>Seasonality</i>	<i>Factor 2, 7% of 25 years of variability</i>	
	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	-	-

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<sup>1</sup> 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. 3.3).

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. 3.3). Such erratic response can be seen, for example, over the

<sup>1</sup> <http://www.bom.gov.au/cyclone/climatology/wa.shtml>

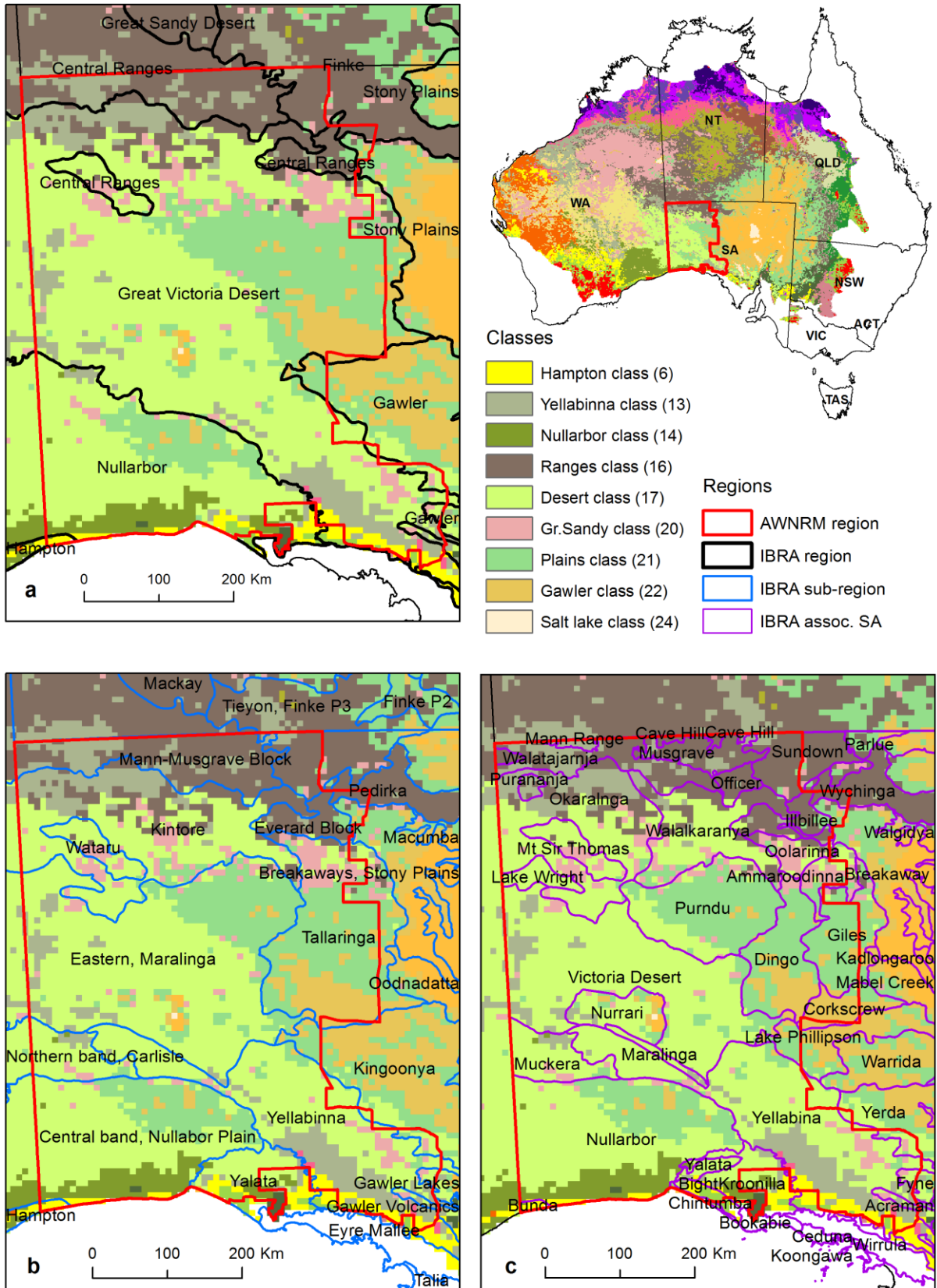
Ooldea Range, at the northern edge of the Nullarbor (Fig. 3.3) where the dominant vegetation is mallee (*Eucalyptus* spp.), a vegetation type which typically grows and flowers in summer.

### 3.3.2 *Classes characterised in relation to the environment*

Lawley et al. (2011) mapped twenty-four classes of spatio-temporal patterns 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<sup>2</sup> to 136,000 km<sup>2</sup> within this region (Table 3.2, Fig. 3.4). To better understand how temporal variability differs across the AW landscape, we interpret each class in sequence, detailing the relevant landscape information and average, variability, seasonality and trends of vegetation growth (Fig. 3.5, Fig. 3.6, Table 3.3) and, where relevant, rainfall (Fig. 3.6, Fig. 3.7).

**Table 3.2 The classes most prominent in the AW region; their extent within the Australian arid zone and within the AW region.**

class	Proxy name(alias)	km <sup>2</sup> in Arid zone	km <sup>2</sup> in AW	% in AW
17	Desert class	264,320	135,808	51.4
21	Plains class	348,096	48,064	13.8
16	Ranges class	501,632	31,360	6.3
13	Yellabinna class	322,496	29,056	9.0
20	Great sandy class	491,328	14,272	2.9
22	Gawler class	364,032	10,432	2.9
14	Nullarbor class	137,728	7,168	5.2
6	Hampton class	155,776	4,096	2.6
24	Salt lake class	30,464	64	0.2



**Fig. 3.4** The study site showing the classes represented within the AW region, with main classes named. Biogeographic regions mapped are, a. IBRA regions, b. IBRA sub-regions, c. South Australian IBRA associations.

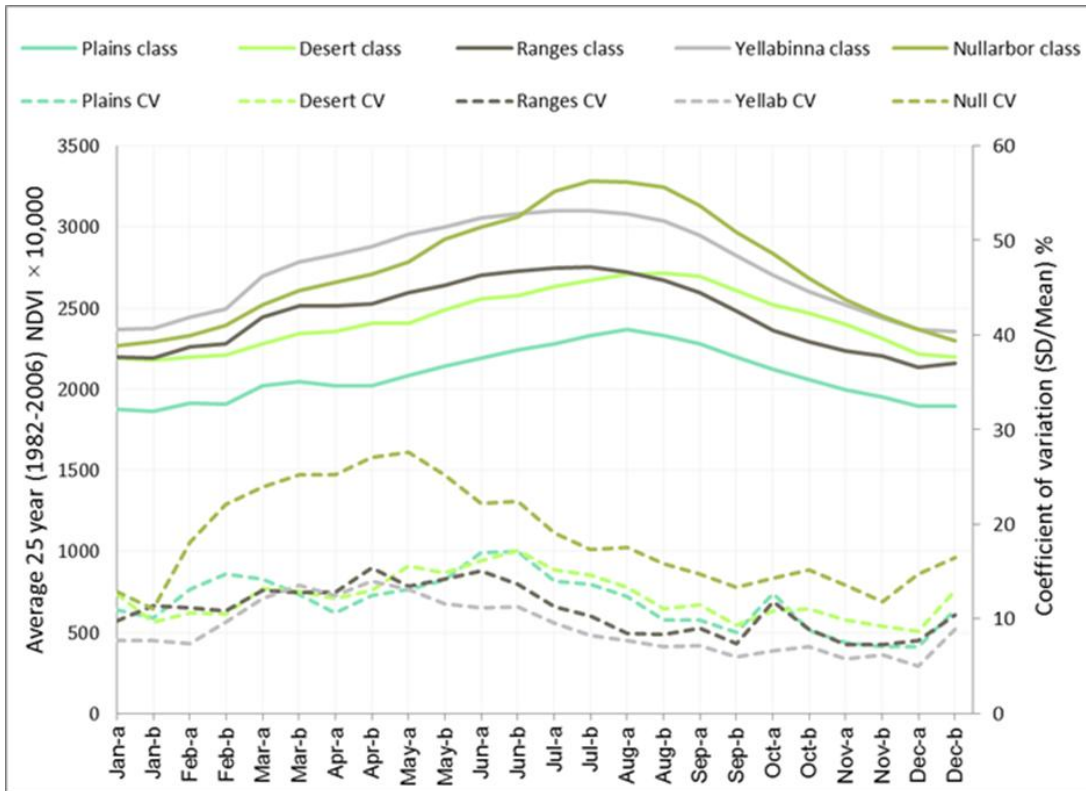
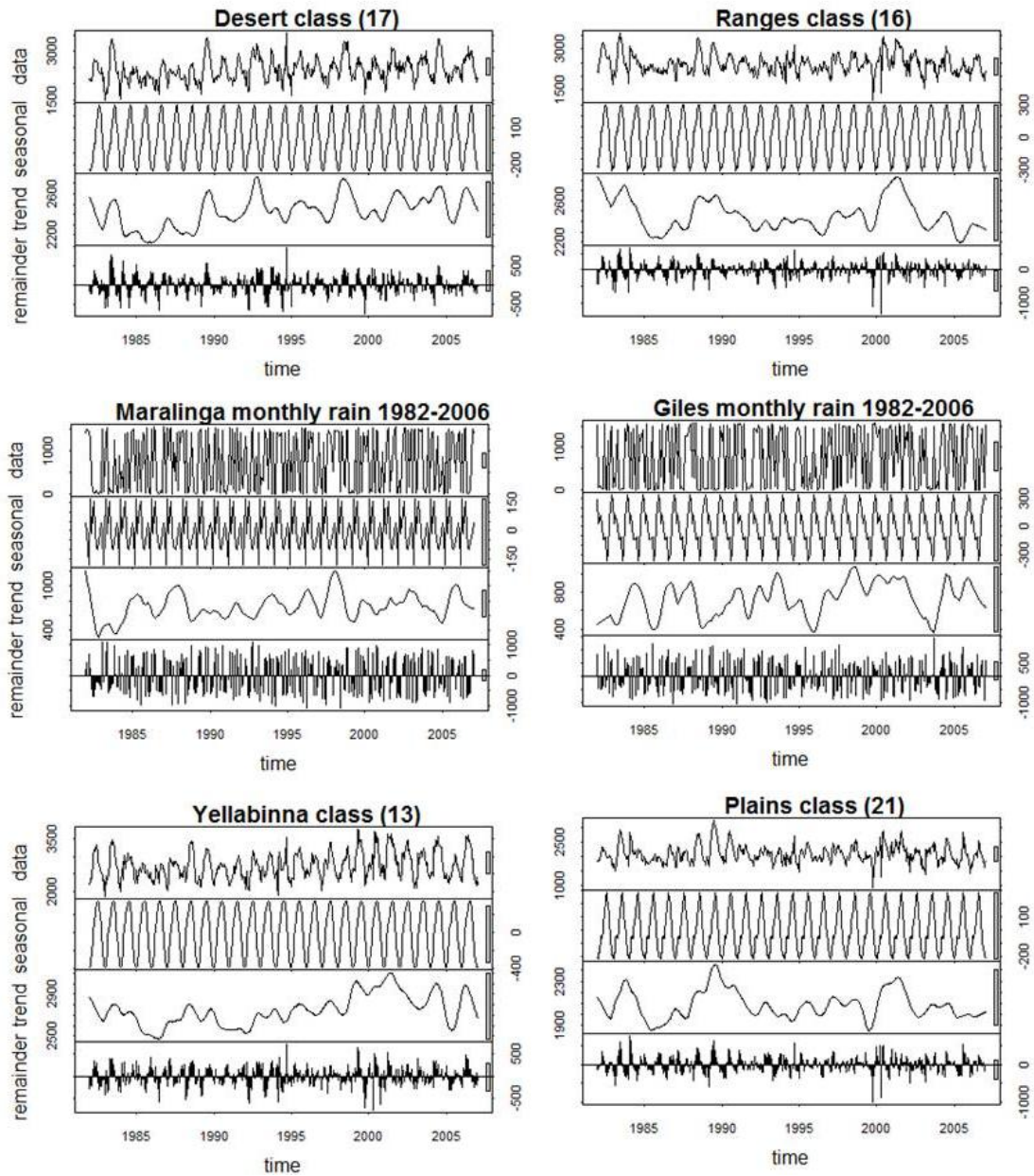


Fig. 3.5 NDVI for each class averaged over 25 years at twice monthly intervals. Variability for each date is shown by the coefficient of variation (CV, dashed lines). For minor classes see Appendix D.



**Fig. 3.6** 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. The grey scale bars shown to the right of each panel indicate the same data range within each individual plot. These values correspond to the relative contribution of the components.

**Table 3.3** STL results summarized.

Decomposition seasonal values	Relative amount	Seasonal IQR	Trend	Low	Peak
Desert class (17)	moderate	68.9%	Upward	Late Jan	Late Aug
Plains class (21)	low	75.9%	Level	Late Jan	Early Aug
Ranges class (16)	moderate	91.9%	Downward	Early Dec	Late July
Yellabinna class (13)	high	95.1%	Upward	Early Jan	Late July
Rain Giles	NA	18.8%	NA	Aug	Dec
Rain Maralinga	NA	6.4%	NA	NA	NA

### **Desert class (17)**

Class 17 is most typical of the study region (Fig. 3.4); widespread, and with greater extent within than beyond the AW boundaries (Table 3.3). It is mainly confined to the Great Victoria Desert in South Australia and Western Australia and is therefore referred to as the Desert class, although it needs to be kept in mind that this class typifies variability also occurring over a large section of the Nullarbor. The Desert class also occurs in the southern outlier of the Central Ranges (Fig. 3.4 a).

The landform of the Desert class in the AW region of the Great Victoria Desert features extensive dune fields of mostly red earthy and siliceous sands. Plains occur between the narrow easterly trending reddish dunes in the south eastern area of this class. The vegetation is predominantly low eucalypt woodland and open acacia scrubland over spinifex grasslands (*Triodia* spp.), and open mallee scrub over spinifex grasslands in the southeast. Spinifex appears to be the main defining species of the Desert class. The portion of the Nullarbor region incorporated in this same Desert class is however a treeless plain, with low shrubland of *Atriplex vesicaria* over the small spiny shrubs of *Eriochiton* and *Sclerolaena* spp. with grassy understory.

The 25-year average NDVI plot for the Desert class shows that growth on average 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. 3.5).

Desert class (17) vegetation annual growth patterns show some cyclic nature (Fig. 3.6) but this is not strong, as revealed in the STL decomposition plot, 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 (Fig. 3.5), which is early in the context of the southern winter/spring maxima of Australia-wide seasonality (Table 3.1). The Loess function, in the decomposition process, smoothes out minor artifacts in the imagery, while a larger image anomaly (June 1994) can be seen as relegated to the remainder plot.

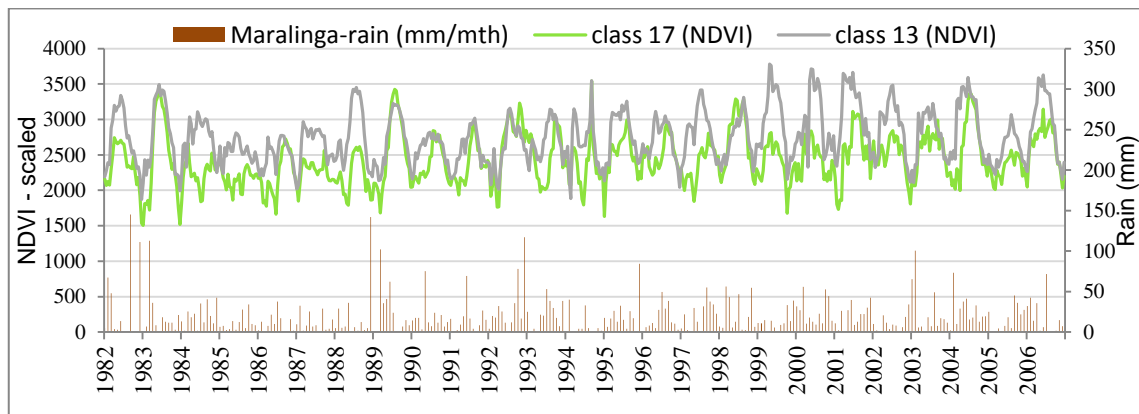
The trend for the Desert class (Fig. 3.6) shows considerable fluctuations over the study period with very low values in 1985-1986 and three separate large peaks in late 1989, late 1992 and early 1998. The overall trend was upward. The positive residuals in the remainder plot are slightly higher than the negative as result of the June 1994 artifact,



but they are overall evenly distributed which retains confidence in the observed trend (Fig. 3.6).

Vegetation growth (raw NDVI) of this class showed on occasions a clear relationship to Maralinga rainfall records, but at other times no correspondence was apparent (Fig. 3.7). Lagged vegetation response to major rainfall events occurred in March 1983, March 1989, February 2003 and February 2004. Two months lag till vegetation growth peaks after effective rain is a common observation for the Australian arid landscape dominated by perennial plants (Pickup and Bastin, 1997).

STL analysis of Maralinga monthly rainfall (Fig. 3.6) indicates that a mere 6.4% of rainfall data was captured within the IQR of the seasonal cycle, which confirms the statement that rain in the Great Victoria Desert is aseasonal (Greenslade et al., 1986).



**Fig. 3.7 Desert class (17) and Yellabinna class (13) NDVI time series showing vegetation growth over 25 years. Rainfall shown was recorded at Maralinga, the most relevant station with comprehensive records for the 1982 - 2006 period.**

Rainfall clearly does not drive the cycles in vegetation growth so strongly demonstrated in the STL NDVI decomposition (Fig. 3.6). 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 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. 3.7).

### **Plains class (21)**

Class 21, here named the Plains class, is the second most extensive class representing vegetation dynamics in the AW region. It covers approximately 48,000 km<sup>2</sup>, geographically distributed partly in the eastern Great Victoria Desert, especially in the Tallaringa Conservation Park, with a secondary area in the north eastern region of the Nullarbor (Fig. 3.1, Fig. 3.4). Landform and vegetation of class 21 varies within the AW region, but the strongest defining vegetation type is the chenopod landscape, typified by the spiny, tough, salt tolerant *Sclerolaena* species on open plains dotted with emergent saltbush such as *Atriplex vesicaria*. Near saltpans the vegetation comprises samphires.

Rainfall comparison was not possible because of the widespread nature of this class; linking it to a particular rain recording station was not realistic.

The Plains class (21) showed by far the lowest vegetation growth of all classes. Its inter-annual variation over the course of a year is very similar to that of the Desert class, but greater variability is shown in late February (Fig. 3.5). 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. 3.5).

The trend for the Plains class showed two low periods (early 1985 and mid 1999) and three high (summer 1984, spring 1989 and winter 2001) peaks, but no long-term upward or downward trend was detected (Fig. 3.5).



### **Ranges class (16)**

The third major class (16), is largely associated with the Central Ranges, and subsequently referred to as Ranges class. Within the AW region this class is confined to the north. This class encompasses the long-established cattle grazing properties in the northeast of the AW region (Fig. 3.1, Fig. 3.4 a).

The landform in the Finke region of the Ranges class includes alluvial plains with inselbergs and silcrete-capped mesas. Vegetation here features low open woodland of mulga, native pine and elegant wattle over grasses, and chenopod shrublands or tall shrublands. Other areas within this class are rugged ranges with steep talus fans fringed by alluvial fans. The vegetation there includes hummock spinifex grasslands as well as low woodlands of mulga, low shrubland of senna, and low woodland of river red gum. The components unique to this class appear to be the spinifex covered slopes and the tree and tall shrub lined gullies and drainage lines.

In this zone growth commences earlier in the year than elsewhere in the AW region (Fig. 3.5), 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. 3.5).

The Ranges class vegetation shows relatively strong seasonal growth (Fig. 3.5; Table 3.3). Peak value 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. This may be explained by rainfall.

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 toward 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. 3.6). This seasonality is likely related to the summer monsoonal rains to the north; geographically the Ranges class (16) is confined to the north of the AW region.

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, time period (AWNRM Board, 2011).

#### **Yellabinna class (13)**

The fourth major class (13) was named the Yellabinna class, because a large block of this class occurs in the Yellabinna area (Fig. 3.4). This class also occurs at the northern edge of the Great Victoria Desert and the southern margins of the Central Ranges and in the west in Mamungari Conservation Park. Although these regions appear quite diverse, the iso-classification process had detected a similar long term pattern of variability in vegetation growth in these separate regions.

The vegetation and landform for the southern portion of this class are characterised by open mallee (*Eucalyptus* spp.) associated with spinifex and closely spaced east-trending sand dunes. In the north the landforms show dune fields to alluvial plains rising into isolated hills or ridges, where red earths and sands support mulga (*Acacia aneura*), desert oak (*Allocasuarina decaisneana*), and spinifex hummock grasslands, and to a lesser extent mallee woodlands and shrubland over spinifex.

Vegetation showed the highest NDVI of any of the four main classes, but also showed least inter-annual variation (Fig. 3.5). 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 and the remainder evenly distributed (Fig. 3.6). Peak seasonal growth occurs in late July and lowest growth in early January.

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 block of the Yellabinna class, but the southern block 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 growing species. This showed that quite different drivers may produce similar growth patterns.

### **Minor classes**

Class 14, the Nullarbor class, is a relatively minor class in the AW region, occurring only at the southern margin of the Nullarbor and covering some 7000 km<sup>2</sup>, 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.

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. 3.3). 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 may be found in 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. 3.4). 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 growth shown for this class in the early part of the year (Fig. 3.5).

Further minor classes investigated in the region were class 20, 22 and 6, covering from 4000 km<sup>2</sup> to 14,000 km<sup>2</sup>. Class 6 (Hampton class) located along the coast in the Hampton and Yalata region (Fig. 3.3) showed by far the highest mean vegetation response (not illustrated) of all classes in the AW. The vegetation type here is mallee woodland and shrubland with *Melaleuca lanceolata* on limestone pavements. By

contrast classes 20 and 22 are very low in growth and show patterns almost identical to Plains class (21); magnitude as the main difference. Class 22 occurs in the southern part of Tallaringa emphasizing that this region shows, apart from the salt lakes, the lowest vegetation response in the AW region.

### 3.3.3 *Comparing the classes with IBRA stratifications*

The four dominant IBRA zones in the AW regions are the Central Ranges IBRA (three separate areas) and the adjacent Finke IBRA in the north, the Great Victoria Desert IBRA (GVD IBRA) with its extensive sand dunes and inter-dune flats covering the central area, and the Nullarbor IBRA comprised mainly of chenopod covered plains extending south to the coast. Each of these IBRA regions extends beyond the AW boundaries.

These IBRA, when compared with the spatio-temporal vegetation response classes at 8 km resolution, show less internal homogeneity in vegetation growth than one might expect. The Central Ranges IBRA for instance contains at least two different classes of variability in vegetation response within the AW region, and these are shared by the adjoining Finke region (Fig. 3.4 a).

In addition the Central Ranges IBRA is mapped with two outliers. One of these, in the east, was, like the Finke IBRA, almost entirely classified as Ranges class, with a clearly defined boundary. The other outlier, in the northwest of the AW region, by contrast, was largely classified as Desert class (Fig. 3.4 a). The vegetation growth patterns in this outlier appear to originate not from the inselbergs on which the Central Ranges IBRA designation for this area was based, but rather from the vegetation communities surrounding the inselbergs. This observation was confirmed in the AWNRM Management Plan stratification, where this IBRA outlier was incorporated in the wider Great Victoria Desert management region (AWNRM Board, 2011).

The GVD IBRA is very large and our analysis reveals that it is internally quite variable with all four main classes present within its boundary. The Desert class covers most of this IBRA, but a large region in the east of the GVD IBRA coincides with the Plains class (21). The far southern part of the GVD IBRA is mapped as the Yellabinna class (13), which represents an area of higher vegetation growth, and at the northern margins of the GVD IBRA this same class occurs intermingled with the Ranges class. The GVD

IBRA clearly includes areas that exhibit distinctly different long term vegetation response.

The Nullarbor IBRA, so named because of its vast treeless plains (null arbor), carries low chenopod shrublands, but our analysis shows that its vegetation response is not at all uniform. Two distinctly separated main classes and two minor classes were identified across the AW region of the Nullarbor IBRA. The Desert class pattern dominates the centre and west of this IBRA, the Plains class the northeast, the Nullarbor class (14) occurs in the south, and the Hampton class (6) forms a narrow coastal strip (Fig. 3.4 a).

IBRA regions may contain several classes of vegetation response, but conversely classes may be geographically distributed across several IBRA regions, such as the Desert class which occurs both in the Nullarbor IBRA and in the GVD IBRA.

Class and IBRA boundaries show little coincidence, with exception of 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. The Hampton IBRA also conforms well to the Hampton class (6) extent for this region, but the same variability also occurs as a narrow strip of high response coastal vegetation outside this IBRA along the Yalata coast (Fig. 3.4 b).

A variety of landforms may be included in a large IBRA region. Division of the IBRA into sub-regions deals with some of this variety. Examination of the sub-IBRA boundaries showed that although by and large the sub-IBRA boundaries do not coincide with the class borders (Fig.4a), conformity between class and sub-IBRA boundary was noted for the Tallaringa sub-IBRA which part coincided with Plains class 21 (Fig. 3.4 b).

The even more detailed South Australian based IBRA-associations revealed that the boundary between the Purndu IBRA-association and the Victoria Desert IBRA-association broadly aligns with the division between class 17 and 21, but at a distance of 40 to 50 km to the north east (Fig. 3.4 c). This may indicate a gradual change in growth pattern or vegetation type from one class (and one sub-IBRA) to the neighbouring class. The vegetation and land form descriptions for Victoria Desert and Purndu associations are very similar; with a point of difference the Purndu region including chenopods, and

the land form varying from the extensive dune fields of the Victoria Desert IBRA-association to the more gently undulating dune covered plain of the Purndu association. The dynamic vegetation response classes here correspond at least partly to the landform and vegetation boundaries of the IBRA-associations. The new classification does not replace the IBRA information but rather adds information about the vegetation functional response that will enable better evaluation and informed use of the IBRA stratifications.

#### 3.3.4 *Implications for management*

This study has presented a detailed examination and interpretation 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 factors that govern long term vegetation growth in this arid region are presented. Iso-classification of the combined factors and extraction of NDVI time traces for each class enabled quantitative analysis in the AW region, which revealed key differences between the dynamic vegetation classes. For management this information delivers a qualitative overview and quantitative detail, indicating where in the region certain vegetation responses may be expected and the strength and variability of such response.

- In some areas low vegetation growth is the governing factor, such as in the Tallaringa area. In these regions small changes noted in on-ground monitoring data are likely significant. By contrast where seasonality is the strongest factor, such as in the narrow coastal strip of the Hampton region, such small change may be merely due to seasonality and no indication of need for management action.
- Annual cyclic response has greater importance in areas such as those covered by the Yellabinna and Ranges classes. Here the timing of monitoring takes on greater importance, especially in relation to summer growth, driven by monsoonal effects in the north and mallee growth in the south.
- Some areas have divergent perennial vegetation types but nevertheless are mapped in the same class. The Desert class includes both spinifex covered dune field and chenopod plains. Monitoring data collected in areas within this class

can be interpreted alike because even though the areas have different vegetation types, they share the same long time vegetation greening patterns.

- Areas where low inter-annual variability is a feature, such as the Yellabinna class, will show a relatively stable vegetation response. This information is useful for managers. When monitoring at anniversary dates a relatively small change in vegetation could be regarded as significant.
- Where cyclonic activity has influence, as in the southern Nullarbor region, high inter-annual variation can be expected during the early part of the year. Cyclonic activity needs to be taken into account when interpretation monitoring data in this region.

Managers often wish to detect trends in land condition, which are difficult to assess using two or three samples over time. Our analysis, based on the decomposition of the greenness signal (NDVI) of 25 years of NOAA AVHRR data showed overall declining trend for the Ranges class, upward trend for Yellabinna and Desert classes and a stable result for the Plains class. The implication of this is that managers can expect a non-uniform response across this landscape, however, the analysis also revealed considerable variation in the trend for each class across the 25 years. This shows that 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 the AW landscape, and draws attention to the likelihood of misinterpretation when using shorter time series for trend analysis.

The finding that the actual vegetation response-based classes are very different from the traditional IBRA stratifications is important for data interpretation. Areas found to have the same actual growth pattern, although these areas are geographically located in different IBRA, may be interpreted the same way. Conversely areas assigned to different classes, even though they occur in the same IBRA region, need to be interpreted differently.

The findings in this research have, beyond improving data interpretation, also implications for ecological sampling and site selection for comparative monitoring points, and for biodiversity management purposes. Broad gradients that became obvious

during this research, such as the NW-SE trend of similar response across the AW region, may be of interest for conservation initiatives such the East Meets West Nature Links programme<sup>2</sup>.

For managers wishing to use remotely sensed imagery for monitoring of ecological indicators it is especially important to be aware that extraction of information using stratifications that represent static information, as is the common practice, may not be the best option. Extracting information using a zonation based on active vegetation growth patterns may be more effective for monitoring of vegetation-growth related flora and fauna phenomena.

### **3.4 Conclusion**

This detailed interpretation for the AW region has illustrated how factors that govern long term vegetation response across the entire Australian arid zone are also meaningful at regional scale. It has shown how the differences in aggregated vegetation growth, seasonality, and erratic east-west responses, are expressed across the AW region. The classification created from these factors mapped the spatio-temporal patterns indicating vegetation response across the landscape, with classes showing difference in timing, magnitude and variability of vegetation growth.

These classes, representing observed historic vegetation response, were shown to be quite different from the IBRA zones which are based on the biophysical properties, of geology, climate, landform and soil and vegetation descriptions recorded from snapshot-in-time survey data. The new classification is not intended to replace IBRA stratifications but rather forms a new and unique source of information on vegetation dynamics. The IBRA is regularly revised as new information comes to hand and there might be scope to incorporate this new and additional information on vegetation function in future IBRA revisions.

This study has given an entirely new perspective of the AW landscape. Interpretation of land condition indicators in the highly dynamic natural areas of the arid zone has been a

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<sup>2</sup> [http://www.environment.sa.gov.au/naturelinks/Corridors/East\\_meets\\_West](http://www.environment.sa.gov.au/naturelinks/Corridors/East_meets_West).



vexing problem for environmental managers. This study goes some way toward addressing this, so managers of these arid zone wilderness regions can better differentiate between environmental degradation and change within the bounds of natural variability.



# CHAPTER 4

EVALUATING MODIS SOIL FRACTIONAL COVER  
FOR ARID REGIONS, USING ALBEDO FROM HIGH-  
SPATIAL RESOLUTION SATELLITE IMAGERY



## STATEMENT OF AUTHORSHIP

### Authorship of chapter 4

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Contribution to the Paper	Co-supervised development, conceptualisation and realisation of the research and evaluated the manuscript.		
Signature		Date	3-4-14



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### **Abstract**

Broad-scale high-temporal frequency satellite imagery is increasingly used for environmental monitoring. While the normalised difference vegetation index (NDVI) is the most commonly used index to track changes in vegetation cover, newer spectral mixture approaches aim to quantify sub-pixel fractions of photosynthesising vegetation, non-photosynthesising vegetation, and exposed soil. Validation of the unmixing products is essential, to enable confident use of the products for management and decision-making. The most frequently used validation method is by field data collection, but this is very time consuming and costly, in particular in remote regions where access is difficult. This study developed and demonstrates an alternative method for quantifying land cover fractions using high-spatial resolution satellite imagery. The research aimed to evaluate the bare soil fraction in a sub-pixel product, MODIS Fract-G, for the natural arid landscapes of the far west of South Australia. Twenty-two sample regions, of 3400 sampling points each, were investigated across several arid land types in the study area. Albedo thresholds were carefully determined in Advanced Land Observing Satellite Panchromatic Remote-sensing Instrument Stereo Mapping (ALOS PRISM) images (2.5 m spatial resolution), which separated predominantly bare soil from predominantly vegetated or covered soil, and created classified images. Correlation analysis was carried out between MODIS Fract-G bare soil fractional cover and ALOS PRISM bare soil proportions for the same areas. Results showed much lower correlations than expected, though limited agreement was found in some specific areas. It is posited that the Moderate Resolution Imaging Spectroradiometer (MODIS) fractional cover product, which is based on unmixing using the NDVI and a Cellulose Absorption Index (CAI) proxy, may be generally unable to separate soil from vegetation in situations where both indices are low. In addition, separation is hampered by the lack of “pure pixels” in this heterogeneous landscape. This suggests that the MODIS fractional cover product, at least in its present form, is unsuited to monitor sparsely vegetated arid landscapes.

## 4.1 Introduction

High-temporal frequency remotely sensed data have received much interest for broad-scale environmental monitoring. Such data are acquired daily by satellite-mounted sensors over most of the earth's surface, but their low-spatial resolution, of 250 m or greater, limits the detail of land-cover information that can be gained. Common approaches to interpreting the mixed reflectance signal of such low-spatial resolution imagery include image indices such as NDVI and sub-pixel modeling.

A number of sub-pixel models have been developed; from spectral mixture analysis (SMA) early in the history of remote sensing (Huete, 1986; Settle and Drake, 1993; Smith et al., 1990) to multiple endmember spectral mixture analysis (MESMA) (Roberts et al., 1998) and, more recently, to relative spectral mixture analysis (RSMA) (Okin, 2007). Sub-pixel analysis generally separates the data into two to four fractions such as photosynthesising vegetation (PV), nonphotosynthesising vegetation (NPV), bare soil (BS), shadow, snow or other components of interest.

In Australia a MODIS fractional cover product has been developed for monitoring of the northern tropical savanna region (Guerschman et al., 2009). A time series of the product, which unmixes PV, NPV, and BS from the data space defined by NDVI and a Cellulose Absorption Index (CAI) proxy, is made available for the entire Australian continent at 500 m spatial resolution<sup>3</sup>.

For the purpose of this study we named this product MODIS Fract-G, to distinguish it from other MODIS fractional cover products (G refers to its author Guerschman). This fractional cover product is proposed to be used across the whole of Australia (Stewart et al., 2011). However, the Australian continent contains a great diversity of climate, soil, and vegetation types (Government of South Australia, 2007). To have confidence that MODIS Fract-G gives a true estimate of land cover fractions in regions other than the northern savanna, wider validation is essential.

Limited quantitative validation of MODIS Fract-G was conducted during the development of the product, based on field-collected grassland curing data. This

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<sup>3</sup> (<https://remote-sensing.nci.org.au/u39/public/html/modis/fractionalcover-clw/index.shtml>).



separated dry biomass from green biomass, which were equated to PV and NPV and scaled to 100%. Bare soil values were not available and therefore not explicitly considered in the validation (Guerschman et al., 2009). Additional field-based validation of MODIS Fract-G is in progress and a handbook of methods for field measurement of fractional ground cover has been produced (Muir et al., 2011). In addition, as part of the national Terrestrial Ecosystems Research Network AusCover program, field data are being collected across Australian rangelands in a format capable of validating satellite data (Foulkes et al., 2011) and field-based evaluation has been performed in the states of Queensland, New South Wales and to a very limited extent in South Australia (Guerschman et al., 2012). No field validation took place in our region of interest, which covers over 280,000 km<sup>2</sup> of the South Australian arid zone.

Validation of satellite image-derived land cover products is most commonly based on field-collected data, using standardised and detailed methods. Field-based validation has several limitations. It is time-consuming and expensive because a large number of widely dispersed field estimates is required (Watson and Novelty, 2004; Watson et al., 2007). Matching the scale of field data with that of broad scale remotely sensed data remains challenging (Barnsley et al., 2000; Guerschman et al., 2012; Liang et al., 2002; Morisette et al., 2002; Turner et al., 2004; Turner et al., 2006). Observer differences may introduce additional variation (Friedel and Shaw, 1987a; Friedel and Shaw, 1987b) and the extent to which the field observations can be extrapolated to the wider landscape is unknown.

This research proposed a different approach for validation, namely the use of high-spatial resolution satellite imagery.

High-spatial resolution imagery provides an objective record in time of land cover and has great potential for the validation of coarser-resolution image products. It has been used for the validation of MODIS products in such diverse environments as the Arctic Circle and southern Africa (Montesano et al., 2009; Morisette et al., 2003). Using satellite data for validation has the advantage that images can be chosen from archives which enables comparisons between test and validation data for corresponding dates across wide regions, and a large number of revisit dates are on offer. Sample locations can be selected anywhere in the landscape within the imagery and spatially comprehensive assessments made, reducing or eliminating the need for extrapolation

from a few field sites. High-spatial resolution satellite data for comparison can also be selected for a single date across an entire satellite path, reducing variables by supplying digital information acquired under identical weather and reflectance circumstances over a very large area, which is nearly impossible to achieve in field assessments due to geographic and time constraints.

This study aims to use high-spatial resolution satellite data to evaluate the bare soil fraction of MODIS Fract-G over the arid regions of South Australia. The bare soil fraction is considered particularly important in the assessment and monitoring of arid and semi-arid land conditions, as it is an indicator of erosion risk and land degradation (Nagler et al., 2000; Tongway, 1995).

Soil exposure, or conversely vegetation cover, can be detected in satellite imagery where individual trees and shrubs can be distinguished, which allows relative bare soil and cover estimates to be made, similar to those made in the field. This study used the albedo in 2.5 m-spatial resolution ALOS panchromatic imagery as the indicator of relative soil and cover fractions.

Using albedo as indicator of land condition is not new. It has been used to detect changes in land cover (Otterman, 1977; Robinove et al., 1981) and to detect degradation from overgrazing (Musick, 1986; Otterman, 1974). The spatial resolution of Landsat data available for those studies did not allow detection of individual trees and shrubs in the imagery and therefore still required field validation, although aerial photography was at times employed (Foran, 1987).

Terrestrial hemispherical photographs revealed a positive relationship between albedo values and soil exposure in a study of broadband albedo for MODIS validation (Barnsley et al., 2000).

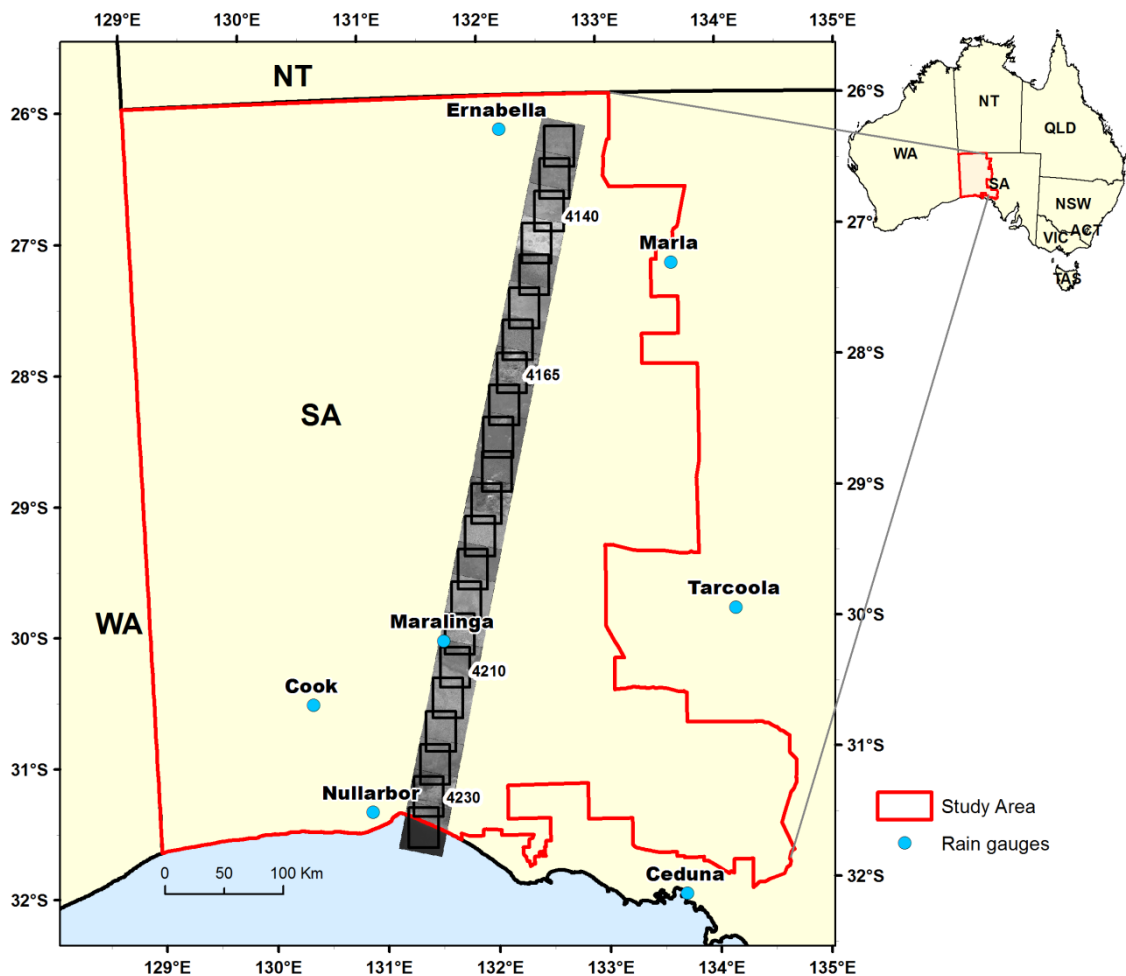
Research in Australian and African arid grazing lands has shown that the reflectance of dry desert soils is consistently higher than that of plants, plant debris, and dry microphytic crust. This is particularly evident in the visible red portion of the spectrum as in Landsat 5TM band 3 (red, 0.62 - 0.69  $\mu\text{m}$ ), or its equivalent in earlier Landsat studies, Landsat MSS band 5 (red, 0.60 - 0.70  $\mu\text{m}$ ) (Graetz and Gentle, 1982; Pech et al., 1986; Ringrose and Matheson, 1987). ALOS panchromatic imagery, at 0.52 – 0.77  $\mu\text{m}$ , represents this region of the electromagnetic spectrum.

## 4.2 Methods

### 4.2.1 Study area

The study was conducted within the 261,180 km<sup>2</sup> Alinytjara Wilurara Natural Resources Management (AWNRM) region of South Australia (Fig. 4.1).

This region is a largely natural, mostly non-pastoral, arid area, managed by the traditional Aboriginal owners in cooperation with the South Australian government.



**Fig. 4.1** Alinytjara Wilurara Natural Resources Management region forming the study area in South Australia. The ALOS PRISM satellite path used in the study and the 22 25 × 34 km sampling regions north to south within this path are shown. Relevant rain-recording stations are indicated.

The climate is warm to hot in summer, with annual mean maximum temperature ranging from 24°C along the coast to 29°C inland; and cool to cold in winter with annual mean minimum temperature of 11°C along the coast to 13°C inland (BOM, 2012). Mean annual rainfall varies from 250 mm in the south to 150 mm in the central

region, and up to 300 mm in the ranges in the north. Rainfall is non-seasonal and intermittent, often marked by high-rainfall events following long periods of drought. Rainfall records are available but the paucity of recording stations across this vast region has resulted in imprecise interpolation maps (Chappell et al., 2013). Evaporation is extremely high, with an annual mean evaporation of 2400 mm in the south and 4000 mm inland (Government of South Australia, 2007).

The landscape consists of a wide variety of landforms and vegetation communities. Dominant landscape features are the Central Ranges in the north descending into alluvial fans and plains with scattered granitic inselbergs and rocky outcrops. The ranges, outcrops, and inselbergs carry a sparse cover of hummock grasses (*Triodia* spp.) and sporadic tall shrubs. The alluvial fans are characterised by low open shrubland of a variety of *Eremophila* and *Senna* shrub species, while the plains support a low woodland of mulga (*Acacia aneura*), needlebush (*Hakea* spp.), and some desert oak (*Allocasuarina decaisneana*). *Eucalyptus* species fringe the dry watercourses.

South of the ranges and plains lie the red dunefields of the Great Victoria Desert. Parallel red dunes rise up to 30 m high and may extend unbroken for up to 100 km. Vegetation on the dunes includes hummock grasses (*Triodia* spp.) and needle bush and sparsely distributed mallee (*Eucalyptus* spp.). Vegetation on the inter-dune flats consists of shrublands of mallee with hummock grass understory and mulga over tussock grasses (*Enneapogon* and *Aristida* spp.). The southernmost part of the study region includes part of the Nullarbor Plain, an extensive flat limestone region carrying bluebush (*Maireana* spp.) and saltbush (*Atriplex* spp.). It is fringed by mallee scrub and ends in a coastline of steep calcarenite cliffs interrupted by areas of white coastal dunes and sandy beaches.

Such a varied landscape naturally contains a variety of soils, including red-brown loams on the northern alluvial plains, red siliceous desert sands of the central region, pale calcareous loamy soils on the Nullarbor, and white sands along the coast. Despite this variety the common feature is that all soil types present are characterized as “bright” soils (Viscarra Rossel et al., 2011). Brightness represents the principal source of spectral variance among soils (Huete and Escadafal, 1991), and highly reflective soils, referred to as bright soils, are said to occur over most of arid Australia (e.g. Pickup, 1989); a fact that is taken advantage of in this research.

Fire is a common occurrence in the study region, and fire scars can be readily seen in both moderate- and high-resolution satellite imagery (Haydon et al., 2000; Turner et al., 2008). No permanent surface water is present, although flooding of the dry salt lakes and ephemeral creeks occurs infrequently after heavy rain.

Ecosystems in the region are under pressure through increased mining activities and incursions of feral flora and fauna species, which necessitates close and frequent monitoring for management.

#### 4.2.2 *Estimating bare soil fraction at high spatial resolution*

The overall aim of this research was to evaluate the bare soil fraction of MODIS Fract-G for the South Australian arid region. To achieve this we developed a method to discriminate the bare soil fraction in high-spatial resolution ALOS PRISM imagery.

The PRISM data were acquired by the sensor on board the ALOS satellite in the wavelengths 0.52 - 0.77  $\mu\text{m}$  at 2.5 m spatial resolution, over a 35 km swath. ALOS had a revisit cycle of 46 days. A single evaluation date of 10 March 2007 (Table 4.1) was chosen guided by availability of prolonged dry period cloud-free ALOS PRISM imagery over the study region. The data were in the form of at-sensor radiance recorded as eight-bit digital numbers.

**Table 4.1** Satellite image acquisition dates and attributes.

<i>Satellite data</i>	<i>Acquisition periods</i>	<i>Spatial res. (m)</i>	<i>Wavelength (<math>\mu\text{m}</math>)</i>	<i>Path</i>	<i>Tiles</i>
MODIS Fract-G 041	10 Febr - 25 Febr 2007	500.0	-	-	-
MODIS Fract-G 049	18 Febr - 5 March 2007	500.0	-	-	-
ALOS PRISM	10 March 2007	2.5	0.52–0.77	55	4130-4235

### **ALOS PRISM scene selection**

For the purpose of this study the following scene selection criteria were used, aiming to maximise the strength and generality of the validation.

- (1) The selected scenes covered as many different landscapes and soils as possible.
- (2) All scenes were acquired on the same date.
- (3) Scenes did not include strongly contrasting soil types.
- (4) No significant rainfall was recorded in the two to three months preceding the acquisition date.

An ALOS acquisition path across the study site (path 55, 10 March 2007) (Table 4.1, Fig. 4.1) was chosen because it covers a wide variety of landscapes including grazed paddocks in the north, linear red sand dunes in the centre, and calcareous saltbush plains and coastal sand dunes in the south. Twenty-two PRISM scenes were available, of which two (scenes 4210 and 4225) were rejected as they did not meet criterion 3.

In regard to criterion 4, rainfall records were available for meteorological stations widely dispersed across the study area, though not all are quality controlled (BOM, 2012) (Table 4.2). The most significant rainfalls in the months preceding 10 March 2007 were recorded on 19 and 20 January 2007 at Tarcoola, which is located 300 km east of the southernmost sampling sites and too remote to have an effect on these, and at Ernabella, 50 km west of our northernmost sampling site (Fig. 4.1). Depending on the spatial extent of the Ernabella rain, this may have affected vegetation in the northernmost sampling sites, although during the summer months the high evaporation rate likely minimised this. Other recorded rainfalls were too low to have an effect on vegetation growth (Fig. 4.2). No other effective rain was recorded from mid-July 2006 to the evaluation date in March 2007. Rain did fall within days thereafter, resulting in a March monthly rainfall of 63 mm and annual (2007) rainfall of 249 mm (Maralinga), but both evaluation- and evaluated imagery were acquired entirely prior to these rain events and therefore represent prolonged dry period imagery.

**Table 4.2 Rainfall records (mm/day) relevant to the study area. Evaluation date is in bold. (N)QC = (not) quality controlled.**

<i>Station</i>	<i>Ernabella</i>	<i>Marla</i>	<i>Cook</i>	<i>Maralinga</i>	<i>Tarcoola</i>	<i>Nullarbor</i>	<i>Ceduna</i>
2007	NQC	QC	QC	QC	NQC	NQC	QC
18 January	1	6	-	-	6.4	-	-
19 January	28.8	3.5	-	-	62.2	-	-
20 January	1.4	4.7	-	0.2	19.8	-	-
21 February	-	-	-	-	21.6	-	-
25 February	-	-	2	8.2	2	-	-
01 March	0.8	-	7	0.6	1.2	-	-
02 March	-	-	4	-	-	-	-
<b>10 March</b>	-	-	-	-	-	-	-
13 March	-	-	11.2	2.2	-	1.4	2.2
14 March	-	-	28.6	11.8	1.4	27.4	4.2
19 march	0.4	1.2	-	4	26.6	-	-
20 March	0.4	-	6	23.4	-	16.2	42.2
21 March	5.4	-	-	1.6	1	0.4	2

Australian arid zone atmospheric conditions are generally clear and are likely to be very similar along a single date path and cloud-free images were selected, hence radiometric and atmospheric corrections were deemed not necessary for the ALOS PRISM imagery. The sun angle contribution to the brightness of the scenes was uniform across all scenes because the acquisition dates were the same. This applied to all satellite imagery used in this study.

All satellite data (Table 4.1) were co-registered and re-projected using nearest neighbour resampling to South Australian Lambert Conformal Conic.

#### **Sampling regions within scenes**

A rectangular sampling grid of 500 × 500 m cells in 50 columns × 68 rows was created. This 25 × 34 km grid was placed within each of the 20 PRISM scenes so the cells coincided with the MODIS Fract-G 500 m raster. The size of this grid was chosen to give consistent sampling size whilst including the maximum practicable rectangular sampling area within each 35 km ALOS PRISM scene (Fig. 4.1).

### Thresholds for soil exposure

For this study we defined soil cover as all vegetative material, alive, senescent, or in the form of plant debris. This includes microphytic crust, a living organism, which darkens bright soil when intact. Clear boundaries between such cover and bare soil do not, however, exist within the Australian natural arid zone landscape, and pure pixels are uncommon, even at 2.5 m ground resolution. To differentiate between these fractions, pixels are assigned to categories of predominantly covered soil or predominantly bare soil using an albedo threshold.

While the Alinytjara Wilurara landscape is largely without built or invariant features, it is traversed by a small number of survey tracks and unpaved roads, leading to small settlements or mining sites. These roads are clearly visible in the ALOS PRISM imagery. The surface material of these roads, providing they are minor tracks not ameliorated by road works, nor overgrown by grasses, is identical to that of the bare soil surface in the surrounding landscape (Fig. 4.2).

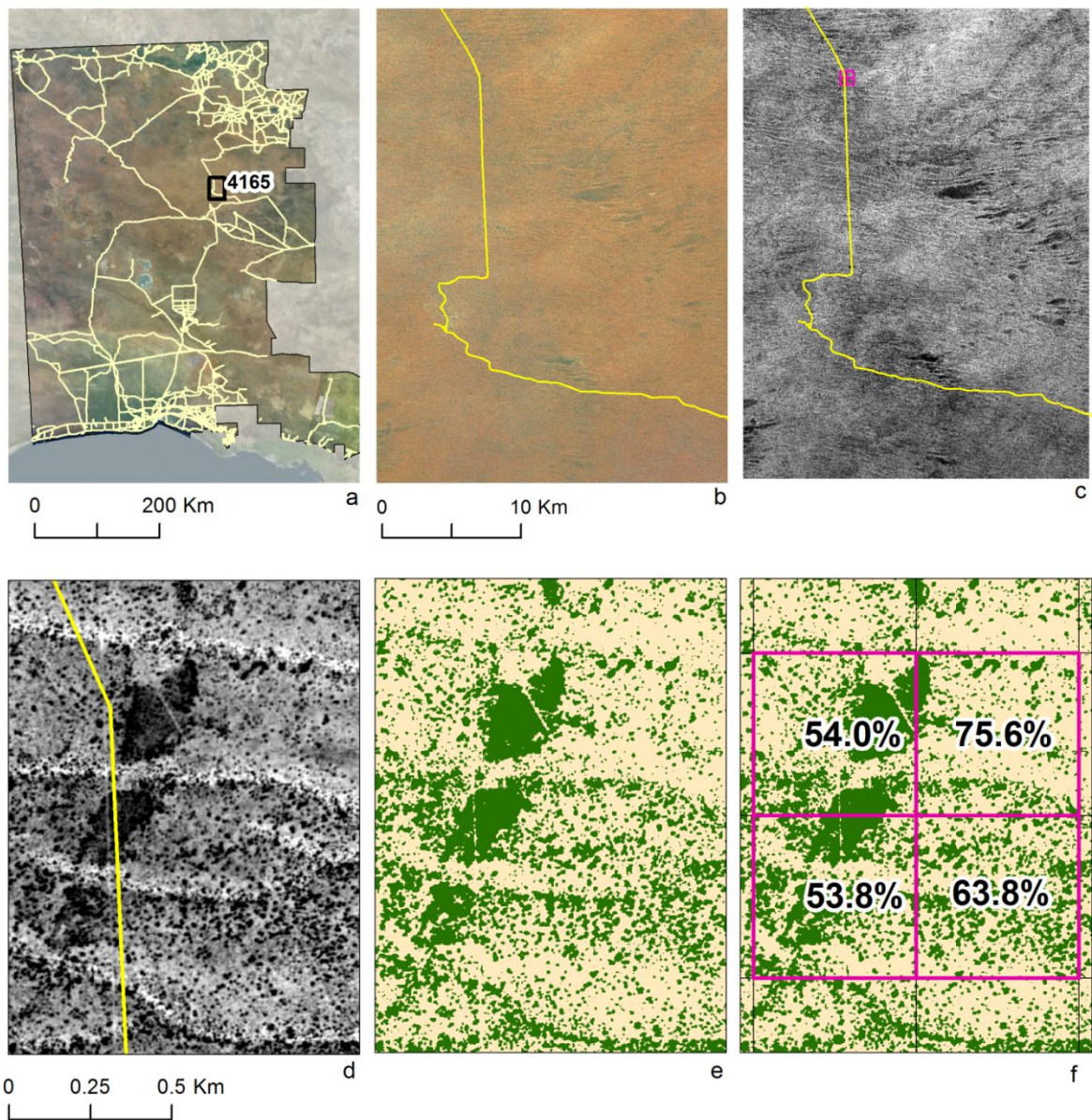


**Fig. 4.2** Bare soil colour of the minor roads is similar to that in the surrounding landscape (image: E Lawley-7/12/2011, 3:30pm, West of Umuwa).

The brightness of these bare soil roads can therefore be used as guide to determine an albedo threshold value. Thresholds were determined for each 850 km<sup>2</sup> sampling area by creating a bare soil/cover classified image using an approximate threshold, visual



inspection of the roads in the classified image, and iteration until satisfied that the roads were adequately classified and delineated in the image (Fig. 4.3 (a)-(d)).



**Fig. 4.3** Illustration of the procedure followed to determine the bare soil albedo threshold and percentage of bare soil. (a) ALOS scene selected, here 4165 in the Great Victoria Desert region of the AWNRM. (b) ALOS sampling area 4165 shown in natural colour with overlay of known road. (c) Same area in ALOS panchromatic 2.5 m, indicating subset in magenta. (d) Enlarged subset, showing parallel east-west dune crests crossed by minor roads that were used to determine the reflectance threshold for sampling region 4165. (e) Same enlargement classified using the threshold; bare soil - yellow, cover - green. (f) The image with 500 m grid and percentage bare soil per cell calculated.

Soils in the AWNRM region are all considered bright soils (Pickup, 1989; Viscarra Rossel et al., 2011), but some variations in soil albedo naturally occur across the landscape, and therefore a unique threshold was determined for each sampling area. Some minor variation in bare soil albedo within the sampling areas was considered

acceptable for the purpose of this study. Images spanning very strongly contrasting soil types were excluded from the analysis, because the different soil reflectance would have required more than one threshold for effective discrimination within those sampling areas. In environments with very heterogeneous soil colours, stratification within the sampling regions and the use of different albedo thresholds may be advantageous.

### **Classification and calculation of fractions**

The thresholds for each sampling area were used to classify all PRISM 2.5 m pixels with values equal to or below the threshold as soil cover, and all pixels with values above the threshold as bare soil ( Fig. 4.3 (e)). Thresholds ranged from 120 to 140, with the highest value on the Nullarbor calcareous soils. The percentage of PRISM pixels classified as bare soil was calculated for each of the 3400 (500 m × 500 m) sample cells within each sampling area (Fig. 4.3 (f)). These percentages of bare soil were then available to be used to evaluate the MODIS Fract-G bare soil estimates.

Although retrospective field verification is not possible, the use of red band reflectance to distinguish bare soil from covered soil in similar dry desert conditions has been previously demonstrated by field sampling (e.g. Graetz and Gentle (1982)).

#### *4.2.3 The MODIS fractional product to be evaluated*

The product to be evaluated was MODIS Fract-G, a time series of fractional cover produced from MODIS MOD43 nadir bidirectional reflectance distribution function (BRDF)-adjusted reflectance (NBAR) data, and developed for the northern savanna region of Australia. The unmixing scheme of MODIS Fract-G is based on two indices. It uses the NDVI, created from red and near infrared (NIR) reflectance, to reveal the PV fraction (Tucker, 1979) and the Cellulose Absorption Index (CAI), created from two shortwave infrared reflectances, to reveal the NPV fraction (Nagler et al., 2000). The third dimension in this three-dimensional data space is the bare soil fraction (BS). The unmixing in the NDVI/CAI space is constrained to produce fractions of PV, NPV, and BS totalling to 100% (Guerschman et al., 2009).

MODIS Fract-G images represent 16-day compositing periods with sequential periods overlapping by 8 days. The images are tagged day of year (DOY), by the first date of the 16-day period.

We downloaded the product for the year 2007 from [http://www-data.wron.csiro.au/rs/MODIS/products/Guerschman\\_etal\\_RSE2009/](http://www-data.wron.csiro.au/rs/MODIS/products/Guerschman_etal_RSE2009/), and extracted the bare soil layers.

We selected from this two sequential MODIS Fract-G bare soil images for dates close but prior to the ALOS PRISM acquisition date (Table 4.1). The MODIS acquisition period being entirely prior to the PRISM acquisition date ensured that no events after this acquisition date, such as rainfall or fire, influenced the MODIS Fract-G composite. The MODIS Fract-G 049 image was chosen for evaluation because it is the image closest to the PRISM acquisition date. The preceding image, MODIS Fract-G 041, was used to appraise the internal consistency of the MODIS Fract-G time series.

The MODIS Fract-G product was re-projected several times: from satellite projection to MODIS sinusoidal and then to Lambert Conformal Conic geographic systems. To counteract the geolocation errors this might cause, we applied a smoothing algorithm (low-pass 3-by-3 filter) to the selected MODIS Fract-G bare soil images. The smoothed images were used in the analysis.

The MODIS Fract-G bare soil percentages were extracted for the cells in each sampling grid. Any pixels in salt lakes and sea, which had been assigned values of 254 and 255 in MODIS Fract-G, were excluded from analysis.

#### 4.2.4 *Evaluation of MODIS Fract-G*

We investigated the internal consistency of the MODIS Fract-G image series by examining correlations between two sequential MODIS Fract-G images (DOY 041 and DOY 049). Because the two images overlapped by 8 days, were based on data acquired during a very dry period over an invariant landscape, and had been smoothed to counter geolocation errors, we expected very high correlations for all sampling areas.

Our main investigation sought to evaluate MODIS Fract-G in order to test it for use across the AWNRM region. We assessed the correlation between the bare soil percentages in MODIS Fract-G and the bare soil percentages as calculated in the high-spatial resolution ALOS PRISM imagery, comparing each of the 20 scenes. Furthermore we assessed whether the degree of correlation was related to the amount of vegetation cover in the scene.

### 4.3 Results

The relationship between two MODIS Fract-G bare soil images representing part-overlapping periods showed correlation coefficients ranging from  $r = 0.43$  to  $r = 0.94$ , with seven sampling areas having correlation coefficients less than 0.75 (Table 4.3). This revealed lower internal consistency in the MODIS Fract-G time series than expected. The lowest correlation,  $r = 0.42$  for scene 4205 could be explained as an anomaly. The first image showed a fire that had not completely burnt out in the first week of the first image period (DOY 041). This fire appeared complete by the second week, as evidenced by the fire scar of comparable extent in the second MODIS Fract-G image (DOY 049) and in the corresponding PRISM bare soil image. No fires were detected in the remaining scenes that could account for the low internal consistency of the MODIS Fract-G data, in this otherwise invariant landscape.

Evaluation of the MODIS Fract-G bare soil fraction using the ALOS PRISM bare soil percentages revealed almost no correlation over most of the sample regions. Correlation coefficients less than 0.30 were common and some of these were negative. Only four of the 20 areas, 4140, 4145, 4205, and 4230, registered correlation coefficients  $>0.30$  (Table 4.3). High RMSE was noted in particular over the Great Victoria Desert area covered by scenes 4175-4200. The strongest correlation ( $r = 0.75$ ) was found in sampling area 4230 (Table 4.3) (RMSE = 21.08). This area contains two contrasting vegetation associations, one of predominantly chenopod shrubland, open scrub, and open heath over brownish calcareous earth, and the other of open red mallee scrub and open woodland of black oak and myall over red calcareous earth (Department of Environment, 2011). This contrast is clearly visible in the PRISM- and MODIS bare soil imagery (Fig. 4.4). This sampling area also had the strongest internal consistency for MODIS Fract-G (Table 4.3, Fig. 4.4 (d) and (e)). Scene 4230 is located not far from the coast (Fig. 4.1).

**Table 4.3** Correlation between two sequential (smoothed) MODIS Fract-G bare soil images showing correlation coefficient (*r*) and RMSE, and correlation between (smoothed) MODIS Fract-G 049 and ALOS PRISM bare soil values showing (*r*) and RMSE. For image dates see Table 4.1.

<i>Sampling areas</i>	<i>Correlation (r) between MODIS Fract-G 041 and 049</i>	<i>RMSE</i>	<i>Correlation (r) between MODIS Fract-G 049 and ALOS PRISM</i>	<i>RMSE</i>
4130	0.76	4.24	0.04	20.51
4135	0.82	3.37	-0.03	28.37
4140	0.90	3.07	0.47	22.09
4145	0.83	4.26	0.35	23.38
4150	0.72	5.37	-0.30	27.65
4155	0.74	5.42	0.04	17.81
4160	0.79	4.18	0.25	11.75
4165	0.78	3.93	-0.07	15.83
4170	0.85	4.38	-0.24	25.83
4175	0.87	3.71	-0.47	57.88
4180	0.82	4.26	0.00	58.70
4185	0.74	5.11	-0.09	51.87
4190	0.73	5.05	0.13	30.13
4195	0.63	3.58	0.04	42.47
4200	0.87	4.25	-0.27	41.97
4205	0.43	5.81	0.31	31.82
4215	0.91	1.43	0.01	31.25
4220	0.80	2.40	0.27	30.16
4230	0.94	2.28	0.75	21.08
4235	0.64	6.19	0.26	20.13



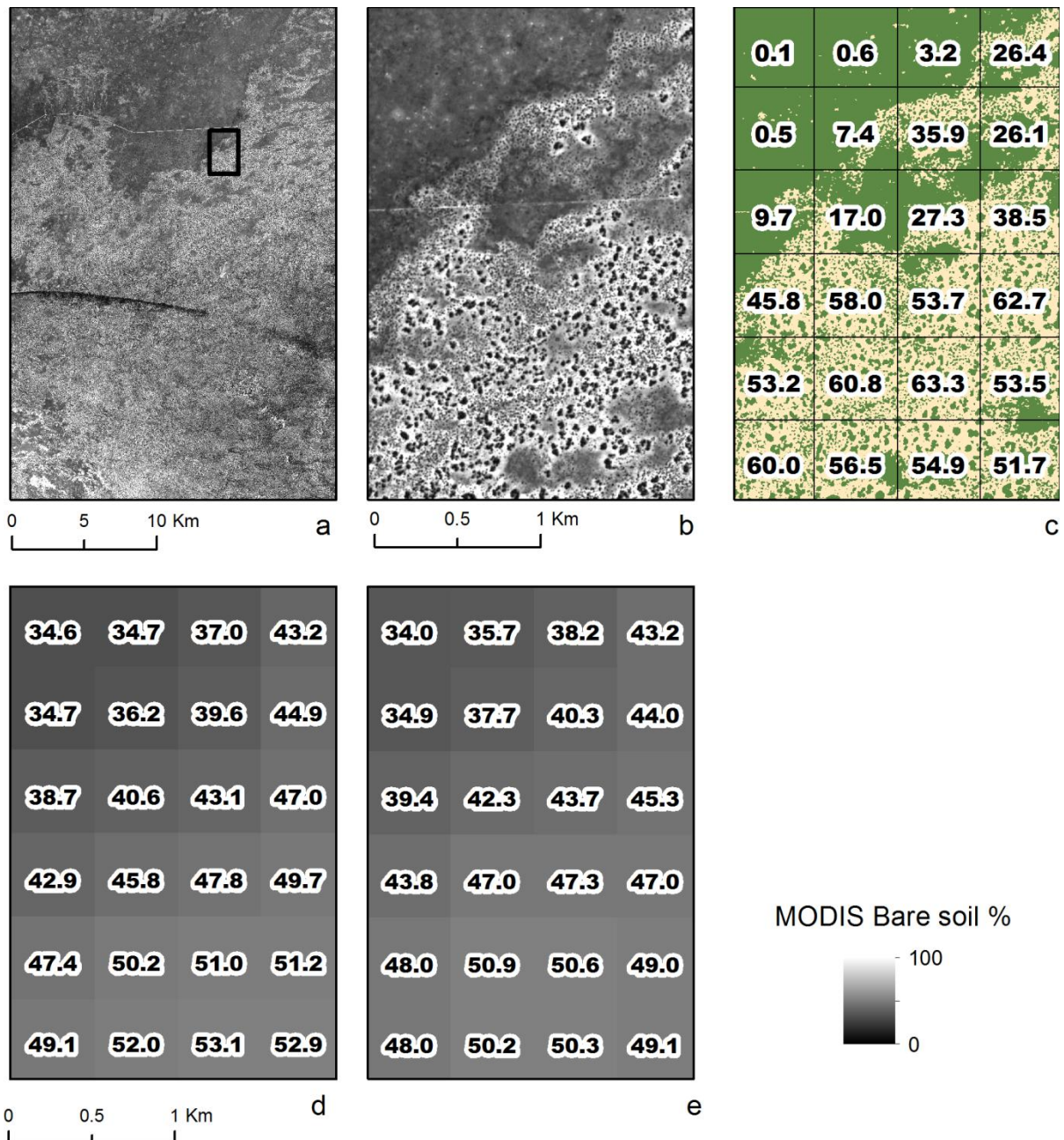


Fig. 4.4 (a) ALOS PRISM sampling area 4230 at the southern edge of the Nullarbor Plain; subset outlined. (b) Enlarged subset showing east-west road and clearly visible tree crowns. (c) The subset classified, bare soil - yellow, cover - green, 500 m sampling grid and percentage bare soil per cell indicated. (d) Same subset in MODIS Fract-G 041 and (e) in MODIS Fract-G 049.

The next strongest correlation between MODIS Fract-G and PRISM bare soil fractions occurred in sampling area 4140 at  $r = 0.47$  (Fig. 4.1). Area 4140 includes hills and ridges of a variety of rock types separated by undulating plains of red massive earths, reddish siliceous sands and red duplex soils. The vegetation comprises low open woodland of mulga and grasses, open tussock grasslands, low shrubland of witchetti bush, senna, and emubush, chenopod shrubland of bluebush, and low woodland of river redgum (Department of Environment, 2011). The most outstanding features are the

outcropping rock formations in the southern part of area 4140. The reflectance of these is lower than that of the surrounding grassy plains, which caused them to be classified as vegetation cover, in both the MODIS product and in the PRISM thresholding.

For the northernmost sampling area, 4130, there was no relationship between the MODIS Fract-G bare soil values and those determined in the ALOS PRISM imagery ( $r = 0.04$ ). The scene shows a eucalypt-lined dry creek, and several roads. In the enlargement of the image subset (Fig. 4.5 (a) and (b)) it is apparent that MODIS Fract-G has assigned areas of high soil exposure, for example south-west of the creek line, as high cover (Fig. 4.5 (d) and (e)), though it is clearly of low cover in the ALOS panchromatic image (Fig. 4.5 (b)).

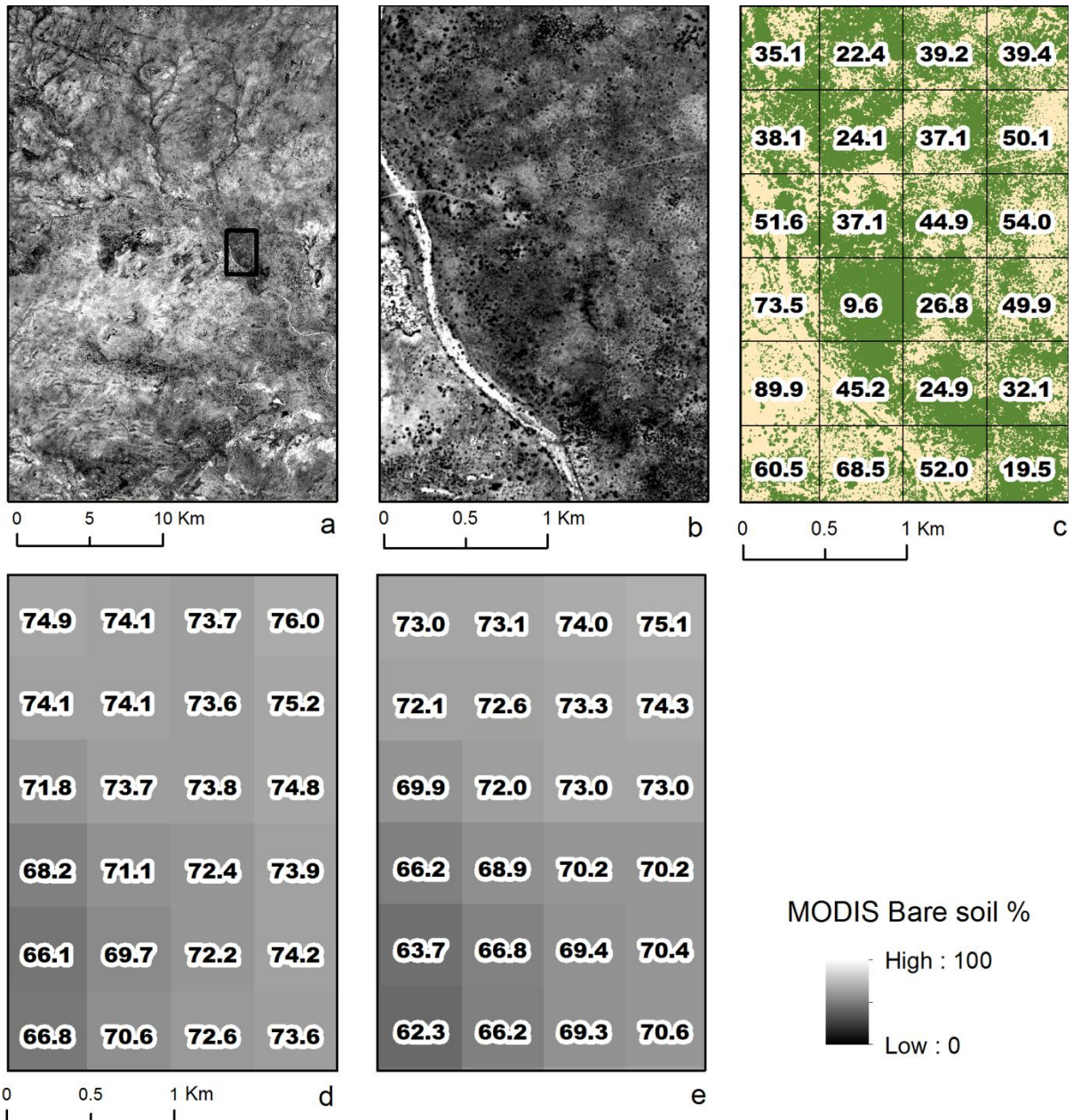


Fig. 4.5 (a) ALOS PRISM sampling area 4130 in the northern pastoral region with subset outlined. (b) Enlargement of the subset showing an east-west road used to determine bare soil threshold and a dry creek bed, with tree crowns clearly visible. (c) ALOS PRISM enlargement classified: bare soil - yellow, cover - green; showing 500 m sampling grid and percentage bare soil per cell. (d) The subset in MODIS Fract-G 041 and (e) in MODIS Fract-G 049. Note that ALOS PRISM and MODIS Fract-G show a contradictory pattern in this subset.

MODIS Fract-G is reported to show good correlation with fire scars (Guerschman et al., 2009). This is visually supported in our analysis. Fires across the sand dunes east of Maralinga in early February 2007 left a large fire scar, visible in sampling area 4205 (Fig. 4.6). The enlarged subset shows a strong relationship between MODIS Fract-G 049 and ALOS PRISM. However, away from the fire scar, MODIS Fract-G does not well represent the on-ground reality revealed in the ALOS PRISM imagery.



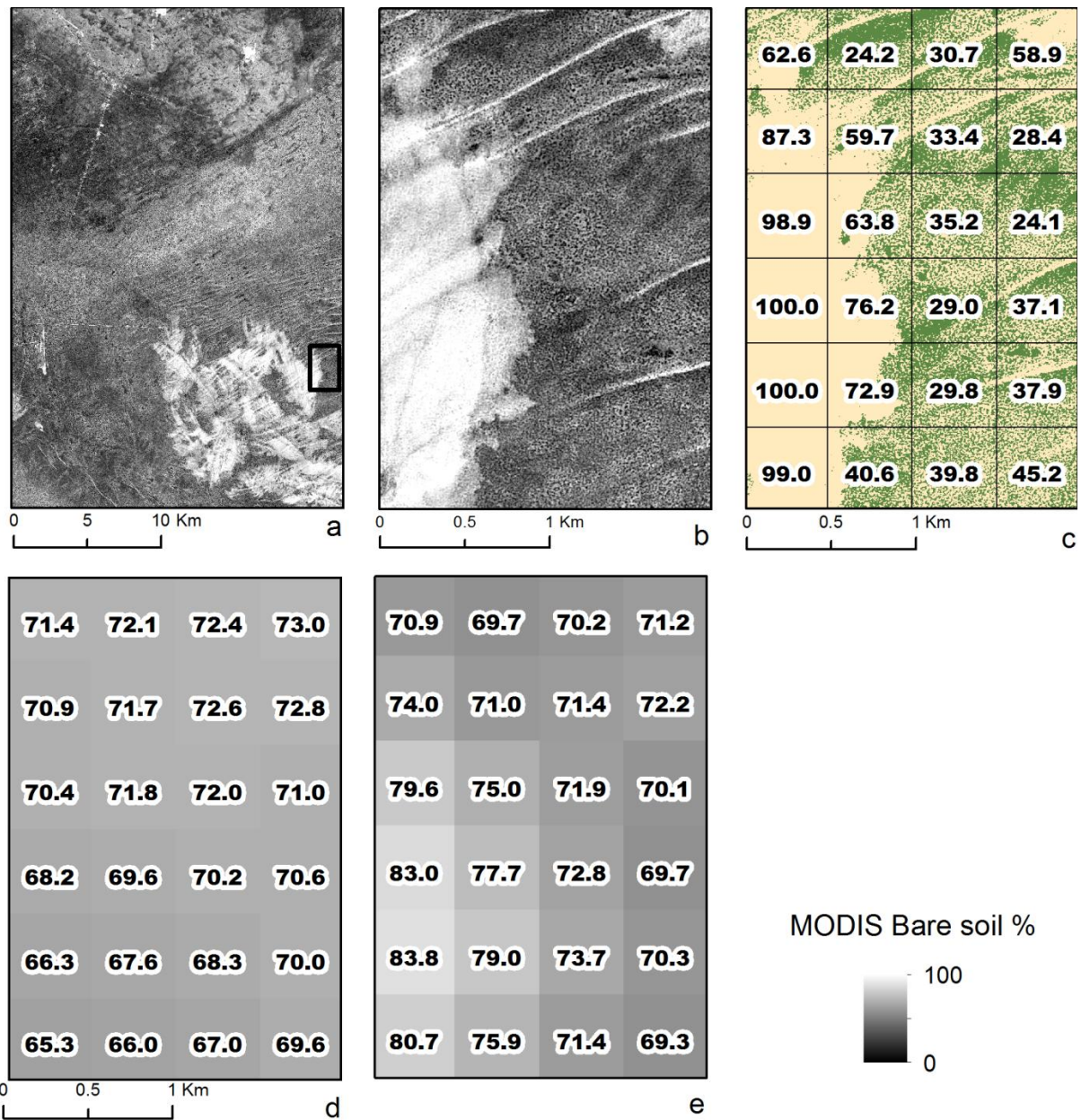


Fig. 4.6 (a) ALOS PRISM sampling area 4205 in sand dunes east of Maralinga showing a fire scar in the south-east of the image and a subset outlined at the fire scar edge. (b) Enlarged ALOS PRISM subset, with bare soil visible in the fire scar and on the crests of longitudinal dunes. (c) The ALOS PRISM subset classified, bare soil - yellow, cover - green; showing 500 m sampling grid and percentage bare soil per cell. (d) The subset in MODIS Fract-G 041 revealing no fire scar. (e) The subset in MODIS Fract-G 049 revealing a fire scar pattern corresponding to the ALOS PRISM pattern in Figure 6(b).

The coefficient for the correlation between the MODIS Fract-G 049 and ALOS PRISM soil fractions for the entire 4205 sampling area is 0.26 (RMSE = 31.82) (Table 4.3).

It is interesting to note that as vegetation cover increases, MODIS Fract-G performance shows a slight improvement (Fig. 4.7).

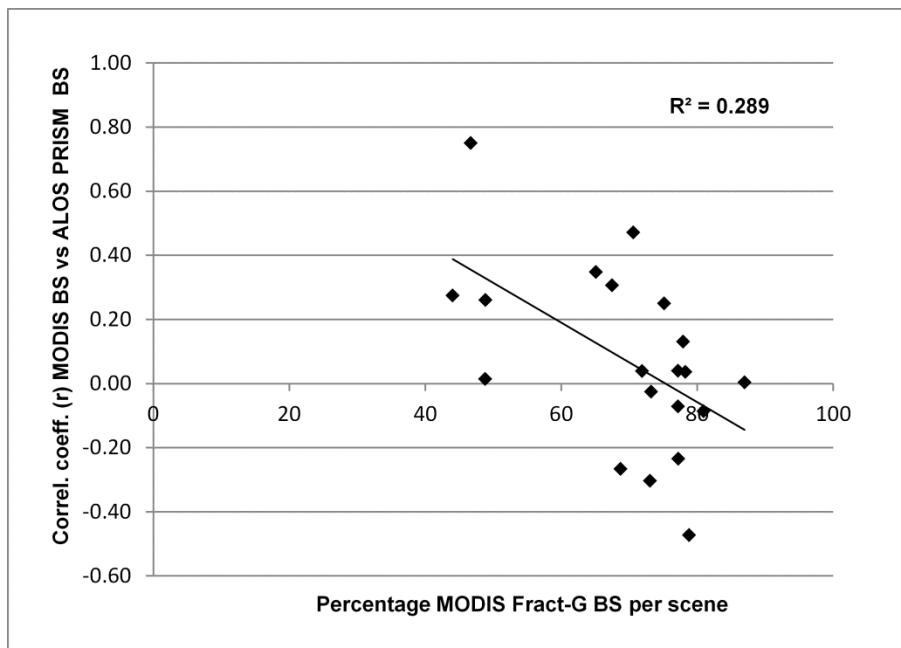


Fig. 4.7 Correlation between MODIS Fract-G and ALOS PRISM bare soil is slightly better in areas with less bare soil.

#### 4.4 Discussion

MODIS Fract-G was initially developed for the Australian northern savanna region to provide a high temporal sub-pixel product that separates NPV, PV, and BS. It is proposed to be used across the Australian continent for land cover monitoring. Validation across a wider range of environments is therefore essential. Validation of remotely sensed environmental measures is usually approached through field data collection. Field validation of MODIS Fract-G is in progress but no evaluation had taken place for the extensive area of interest in South Australia.

This study used high-spatial resolution ALOS panchromatic imagery to evaluate the MODIS bare soil fractional cover estimates, thereby overcoming some of the challenges of field validation such as extrapolation uncertainties, difficulties of site access, and the high expense and time demands. Although not validated by *in situ* cover data, the bare soil fraction estimates in the ALOS PRISM imagery are based on the well-recorded phenomenon that the visible-near infrared albedo in arid environments is strongly correlated with relative soil exposure – both photosynthesising and non-photosynthesising vegetation darken the bright reflectance of these soils. In this study the reflectance values of unpaved minor roads were used to set thresholds, and classify and calculate bare soil percentages, in  $500 \times 500$  m cells, over large areas of the landscape.

Evaluation of MODIS Fract-G using high-spatial resolution ALOS PRISM imagery revealed that MODIS Fract-G apparently does not give a good representation of the bare soil fraction across the South Australian arid zone. Only minimal correlation was found between MODIS Fract-G bare soil and the bare soil distribution revealed in ALOS PRISM imagery. The high RMSE appears to suggest that the ALOS PRISM records greater variability in the landscape than that detected by MODIS Fract-G. It appears that the MODIS NDVI-CAI (proxy) unmixing scheme that was developed for the tropical savanna does not perform well in the arid region of South Australia.

Some of this lack of correlation may be explained by the lower than expected internal consistency within the MODIS Fract-G time series. The expectation of very high correlation between two sequential images is based on the fact that they represent composite values that overlap by eight days. In this arid landscape with predominantly perennial vegetation, under prolonged dry weather conditions very little change occurs over eight days, and providing no fires occur, bare soil values can be expected to remain constant over such a short time period. Contrary to expectation, the sequential MODIS Fract-G images did not correlate well with one another (Table 4.3). Two of the sampling areas that showed greatest MODIS Fract-G internal consistency, 4230 and 4140, were the same ones that showed strongest correlation between MODIS Fract-G and PRISM bare soil. This appears to indicate that some of the lack of correlation can be attributed to the internal noise, likely inherent in the original MODIS NBAR data and propagated into the MODIS Fract-G.

This can, however, only partly explain the wider lack of correlation. The greater lack of correlation between MODIS Fract-G and PRISM bare soil fractions might be explained by the fact that in an arid sparsely vegetated landscape, under dry conditions, the MODIS data have very low spectral dimensionality, particularly in the NDVI/CAI data space. During dry periods, when there is little photosynthetic vegetation, the data are in effect two- rather than three-dimensional (Graetz and Gentle, 1982). However, within the two-dimensional data space there is a significant variation in soil albedo or colour, which was evident in the need to set unique threshold values for each scene. One bare soil spectrum, as used in the unmixing scheme to produce MODIS Fract-G, does therefore not represent the landscape very well (Graetz, 1987; Pickup et al., 1993). MODIS Fract-G may in effect be responding to the differences in soil colour rather than to those between soil and cover.

The low spectral dimensionality may offer some explanation why scene 4230, located near the shores of the Great Australian Bight, showed the highest correlation between the MODIS and PRISM bare soil fractions. A study on vegetation dynamics of the arid zone (Lawley et al., 2011) showed that NDVI response in the coastal AWNRM region was stronger than for inland regions over a 25-year period. Cooler moist sea air supports vegetation growth, in this instance coastal mallee, which leads to elevated NDVI levels, even during generally dry periods. Consequently MODIS Fract-G, which is partly based on NDVI, is better able to define the fractions. This is further supported by our finding that a greater amount of vegetation cover appears linked to a somewhat improved performance of MODIS Fract-G.

Higher NDVI, however, does not explain the next strongest correlation ( $r = 0.47$ ) between the MODIS Fract-G and PRISM bare soil fractions. This is in sampling area 4140 which is located far inland (Fig. 4.1). A possible explanation of why MODIS Fract-G better correlates with the PRISM bare soil here is that the southern part of this scene contains areas of rocky hills and outcrops. This manifests in large areas of strongly defined contrast within the landscape. MODIS Fract-G may reveal this greater contrast in background colour, even though it fails to show the finer contrast between bare soil and cover apparent in the ALOS PRISM imagery. The rocky outcrops are classed as cover rather than bare soil, in both the MODIS Fract-G and PRISM estimates, undoubtedly due to the rocks being much darker than the surrounding dry bright soils.

The scene used to illustrate the method, sampling area 4165 (Table 4.3), is located in a relatively uniform region of parallel dunes in the Great Victoria Desert. MODIS Fract-G does not record any of the bare soil patterns revealed in the PRISM bare soil analysis for this scene ( $r = -0.07$ ) and there are no large, strongly contrasting landscape components within this scene. The remaining sampling areas across the AWNRM region showed very low or no correlation or even low negative correlation between MODIS Fract-G and PRISM bare soil.

#### **4.5 Conclusion**

This study used 2.5 m-ground resolution ALOS PRISM imagery to evaluate the bare soil fraction of the 500 m-ground resolution MODIS Fract-G cover product. Accuracy assessment of fractional cover data is essential prior to use, but remoteness or lack of

access may make field data collection impractical, too costly or impossible. High-spatial resolution satellite imagery is especially useful as field data substitute in these situations as it provides extensive coverage of even areas where access is difficult, at relatively low expense.

Evaluating the MODIS Fract-G bare soil component using such high-resolution data showed that the distribution of the bare soil fractions across the landscape as indicated by MODIS Fract-G bears little resemblance to that shown in the ALOS PRISM classified images, which suggests that MODIS Fract-G in its current form cannot yet be relied upon for monitoring purposes over the arid sparsely vegetated landscapes of South Australia.



# CHAPTER 5

## DISCUSSION AND CONCLUSIONS





## **5.1 Overview of the research contributions**

This thesis demonstrates how satellite imagery can improve assessment and monitoring of land condition in the highly variable arid regions of Australia.

Monitoring change in land condition and interpreting the significance of such change is essential for arid zone environmental management. However, such monitoring is challenging, especially in the vast and highly variable regions of Australia. Collecting adequately representative field data in these remote regions is difficult and costly, site revisit frequency is low, and interpreting change through such sparse field data is very difficult, especially in such highly variable landscapes. Satellite remote sensing, with its ever growing archives of historical surface reflectance data, offers opportunities to characterise long-term patterns of vegetation growth over these vast and remote regions.

The need for frequent land condition assessments has in particular in the wilderness regions become urgent. These ecosystems are under pressure from the effects of economic developments in the form of mining, livestock grazing and tourism, and from change caused by proliferation of non-native flora and fauna. Remote sensing offers a potential solution with satellite fractional cover products now available. These products are able to detect land condition indicators, such as proportions of vegetation cover and bare soil, and track these at high-temporal frequency. These fractional cover products need evaluation over regions of interest prior to use.

This study focusses on the Alinytjara Wilurara (AW) Natural Resources Management (NRM) region, an extensive predominantly natural wilderness region in the far west of South Australia, but the methods developed here are equally applicable to other regions within the Australian arid zone. The research was motivated by the desire of the AWNRM Board to use remote sensing to improve monitoring of land condition.

The overall purpose of the research presented in this thesis is to improve land condition monitoring in the arid regions through the use of remote sensing. The findings are summarised and discussed in the following sections, covering the detection and description of Australia-wide long-term patterns of vegetation response (5.1.1), the characterisation of these patterns and their application for management in the AWNRM region (5.1.2), and the evaluation of a MODIS satellite-derived fractional cover product, for use over the AWNRM region, including the development of a field-data surrogate to

effect this evaluation (5.1.3). Suggestions for future research are presented in section 5.2.

#### 5.1.1 *Spatio-temporal vegetation dynamics Australia-wide*

One of the pressing needs in land condition monitoring is to be able to distinguish between environmental damage and natural variability in vegetation growth. Long-term natural patterns, cycles and trends of regional vegetation growth need to be understood to make such distinction. Previous approaches to understand these long-term patterns and trends have generally been confined to the region of interest, and assessed long-term variability within these regions (Bastin et al., 2012). Alternately these long-term patterns have been interpreted and classified into classes, based on phenology or annual cycles (Lu et al., 2003; Lymburner et al., 2011; Tan et al., 2013). The research in this thesis takes a different approach, namely that vegetation response patterns do not occur in geographic isolation, but are inextricably linked to the wider climatic and environmental framework in which they occur. To understand the variation at regional scales, it is imperative to identify and understand the long-term patterns that define the dynamics of the wider environment. The aim of this part of the thesis was to detect and define the patterns and dynamics of long-term vegetation growth, at the extent of the entire non-cultivated arid zone of Australia.

The research reveals for the first time the patterns and key factors that define long-term vegetation dynamics across continental arid Australia, derived through principal component analysis of 25 years of twice monthly NOAA AVHRR NDVI satellite imagery (Chapter 2; Lawley et al. (2011)). Unsupervised classification of these factors produced classes that are not confined to boundaries based on vegetation types, or other stratifications, but that are instead dictated by the iso-classification process. In other words, this lets the landscape speak for itself.

Pixels with similar long-term patterns of variability were clustered in classes that often had several separate geographical occurrences. Geographically disjunct regions showing similarity in response is not new. This was also found in a stratification study incorporating MODIS NDVI. That study incorporated a complex of climatic, soil and terrain factors, and was based on a shorter time series of five rather than 25 years (Mackey et al., 2008).

Unsupervised iso-classification based on the main factors governing variability, including distribution of total vegetation response, seasonality, and erratic east-west response, mapped continental arid Australia into 24 classes representing zones with characteristic patterns of vegetation growth. Each zone has a characteristic vegetation response, as extracted from the original AVHRR NDVI time series, and shows class-specific amounts of growth: mean, maximum and minimum amplitude, and regularity and timing of growth pulses. This gives a new and unique insight into previously unknown vegetation functional response in the Australian arid zone. The unsupervised nature of the classification means that the zonation is based on actual vegetation growth, not confined by boundaries or vegetation types.

Other conventional approaches to mapping natural environments use static landscape stratifications such as the IBRA, which are based on biogeographic information, aerial and satellite images and field surveys to characterise the mapping units. Inventory-type field surveys have of necessity focussed on the vegetation species likely to persist after prolonged dry periods, thereby excluding annual or ephemeral plant growth (Heard and Channon, 1997; Kenny, 2008; Kenny and Thompson, 2008). The IBRA strata, as a consequence, provide information on vegetation *structure* and perennial species *composition*. This contrasts with the information on vegetation *function* presented in the new zonation, which comprises perennial and ephemeral growth combined.

#### 5.1.2 *Spatio-temporal dynamics for regional management*

The study aimed to improve monitoring and data interpretation for the AW region. The key factors that govern Australian arid zone vegetation-variability were therefore investigated within the AW region in order to detect their significance for this region.

Chapter 3 shows that the Australia-wide spatio-temporal patterns and key factors that describe variability at continental scale are also applicable within regions relevant to AWNRM management authorities. The aggregated amount of growth, seasonality of growth and erratic growth contribute in various measures to the variability in vegetation response across the AW region. Although only a means of display, the colour composite created from the three main factors proved a very useful tool, to provide managers with an instant qualitative impression of how these key factors are expressed across the AW landscape and the relative magnitude of their influence. This visualisation highlights the landscape-wide heterogeneity of vegetation response patterns across the AW region.

Quantitative information was computed from the NDVI time traces of the four dominant zones in the AW region. The classes were examined in relation to their geographic location, climate, landform and vegetation types, and in relation to current IBRA stratifications. The distinct differences in mean amount of growth, timing, and stronger or weaker seasonal response within these zones provides managers with information about the variation in vegetation functional response across the region, which was previously unavailable and will aid interpretation of monitoring data. Changes can now be interpreted within the context of expected or potential landscape response.

Unexpectedly, and considering the aseasonal nature of the rainfall, the analysis clearly showed seasonal cycles of vegetation response across the entire AW region. The cyclic pattern of low summer and higher winter photosynthesis is evidently driven by factors other than rain. We suggest that variations in temperature, day length and the phenology of some vegetation types are the likely source of this seasonal growth response. In particular temperature would be a strong factor. While rainfall is generally seen as a limiting factor to growth, in this arid landscape where deep rooted perennials have access to water even through dry periods, temperature is also a strongly limiting factor. Shoot growth ceases when temperature increases above a certain level (Specht and Specht, 2002).

Different drivers, such as northern summer rain and southern mallee phenology, may produce long-term growth patterns sufficiently alike for these to be clustered in the same class, as shown in Chapter 3. This underlines that satellite data alone can supply a great deal of information impossible to obtain from field data, but the interpretation of satellite data can be much enhanced by auxiliary regional information, such as climate and vegetation data. It also revealed that separate and apparently disparate regions may potentially be managed in a similar manner, when classification has shown that they exhibit the same long-term variability and temporal patterns of growth.

The erratic east-west response was not expected to be evident in the AW region as the nearest coastline from where cyclonic activity moves inland is more than 1000 km distant, but the analysis revealed that cyclones from the western Australian coast do affect growth on the Nullarbor. The imagery showed that this mainly affected growth in

the Western Australian section of the Nullarbor, and to a lesser extent in the AW Nullarbor region (Appendix E).

This analysis has therefore added important information for managers in the AW region, as Western Australian cyclonic activity needs to be taken into account when interpreting monitoring data collected within the geographic region covered by this class. This finding exemplifies the importance of using information from beyond the management region. The thesis makes a number of further suggestions (Chapter 3) on how the findings of this research can be applied by managers to aid interpretation of monitoring data.

One of the findings of the research was the obvious difference between the new zones, representing active vegetation growth, and the IBRA zones which define vegetation in terms of perennial vegetation structure and composition. It underlined the great variability in this landscape driven by erratic rainfall, seasonal perennial vegetation growth and pulses of ephemeral growth. The vegetation photosynthetic response showed a weaker link to the perennial vegetation component of the IBRA than one might intuitively assume. Boundaries of large IBRA as well as those of the more detailed divisions of sub-IBRA and IBRA associations rarely coincided with the boundaries of the new classes. Exceptions to this occurred where strongly contrasting soil or vegetation types adjoined, such as the calcareous chenopod regions of the Nullarbor adjacent to the red sand and eucalypt-acacia regions of the Great Victoria Desert. Here vegetation response was clearly confined to a particular land form, soil type and/or vegetation community, but this is the exception, and the analysis has shown that growth pulses are noticeably not constrained by the boundaries of perennial vegetation communities, but form their own spatio-temporal patterns. For managers wishing to use remotely sensed imagery for monitoring, it is especially important to be aware that extraction of information using IBRA stratifications, as is the common practice, is not necessarily the best approach. Stratifying the landscape using a zonation based on active vegetation growth patterns may be more effective for monitoring of vegetation growth-related flora and fauna phenomena.

The analysis of long-term NDVI, average variability and seasonality, of the classes presented in this thesis also provides a useful basis for design of future on-ground monitoring. The dates or seasons for field sampling can be chosen with knowledge of

the growth cycle or status of the vegetation. Where the aim is to monitor condition over time it may be desirable to choose “anniversary dates”. Conversely if the intention is to sample as much biodiversity, or as many species, as possible, it may be desirable to survey at different times of the year. The findings of this study can inform and guide these choices.

The research has thus provided information on landscape functional response which allows better interpretation of change observed in monitoring data, regardless of whether such data are obtained in the field or remotely sensed.

### 5.1.3 *Fractional cover imagery for rapid monitoring*

Frequent land condition assessments in the AW region may potentially be achieved through the use of high-temporal-frequency satellite fractional cover imagery. Low-spatial resolution satellite time series have been separated into sub-pixel fractions (as for example by Gill and Phinn (2009), Guerschman et al. (2009), and Okin et al. (2013)). Fractional cover imagery can potentially be used to track land condition indicators such as proportions of vegetation cover and bare soil. Evaluation of such imagery over the region of interest is essential prior to use, but vast distances, logistic difficulties and the high spatio-temporal variability of the arid landscape make this difficult.

The research aimed to evaluate a promising MODIS fractional cover product (Guerschman et al., 2009) in order to assess its suitability for monitoring land condition in the AW region. This evaluation is highly important, because this product is intended to be used Australia-wide, but had not been evaluated for the AW region. Such evaluation is generally performed using field data which are preferably collected at the time of satellite overpass. However, no field data for evaluation of satellite products were available over the AW region, and scarcity of field data generally inhibits evaluation of broad-scale satellite imagery across the wider Australian arid zone.

Field data collection for monitoring has been focused almost solely on areas under grazing lease, where data are periodically collected at specified field points in order to monitor for fodder production and meet legislative requirements. Monitoring in the natural wilderness regions across Australia, by comparison, is in its infancy. Limited inventory-type field survey data are available for the AW region, but field data for evaluation of satellite products are lacking entirely.

Field data collection for calibration and validation of satellite products is currently in progress, but while 90% of effort was targeted at the Australian rangeland zone, budget constraints restricted site selection, and conservation and indigenous protected areas were excluded (Malthus et al., 2013); no sampling sites have been projected for the AW region. This thesis is therefore very timely, as it is urgent that some form of evaluation be devised for this region.

This component of the thesis therefore had two objectives: to create a field-data surrogate from high spatial resolution satellite imagery for use as an evaluation tool; and to use this field-data surrogate to evaluate suitability of the MODIS fractional cover for monitoring land condition indicators in the AW region.

The creation of a field-data proxy from high spatial resolution satellite imagery is a new development for this region, and it adds information to a field that lacks comprehensive research over arid zones world-wide. Here (Chapter 4; Lawley et al. (2014)) we used the phenomenon that vegetation reflectance is consistently lower than bare soil reflectance in arid bright-soil areas under dry conditions (Barnsley et al., 2000; Graetz and Gentle, 1982; Pech et al., 1986; Ringrose and Matheson, 1987). We used this to create an extensive and spatially comprehensive surrogate for field data. Albedo thresholds in high-spatial resolution ALOS PRISM data separated vegetation cover and bare soil in twenty sampling areas of approximately 850 km<sup>2</sup> each. These cover a wide variety of landform and vegetation types across the AW region. Satellite data here clearly offer an advantage over field-based data, as collecting data over such vast, widely dispersed regions is not practicably achievable through field campaigns.

The difficulty of determining a threshold value in the ALOS PRISM imagery was resolved by the novel and simple but effective technique of using the reflectance values of minor unpaved roads as guide to separate exposed soil from vegetation cover. While this method can be challenged on grounds that these thresholds cannot be validated with *in situ* data, confidence in the method arose from previous investigations that used field sampling to evaluate separation between bare soil and vegetation cover in a comparable range of the electromagnetic spectrum e.g. Graetz and Gentle (1982). Furthermore the evaluation date was pinpointed after an eight month period of negligible rain, therefore at the time of satellite overpass senesced grasses, which might be bright when freshly dried, had likely dulled or disintegrated. All cover in the landscape is therefore surmised

to have lower reflectance than the bright soils of the Australian arid zone. While this method may benefit from refinement, it has shown a method of evaluation especially useful where field-data collection is problematic, with the added advantage that it provides comprehensive coverage, rather than point-based data only.

Evaluation of the MODIS bare soil fraction using the ALOS PRISM proxy bare soil percentages revealed that MODIS fractional cover performs slightly better in areas of higher vegetation cover, but correlation between the MODIS fractions and field-surrogate estimates was overall very low, and over some regions such as the desert sand dune areas no correlation was detected. Based on this assessment the MODIS fractional cover product appears to be not well suited for use over the AW region.

Reasons for such low correlation are explored in Chapter 4, in order to find directions to improve or develop MODIS fractional products for regional use. It is suggested that some of the low correlation arises from internal noise in the MODIS fractional cover time series, possibly propagated from the MODIS time series on which the fractional cover is based. The extremely dry circumstances and invariant landscape presented a unique opportunity to test this, using two sequential 8-day overlapping MODIS fractional cover images. This pointed to relatively high noise in the MODIS fractional cover series, which is of interest to those assessing potential errors affecting the fractional cover estimates (Malthus et al., 2013), and important to know for monitoring, because subtle vegetation change may be swamped by internal noise in the time series, with only major on-ground change detectable in the fractional cover imagery.

MODIS fractional cover appears to perform better as vegetation cover increases. This may be explained by the fact that one of the fractions is based on NDVI. Conversely where vegetation is very sparse, and there is little photosynthetic activity, NDVI is very low and hence MODIS reflectance has very low spectral dimensionality, resulting in two dimensional rather than three dimensional data, and differences in soil colour being detected rather than the differences between soil and cover.

Even though there was no positive indication to use MODIS fractional cover in its current form for monitoring the AW region, the thesis has added an important aspect to the evaluation of fractional cover satellite products over arid wilderness regions. The MODIS fractional product may be improved, or the development of new products may



be aided by these findings, which in turn will be of further benefit for monitoring of the AW region.

#### 5.1.4 *Summary*

The purpose of this research was to improve land condition monitoring for the AW region using remote sensing. The study confirmed that remote sensing clearly has much to offer for environmental monitoring. In particular satellite-based imaging delivers spatially-comprehensive and frequently repeated coverage, acquired over wide regions of interest, and archived over long periods of time.

In this study several forms of satellite imagery and a variety of analyses were used to reveal previously unknown environmental information and enhance land condition monitoring.

- Satellite imagery of low-spatial resolution and high-temporal frequency was used, to show spatio-temporal dynamics of long-term vegetation growth at continental and regional scales.
- Fractional cover satellite imagery of low-spatial resolution, and high-temporal frequency was evaluated for regional use.
- Single-date satellite imagery of high-spatial resolution, was used to create a field-data surrogate to effect this evaluation.

The methods used in this thesis can be applied more widely and may inspire further investigation of the high-biodiversity wilderness areas of Australia that are under risk of environmental deterioration, such as the AW region. Land condition in these regions needs careful management, and close and frequent monitoring. The thesis demonstrated that the spatially explicit and comprehensive land surface information supplied by satellite imagery can form the basis for extensive and intensive assessment of such arid zone landscapes.

## **5.2 Recommendations for future research**

We suggest that further investigation be directed towards improvement of the satellite field-data proxy as evaluation tool. While the surrogate developed here was confined to the immediately available data (ALOS PRISM), the method can be applied to other data. Exciting possibilities present themselves with the development and launch of new satellite-mounted sensors that acquire data suitable for environmental observation.

Using such data to create field-surrogates in order to replace, or support, field data collection should be a high priority. Alternately high- and very-high spatial resolution data from aerial missions may provide a suitable field-surrogate, which itself could be calibrated by field spot-checks at the time of overpass.

Recently developed Landsat-based information products for Australia are now available online through the Terrestrial Ecosystem Research Network (TERN) portal <sup>4</sup>. Comparison of the finding in this thesis with these products may lead to further insights for the AW region. The spatio-temporal patterns of long-term variability in Chapter 2, could be tested against the Dynamic Land Cover Dataset (Lymburner et al., 2013), to detect where the dynamics are in agreement. With regard to fractional cover monitoring, although we could not show strong positive correlation between the MODIS fractions and the high-spatial resolution bare soil proxy, the study revealed new and important information. Our findings suggest that higher vegetated areas correlate better; therefore an algorithm for monitoring that incorporates NDVI will not perform well when vegetation cover is low, or where cover is moderately high but vegetation photosynthetic activity is low, as in the AW region. Algorithms need to be developed especially for these regions where photosynthesis of perennial vegetation is minimal during dry periods. NDVI has been such a useful index for vegetation monitoring that it is difficult to set aside its use, but in these regions using NDVI to separate vegetation fractions from exposed soil is contra-indicated. This suggests that using albedo to monitor soil exposure in these regions may be more successful and MODIS albedo imagery needs to be investigated for high-temporal frequency monitoring of land condition over the AW region.

Finally we suggest that remote sensing and particularly satellite remote sensing become an essential component for environmental monitoring over these remote but ecologically and environmentally highly valuable arid regions. This study has given an entirely new perspective of the AW landscape, which is made possible through remote sensing, revealing the vegetation functional response and thereby improving the ability for managers to differentiate between environmental degradation and the natural variability inherent in the landscape.

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<sup>4</sup> <http://data.auscover.org.au/data/product-list>

This research is of particular importance for high-biodiversity wilderness areas of Australia that are under risk of degradation, such as the Alinytjara Wilurara region, but the principles used in the study can be applied to land condition monitoring in arid zone regions worldwide. These regions need careful management to maintain land condition, supported by widespread and frequent monitoring. The thesis demonstrates that the spatially explicit and comprehensive land surface information supplied by satellite imagery can form the basis for extensive and intensive assessment of such arid zone landscapes.



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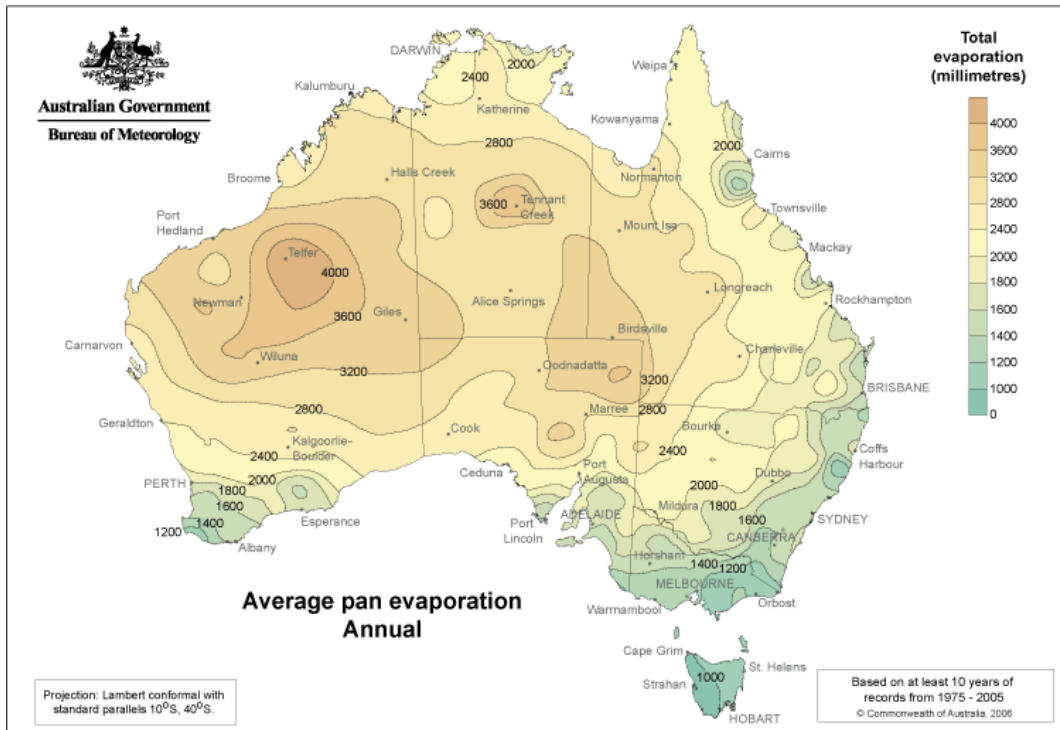
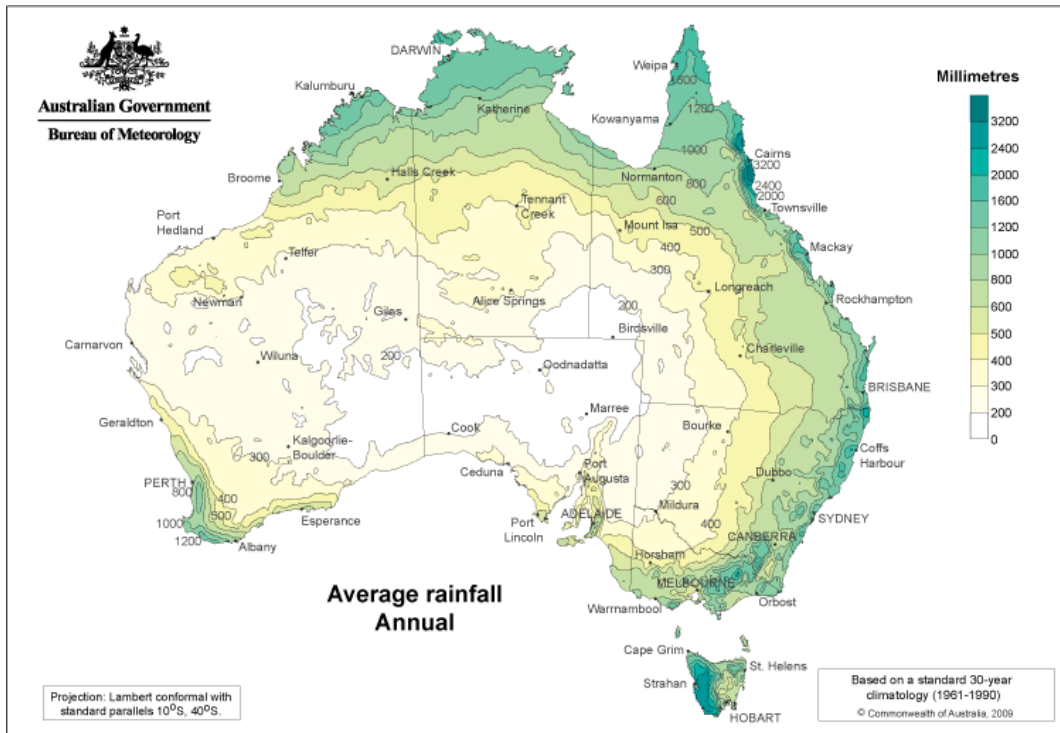


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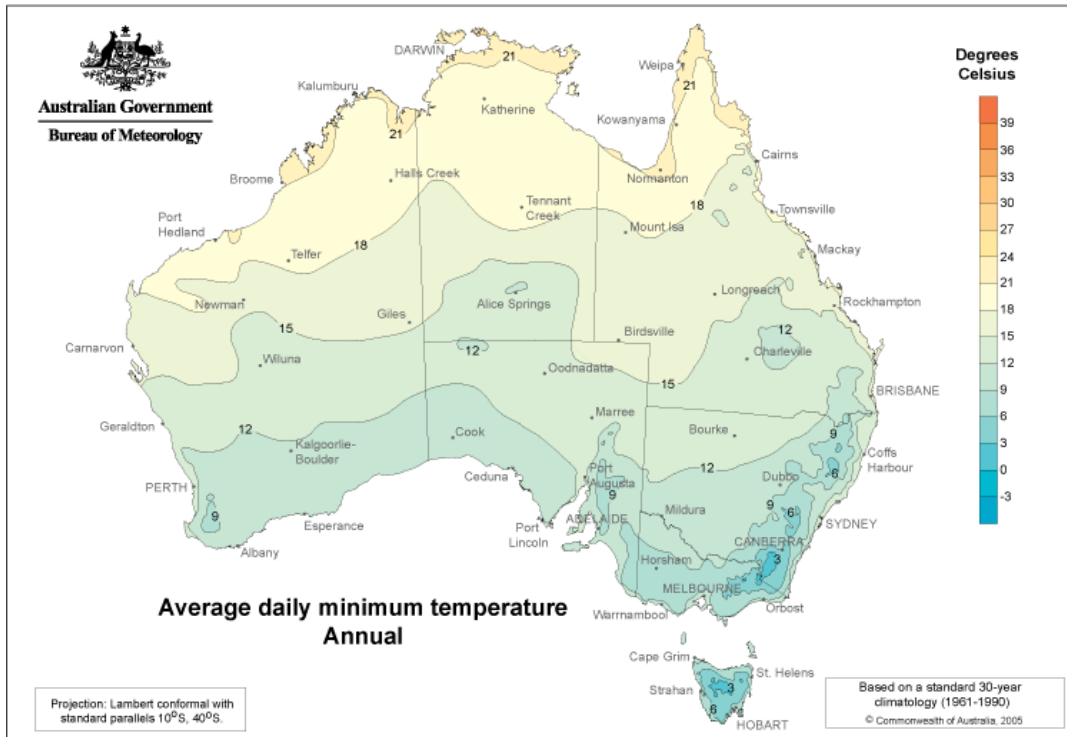
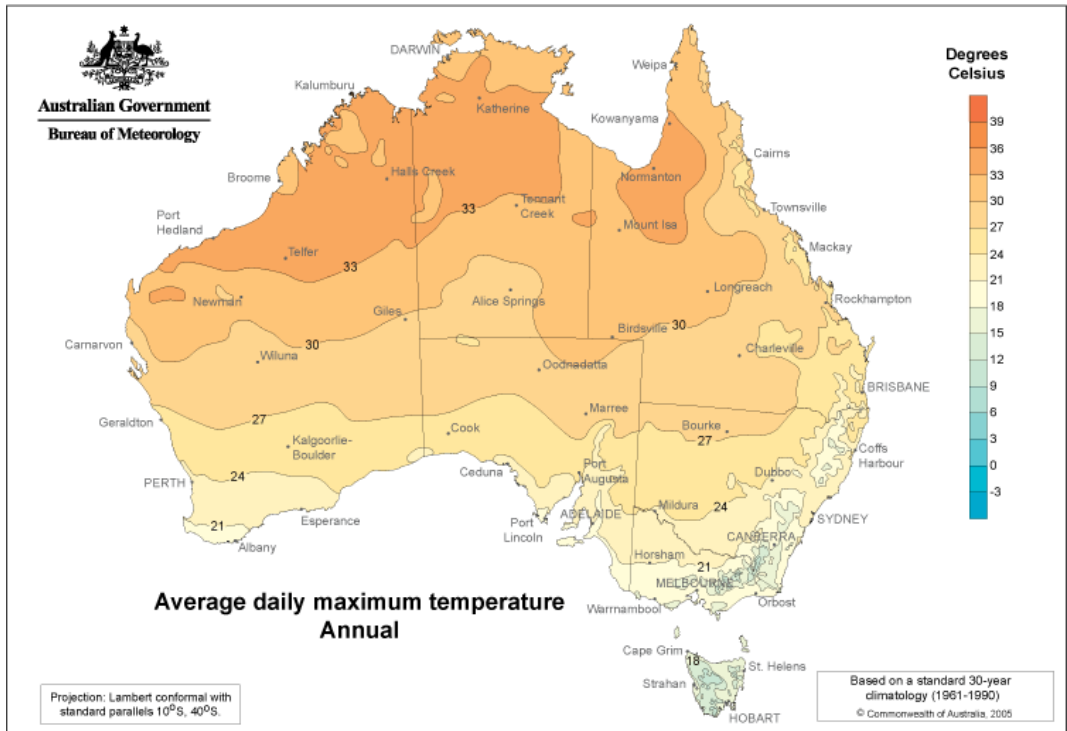
# APPENDICES

## Appendix A. Average annual rainfall and pan evaporation.





**Appendix B. Average daily annual maximum and minimum temperature.**





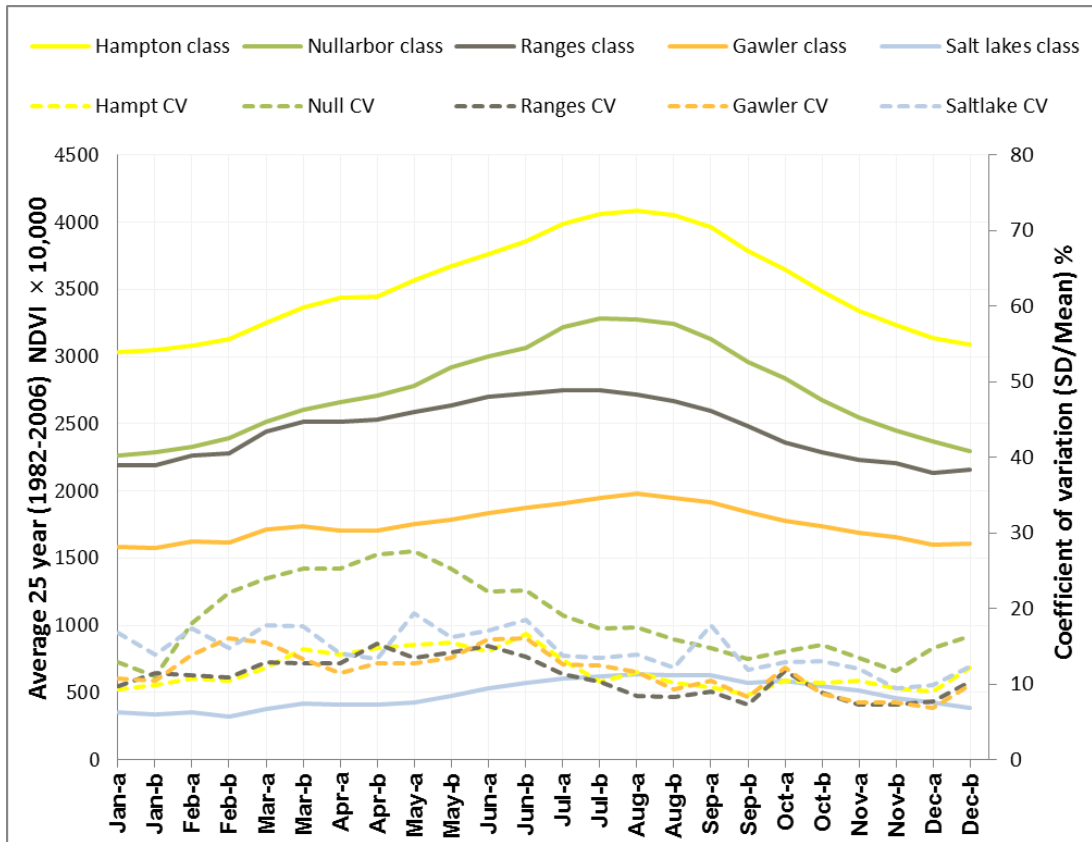
### Appendix C. Satellite imagery used in the study

<i>Satellite parameters</i>	<i>Bands</i>	<i>NOAA AVHRR</i>	<i>EOS -MODIS (bands for vegetation)</i>	<i>ALOS PRISM</i>
Launch dates		(1) Oct 1978, 4 band; (2) Jun 1981, 5 band; (3) May 2005, 6 band	Dec 1999 (Terra) May 2002 (Aqua)	24-Jan-06
Ground sampling interval		1.1 km	250 m Bnd 1 - 2 (Terrestrial) 500 m Bnd 3 - 7 (Terrestrial) 1000 m Bnd 8 - 36 (Water, atmosphere, cloud)	2.5 m (panchromatic)
Swath width		2399 km	2330 km	35 km
Equatorial crossing		2:00 pm, 2:30 pm	10:30 am desc., 1:30 pm asc.	~ 10:30 am
Repeat cycle		2 per day	1 -2 per day	46 days
Sensors		several incl. AVHRR	MODIS	PRISM
band, width	blue		3, 0.459 - 0.479 $\mu\text{m}$	
band, width	green		4, 0.545 - 0.565 $\mu\text{m}$	
band, width	red	1, 0.58 - 0.68 $\mu\text{m}$	1, 0.620 - 0.670 $\mu\text{m}$	0.52 - 0.77 $\mu\text{m}$
band, width	NIR	2, 0.725 - 1.00 $\mu\text{m}$	2, 0.841 - 0.876 $\mu\text{m}$	
band, width	NIR		5, 1.230 - 1.250 $\mu\text{m}$	
band, width	SWIR	3a, 1.58 - 1.64 $\mu\text{m}$	6, 1.628 - 1.652 $\mu\text{m}$	
band, width	SWIR	3b 3.55 - 3.93 $\mu\text{m}$	7, 2.105 - 2.155 $\mu\text{m}$	
band, width	Thermal	4, 10.30 - 11.30 $\mu\text{m}$		
band, width	Thermal	5, 11.55 - 12.50 $\mu\text{m}$		





## Appendix D. Minor classes average 25 year NDVI



NDVI averaged over 25 years at twice monthly intervals for each minor class (Nullarbor, Hampton, Gawler and Salt lakes). The Ranges class is shown for comparison. Variability for each date is shown by the coefficient of variation (CV, dashed lines). Major classes are displayed in figure 3.5.



## Appendix E. Tropical cyclone paths onto the Nullarbor

Tropical cyclone paths that encroached onto the Western Australian Nullarbor from 1982 – 2006.

<i>Name of tropical cyclone</i>	<i>End date</i>	<i>Approximate direction from</i>
Lindsay	March 1985	North northwest
Billy	May 1986	West
Connie	January 1987	Northwest
Orson	April 1989	West
Annette	December 1994	Northwest
Kristy	March 1996	Northwest
Olivia	April 1996	Northwest
Vance	March 1999	West northwest

Records obtained from:

<http://www.bom.gov.au/cyclone/climatology/wa.shtml>

NB: No tropical cyclones were recorded entering the Nullarbor region from 2000-2006.

