Exploring Remote Sensing and Geographic Information Systems Technologies to Understand Vegetation Changes in Response to Land Management Practices at Finke Gorge National Park, Australia Between 1989 and 1999

by

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This thesis is dedicated to every scientist whose imagination and creativity were standardized in a test, labelled, and placed in a symmetrical box; there is always time to open the box.

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List of Abbreviations

BOM	Bureau of Meteorology
BTEC	Brucellosis and Tuberculosis Eradication Programme
DN	Digital Number
ENSO	El Niño - Southern Oscillation
ERTS	Earth Resources Technology Satellite
FGNP	Finke Gorge National Park
GIS	Geographic information system
IBRA	interim biogeographic regionalisation for Australia
JRSRP	Joint Remote Sensing Research Program
LULC	Land Use and Land Cover
LVMP	Long-term Vegetation Management Project
NASA	National Aeronautics and Space Administration
NT	Northern Territory
PC	principal Components
PCA	Principal Components Analysis
RMSE	Root-Mean-Square Error
RS	Remote Sensing
SSI	Spatial Sciences Institute
TERN	Terrestrial Ecosystem Research Network
TM	Thematic Mapper
USC	University of Southern California
WWF	World Wildlife Fund

Abstract

This project aims to increase knowledge of vegetation changes in arid and semi-arid areas in central Australia. Most of these zones are located across remote, sparsely-populated, large and geographically diverse regions, making them difficult to study (Burns et al., 2014). Satellite imagery and geographic information systems (GIS) are viable options to decrease the knowledge gap in time- and cost-effective ways and to understand how vegetation changes in areas with atypical annual seasons. The main goal of this thesis is to use modern techniques to understand vegetation dynamics occurring during 1989 – 1999 in Finke Gorge National Park (FGNP). During this time, land managers placed a fence around some park boundaries and removed a significant number of wild horses to enable the vulnerable vegetation to recover. An ensuing eight-year field study observed and documented changes. This thesis intends to do the same, using remote sensing (RS) and GIS techniques. A supervised classification of soils and plants is done using data collected during field surveys. Principal components analysis (PCA), a data reduction technique, is used on multitemporal images to enhance continuous spatial and temporal changes and to extract factors that can be attributed to land management efforts at FGNP. Visual interpretation of components and analysis of classification information allowed for exploration of vegetation dynamics at an appropriate spatial and temporal resolution to understand variation and trends across time. The resulting components are compared to results of previous field surveys conducted at the time. The principal components indicate there are natural and human-derived sources of variation. Rainfall and other environmental factors play a major role on vegetation recovery of areas inside the fence, however, components also indicate that other sources of variation, such as land management practices conducted in the area, are contributors to variation. The field survey results are comparable to the thesis results; however, modern technique use provides a different perspective of trends and variation.

1 Introduction

An increasing number of areas in arid and semi-arid central Australia have been identified as culturally and ecologically significant, requiring detailed information about how their condition is changing through time. Most of these sites are located across remote, sparsely-populated, large and geographically diverse regions, making them difficult to study (Burns et al., 2014). Australia's government has recognized the importance of a healthy environment to maintain its way of life and has developed, and successfully implemented, several management policies at national, regional and local levels to understand vegetation changes, protect the land and conserve existing natural resources (Department of the Environment and Energy, 2016).

In arid central Australia, multiple forms of human-induced disturbance influence the structure and composition of endemic vegetation (Bradshaw, 2012). Some land management options are readily devised and implemented (e.g. fences for eroded areas, feral herbivore culls to reduce over-grazing, and management burning to minimize the risk of uniformly-severe wildfire). Management-related trends are difficult to distinguish due to central Australia's extremely variable climate (Bastin et al., 2012). The effects of these human-introduced factors can be measured and partially quantified, but no one factor works in isolation. For example, vegetation responses to rainfall are known to differ according to season, implicating factors such as temperature and day length, as well as available plant soil moisture *per se*. Further, negative trends such as an increase in bare soil may result from drought, over-grazing, increased fire or a combination of all factors. Thus, temporal vegetation trends need to be examined in the context of the prevailing climate and disturbance regimes, and at appropriate spatial and temporal scales.

To thoroughly understand landscape changes and the effectiveness of land management efforts, multiple factors must be simultaneously considered, making remote sensing (RS) and geographic information systems (GIS) valuable technologies to use. Further, Principal Components Analysis (PCA) is a technique typically used to compress data from a large number of variables to a smaller set, effectively reducing redundancy, minimizing data loss and maximizing variation between variables. The application of this technique seems a good fit for digital image processing and geographic time-series analysis. Notably, however, the technique to date has been applied to a limited set of study systems, and its potential is therefore under-explored.

Townshend, Goff, and Tucker (1985) for example, used PCA as an exploratory tool to understand the relationships between multitemporal images in the continents of Africa and North America. A decade later, Piwowar and Ledrew (1995) discussed PCA as one of three useful techniques for hypertemporal image analysis to identify connections between variables and to identify redundancy. In a contemporary study, Piwowar (1996) used PCA to isolate temporal and spatial variations to identify patterns in ice concentration over a nine-year time-series. Most recently, Henderson (2010) used PCA to understand vegetation productivity changes and normal variation in areas of Grasslands National Park, Saskatchewan, Canada. To summarise their contribution, these studies were successful in defining spatial and temporal localized anomalies and highlighting the predictive capacity of the technique in relation to landscape changes across a diverse set of landscapes in the continents of Africa, North America and the Arctic. It is possible therefore, that PCA as applied to a set of time-series RS images will be similarly useful for exploring patterns of vegetation change in remote and isolated areas of Australia.

1.1 Thesis Evolution and Research Design

A vegetation monitoring project, known as the Long-Term Vegetation Management Project (LVMP), was conducted in central Australia in the 1990's to assess changes after land management efforts. This project monitored Finke Gorge National Park (FGNP), Northern Territory (NT) and occurred between 1991 and 1998. The LVMP documented the vegetation response in the years after large, grazing animals (mainly feral horses) were removed from the FGNP and a fence was placed around some of the boundaries to minimise further incursion. The intention of these land management efforts was to aid the recovery of native vegetation at this important site (Low, Foster, and Berman, 1991). One main objective of the survey was to document long-term vegetation response to these specific efforts, inside and outside of the fence (Low, Foster, and Berman, 1991). During that time, satellite images were not readily available and GIS tools were not specialized, nor accessible enough, to conduct advanced analysis or calculations (Low, 2016).

After examining the survey documents and reports available, including an extensive photographic record of each site inside and outside of the park boundaries, the LVMP was selected as a model case-study for the thesis, using similar scope, spatial and temporal scales. In this thesis, however, GIS techniques and RS image composites collected over the park in the 1990's are used. The availability of the field survey documentation allows: (1) the establishment of a baseline of how the area looked in 1991 and changed during that decade; to (2) compare and validate the results from this analysis with the conclusions from the field survey, to (3) evaluate the efficacy modern remote imagery techniques as a low-cost alternative to field surveys by way of evaluating land management practices; and to (4) assess changes in central Australian remote arid zones using GIS techniques and satellite imagery, beyond that which the field survey could provide. Overall, the aim is to use modern techniques (RS and GIS components) to evaluate vegetation responses to land management at FGNP during the same time frame as the long-term vegetation field survey in the 1990's. Although other studies have used PCA to explore changes in vegetation cover, the technique has not been applied to central Australian landscapes. This region is marked by highly variable and unpredictable inter-annual rainfall patterns (Box et al., 2008), introducing a level of complexity not found in many other arid areas.

The potentially confounding effects of environmental (viz climate, atmospheric CO2, wildfire) and anthropogenic (specifically feral herbivore herbage offtake, soil impacts, etc) factors at FGNP is acknowledged from the outset of this study. Specifically, increasing shrub cover through time may result from changed rainfall, decreased browsing or both. This makes the task of assessing the efficacy of land management implementation somewhat challenging. This was motivation to attempt to identify contributing factors, underlying variations and their sources, and to quantify them. PCA was used to partition the influencing factors, to distinguish the sources of variation, and to explore and summarize temporal and spatial change within the park. Time-series image analysis, also referred to in the literature as hypertemporal or multitemporal image analysis, is the basis to represent each component resulting from the PCA. For instance, healthy and well managed areas may fail to respond due to seedbank loss, top-soil loss and/or excessive runoff, while degraded sites may instead exhibit a pronounced response to well-above-average rainfall. This means that short-term changes that are detected by remote imagery need to be understood within a longer temporal context.

To address the above issues, it was best to use seasonal fractional vegetation cover (SFVC) digital composites derived from geometrically and radiometrically corrected Landsat images, between 1989 to 1999. Each composite represents the summary of land cover over a three-month period and each pixel represents the percentage of cover of three continuous values: bare ground, living vegetation and dry vegetation. The images were clipped to include FGNP and surrounding areas. Out of the possible 40 composites (one for each season over a 10-year period), only 27 displayed complete, cloud-free images of the park and were suitable for use. The method used in this thesis is sensitive to missing data, and the exclusion of incomplete images was a better option than their inclusion.

A supervised classification was completed for soil and vegetation using data from the surveys as training samples. The classification method allows for decomposition and the labelling of vegetation cover and soil units. The two classified maps were combined to make a soil /vegetation map. A total of 16 classes were derived from this classification. Charts for each class were constructed, resulting in an analysis of the vegetation and soil classes over time.

Following the classification, a PCA was performed on all the SFVC composites. The resulting principal components (PC), as well as the information from the classification, were used to explore spatial and temporal localized anomalies, based on knowledge of vegetation composition and soil units. The use of time-series composites, versus a two-image analysis, helped explain the response and variability of the vegetation community within the park at a more appropriate time scale. This is a more gradual approach to land cover change analysis because it considers all the changes that occur internally. The results of this project can provide data to facilitate more efficient implementation of land management practices in vulnerable and threatened bioregions.

1.2 Definition of Research Question and Project Stages

It is crucial to recognize the complexity and interdependence of all factors affecting the vegetation communities in arid zones before enforcing a land management plan or determining its success. This thesis presents an opportunity to use existing techniques and technologies to: understand changes in vegetation in an area that has been observed and well-documented, their connection to land management practices and to each other, as well as the opportunity to use them as an exploratory technique.

The research question in this thesis was: *Can similar vegetation changes be identified at FGNP using modern techniques, as they were identified during the field survey in the 1990's?* Specific objectives were:

- To evaluate the use of principal components analysis as a suitable technique to understand sources of variation through time
- To determine which areas had the most and least variability in and around FGNP
- To assess the suitability of Landsat imagery temporal resolution from 1989 to 1999
- To correlate droughts and rainfall events with significant vegetation changes
- To compare the thesis findings to the findings of LVMP conducted in the area at the time

FGNP and surrounding areas encompass the spatial scale of this thesis.

The temporal scale is between 1989 and 1999, including the years when the Long-Term Vegetation Management Project took place.

2 Literature Review and Related Work

Chapter 2 discusses where this thesis exists among other work. Section 2.1 discusses early history of RS and GIS with a focus on Landsat use in arid zones, and what others have done to study these areas. Section 2.2 examines Australian arid rangelands and the NT in terms of environmental and land management factors. It describes the interim biogeographic regionalisation for Australia (IBRA) framework, used to manage resources. Section 2.3 describes FGNP in detail, since it was established and presents main issues the vegetation in the park has endured, and the efforts by land managers and ecologists to understand the area and preserve. This section includes detailed explanation of the long-term vegetation management project. Section 2.4 touches on the use of RS and GIS in arid zones to monitor and manage natural resources, to include change detection methods. Section 2.5 presents the possibility that a mathematical technique such as PCA can provide information about the localized variations in the area, to improve the understanding of complex processes, as well as vegetation response to land management. RS, GIS, vegetation cover, overgrazing, invasive species, land management, sources of variation and arid zones are topics contributing to the research question for this thesis and the topics driving the literature review.

2.1 Early Remote Sensing

In December 1968, the crew of the Apollo 8 took and shared a remarkable colour image of the Earth rising over the moon, known as Earthrise (Kluger, 2013) shown in Figure 1. It is argued that this image, revealing a solitary, brightly-coloured sphere rising over the ashy lunar landscape, inspired a new global perspective that set-in motion the environmental movement as a response to furthermore understand our planet (Kluger, 2013). By the time Earthrise made headlines, National Aeronautics and Space Administration (NASA) was well into the development of the Landsat program, originally called Earth Resources Technology Satellite (ERTS) program.

Figure 1 Earthrise photograph by William A. Anders, December 24, 1968 from Apollo 8.

The Landsat program was a RS satellite effort inspired by the early Moon-bound Apollo missions, where pictures of Earth's land surface were taken for the first time (NASA, 2017). The experimental program had as a main purpose to study and monitor Earth landmasses and its resources (NASA, 2017). In 1970, the Landsat program was officially approved and in 1972 the first of its satellites, Landsat 1, was launched into orbit around the Earth (NASA, 2017). Digital images from satellite sensors were preferred over aerial photographs because they could be processed with computers, automatically enhanced, required less manual processing, cover a larger area, and ultimately were more cost effective (Woodcock, Strahler, and Franklin, 1983.)

By 1974, the British Antarctic Survey used Landsat images to create and publish several maps of Antarctica at the fraction of the cost (Fischer, Hemphill, and Kover, 1976). Story, Yapp, and Dunn (1976) used Landsat imagery to successfully recreate about half of the patterns in topographic maps of central Australia that had been conventionally surveyed between 1956 and 1957.

Over the following decades, largely due to Landsat's success in providing quality imagery of all land surface, a realization that Earth's resources are finite ensued, highlighting the importance of careful resource management with the aid of new technology (Strahler, Woodcock, and Smith, 1986). GIS were concurrently developed as a complementary technology to RS where spatially-referenced images were stored, processed, retrieved, and displayed (Woodcock, Strahler, and Franklin, 1983.) As RS and GIS technologies improved, satellite images, processing software and data analysis became increasingly available to the public and, naturally, their application to previously hard-to-access, arid areas increased exponentially.

Prior to satellite digital imagery becoming accessible to the public, ground and aerial photography was used to derive topographic, soil, vegetation, and environmental geology maps, and was most useful to monitor surface conditions and land management planning (Woodcock, Strahler, and Franklin, 1983.) Field surveys also served to collect data in remote or inaccessible areas, however they lacked the temporal scale necessary to represent the dynamics of the study area. Remotely sensed digital images are collected at large spatial scales and small enough temporal scales to detect slower processes (Tueller, 1987). The ability of using RS and GIS for image and data processing over large areas, without costly and time-consuming aerial photography or field surveys is a significant advantage to land management efforts, especially in arid, remote or scarcely populated zones.

2.2 Australian Arid Rangelands

The island continent of Australia covers an area of 7.69 million square kilometres with a coastline almost 60,000 kilometres long (Geoscience Australia, 2016) and population of under 23.5 million, as of 2014 (Australian Bureau of Statistics, 2016). Arid rangelands make up 70% of the continent, including arid and semi-arid inland areas (Smyth and James, 2004). This thesis is concerned with those regions, referred to as central Australia hereafter.

Thackway and Cresswell (1995) described an interim biogeographic regionalisation for Australia (IBRA) to establish common criteria for the conservation and management of biodiversity. A number of regions were classified as distinct ecosystems, or ecoregions, based on biogeographic regionalisation, geology, geomorphology, climate, present and natural vegetation, and biogeographic knowledge about flora and fauna (Thackway and Cresswell, 1995). The boundaries of bioregions and sub-bioregions, delineated as IBRAs, fluctuate as they are updated when protected areas are identified (Department of the Environment and Energy, 2017). IBRAs are not exactly bound by the limits on a map, but they are geographically distinct with common characteristics such as climate, ecology, and geology (Department of the Environment and Energy, 2017). Figure 2 shows the most recent IBRA boundaries. Desert and Xeric Shrublands (in beige) is the dominating ecoregion in central Australia, where FGNP is located. This ecoregion is further classified into smaller bioregions, and even smaller eco-regions.

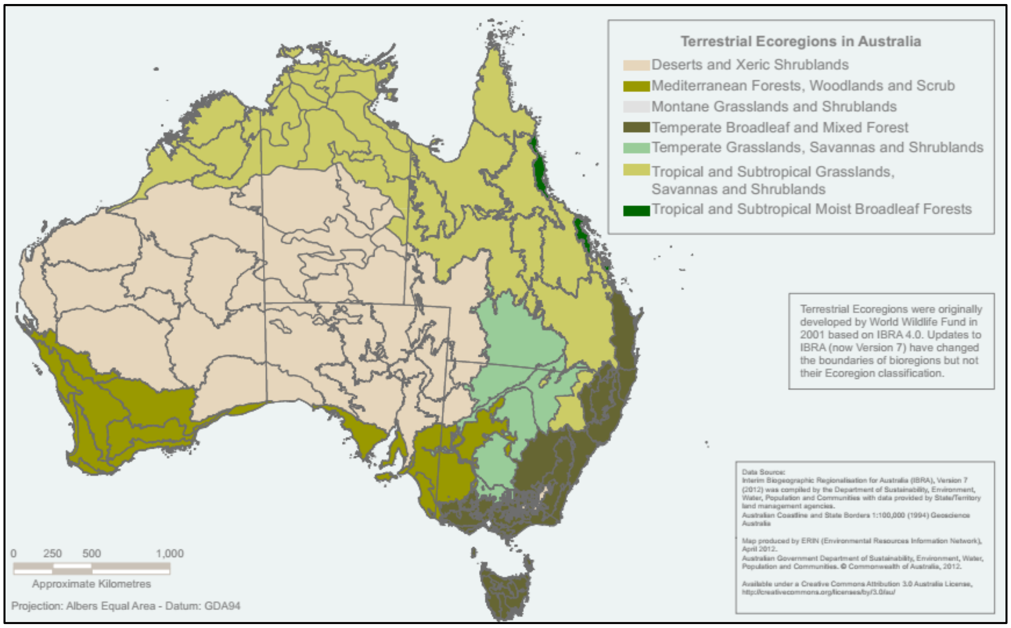


Figure 2 Map depicting IBRA boundaries in Australia. *Source*: Department of the Environment and Energy, 2017

The words ‘ecoregion’ and ‘bioregion’ seem to have a similar meaning in the literature found; ‘ecoregion’ is used by the World Wildlife Fund (WWF) to refer to distinct flora, fauna and environmental conditions within a geographical area, whilst ‘bioregion’ is used by the Department of the Environment and Energy in Australia to describe the same concept, as well as common geology. Bioregions place loose boundaries around areas with similar characteristics, whereas ecoregions describe the life and conditions within these dynamic boundaries. These two similar, yet different, categorizations are a significant point to mention because they reflect the complications in depicting a dynamic environment in a static form and the difficulties in managing these areas. Further complications arise when bioregions or ecoregions change, requiring quick and deliberate changes to management plans.

2.2.1 Central Australia

Central Australia encompasses more than 175,000 sq. km, including FGNP. Its dominating ecoregion, as well as for the NT, is Deserts and Xeric Shrublands (Department of the Environment and Energy, 2017) (Figure 2). These habitats are generally characterized by extreme temperatures, with evaporation exceeding rainfall, although each bioregion within is distinctly classified (WWF, 2016).

The NT has an area of 1.35 million sq. km, equivalent to twice the size of Texas, and a population of 200,000 (Australian Bureau of Statistics, 2016). Having such low population density, the territory does not experience the same rates of urbanization or over-population as coastal regions in Australia, resulting in advantages and disadvantages, ecologically speaking. An advantage is that natural processes and resources are generally not under great pressure, and human interaction with vegetation and wildlife is relatively low. In this respect, an area can be studied without placing much weight on complex human variables. However, large and scarcely populated areas tend to not be monitored frequently (Burns et al., 2014) and issues affecting ecosystems can go unnoticed for extended periods of time.

The MacDonnell Ranges bioregion, with an area of 39,290 square kilometres, is described as high relief ranges and foothills covered with spinifex hummock grassland, sparse acacia shrublands and woodlands along watercourses (Thackway and Cresswell, 1995). Figure 3 shows that the bioregion is further divided into three smaller sub-bioregions (Hartz Range, MacDonnell and Watarrka), to provide a more detailed description of the landscape (Department of the Environment and Energy, 2017). FGNP is within the boundaries of the Watarrka sub-bioregion (Department of the Environment and Energy, 2017). The specified boundaries support administration and protection efforts in the area. However, it is understood that the processes that affect, and are affected by, ecological factors may not have defined boundaries. Each of these political, geographical and ecoregion boundaries influence FGNP in the way the park is used, conserved, and managed. Research and surveys on land management effects aim to increase the knowledge and understanding of complex ecological systems.

Figure 3 MacDonnell Ranges bioregion an its three subregions. *Source*: Department of the Environment and Energy, 2017

2.2.1.1 Climate and Vegetation

The climate in Australia's rangelands is exceedingly variable and unpredictable, with several high rainfall events occurring in one year followed by several years without any rain (Morton et al., 2011). Consequently, regional-scale biological dynamics are tightly structured by a direct relationship between sporadic, large rainfall events and pulses of plant growth and reproduction (Morton et al., 2011; Smyth and James, 2004). This relation motivates the abrupt, and often striking transformation of usually red-brown landscapes into green areas through the arid Australian centre (Wardle, Pavey, and Dickman, 2013).

Figures 4a and 4b show hills at Heavitree Gap in Alice Springs, east of FGNP. Both pictures were taken mid-February, towards the end of the summer. Figure 4a was taken in February 2013, during a dry summer. Figure 4b was taken in February 2017 after an unusually wet year. In many places, vegetation follows a predictable pattern of growth, however, central Australia's rainfall patterns are unpredictable and variable leaving a stark contrast between these two photographs taken almost four years apart.

Figure 4a Hill at Heavitree Gap February 2013. *Photo credit*: Adlin Botkin

Figure 4b Hill at Heavitree Gap February 2017. *Photo credit*: Adlin Botkin

Quick vegetation growth followed by long periods of drought can also increase the fire fuel load, affecting the frequency, intensity and extent of bushfires (Griffin and Friedel, 1984). Domestic and feral large animals have also placed pressure by significantly overgrazing areas, thus displacing native perennial grasses and palatable shrubs (Smyth and James, 2004), and degrading and eroding areas that serve as habitat to smaller animals (Morton et al., 2011).

Central Australia's deserts and xeric shrublands, inclusive of FGNP and its surroundings, are climatically dominated by high variability, generally very low rainfall, prolonged droughts, and marked by occasional periods of high rainfall. Vegetation change monitoring requires the consideration of the inconsistent and erratic rainfall patterns that mark the area (Amiraslani and Dragovich, 2013). While the wet to dry seasons can be described as somewhat cyclical, the cycles are irregular and can take decades to complete. Temperatures routinely exceed 40° Celsius for most the summer and below freezing in the winter (Box, 2014-2016). Many plant species remain dormant during periods of drought and harsh conditions, but become very active during the infrequent rain episodes (Nano, 2014-2016). Field surveys conducted during droughts can give the impression that few species live in the area. However, after periods of heavy rainfall it is not uncommon for botanists and wildlife biologists to express surprise at the reappearance of species presumed to be extinct from the region (Box, 2014-2016).

When areas are designated as vulnerable, land managers proceed with conservation efforts. Management-related trends are difficult to distinguish due to central Australia's exceedingly irregular climate (Bastin et al., 2012). There may also be a substantial lag between land management action and observable events in the region. For example, conservation measures conducted during a dry period may not produce observable effects until several years later when the next significant rainfall event occurs. So, it can be very difficult to correlate ecosystem conditions with land management decisions, even when detailed records exist.

2.3 Finke Gorge National Park

FGNP is located 138 kilometres west of Alice Springs, near the geographical centre of Australia, and occupies an area of 42,253 hectares of arid rangelands, shrublands and desert in the NT (Figure 5a and 5b). The park contains a wide range of land forms, flora, fauna, cultural and recreational areas. It is home to the rare and endangered Red Cabbage Palm (Livistona Mariae), Western Arrernte people sacred sites and the Finke River, thought to be one of the oldest rivers in the world sites (Parks and Wildlife Commission, 2011).

(5a)

(5b)

Figure 5a Finke Gorge National Park is located near the geographic centre of Australia. *Photo credit*: Adlin Botkin. Figure 5b FGNP signage. *Photo credit*: Adlin Botkin

The first portions of the park were proclaimed a conservation reserve (Parks and Wildlife Commission, 2011) in 1966 after Henbury Station, a private cattle operation, and the Finke River Mission in Hermannsburg (Parks and Wildlife Commission, 2011) surrendered the lands to the

NT. The landscape was over-grazed and eroded for years prior to the incorporation of the park. The FGNP was established in 1978 and more land portions were subsequently included. The boundaries of FGNP, as we know them today, were officially recognized in 2004 (Parks and Wildlife Commission, 2011). Since 2011, the park has been jointly managed between Arrernte Traditional Owners and the NT Government, and recognized as being ecologically and culturally important. FGNP and surrounding areas encompass the spatial range of this thesis.

Before major land management measures were taken in the 1980's and 1990's, feral horses and cattle roamed freely, over-grazing, denuding the area, contaminating the scarce water resources and eroding and compacting the soil (Box 2014-2016). Although cattle, camels, donkeys, and other animals were present in the park, horses were the main concern because of their larger population in the park (Graham and Johnson, 1986). Overgrazing by feral horses (Equus caballus) systematically reduced native vegetation cover as animal numbers increased, which in turn enabled soil erosion and compaction, especially in areas near water bodies (Box et al., 2008). In arid zones, water resources are precious and vital to the sustainment of ecosystems and the livelihood of people. A decrease in water quality and availability can result in competition, species displacement or disease propagation (Nano, 2014-2016). These problems are magnified in FGNP where invasive flora and fauna species cause significant stress to the native wildlife (Parks and Wildlife Commission, 2011).

Many attributes of biodiversity can be used as measurable indicators to monitor natural resources in arid zones (Smyth and James, 2004). Biodiversity indicators can be environmental or biotic, indicating changes caused by pressure (Landsberg and Crowley, 2004). Landsberg and Crowley (2004) argue that plants offer substantial information about their surroundings and are valuable indicators of the pressure associated with land use. Landsberg and Crowley's (2004) focus on the national and regional scales limits the utility of these indicators to changes occurring over smaller areas such as FGNP. The use of plants as indicators of change is not novel but it is key to land managers and ecologists when studying complex and variable ecosystems at a smaller, local spatial scale.

A fence placed around some areas at FGNP, in combination with drastic horse-removal efforts, have allowed the vegetation of the area to recuperate (Brim Box, 2014-2016). As seen in Figure 6, Landsat images show a clear boundary where the fence stands. The fence boundary has become increasingly visible over time as the land management efforts have translated into increased vegetation cover. FGNP has been routinely monitored and actively managed since becoming a national park, making it a suitable candidate for hypertemporal image analysis using RS and GIS.

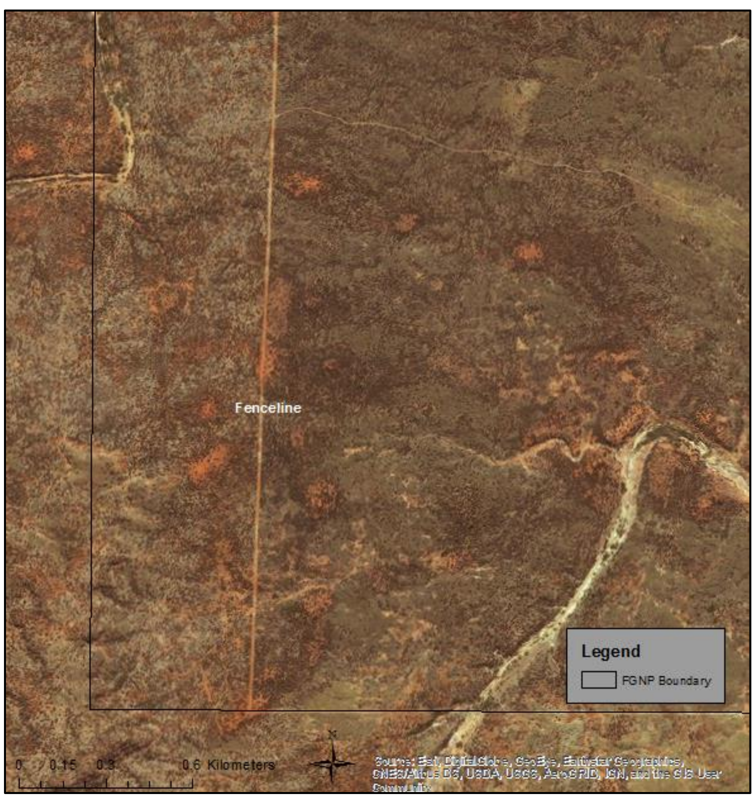


Figure 6 FGNP boundary and visible fence line. *Source*: ESRI Images

2.3.1 *Climate and Ecology*

The regional climate in FGNP is semi-arid and hot, with temperatures routinely exceeding 40° Celsius during the summer and falling below freezing during the winter (Box 2014-2016). Precipitation has high inter-annual variability, low predictability, is characteristically low (< 250 mm per annum) and it is driven by El Niño - Southern Oscillation (ENSO) cycle (Van Etten, 2009; Morton et al., 2011). Broadly speaking, the ecosystem in the park typically exists in two states: a prolonged drought, or more rarely, under non-arid conditions (> 350 mm per annum) underpinned by a concentration of discrete, but temporally connected summer rain pulses (Nano et al., 2012). Figure 7 shows rainfall data for Palm Valley weather station from 1989 to 1999, where five out of the ten years were under drought conditions.

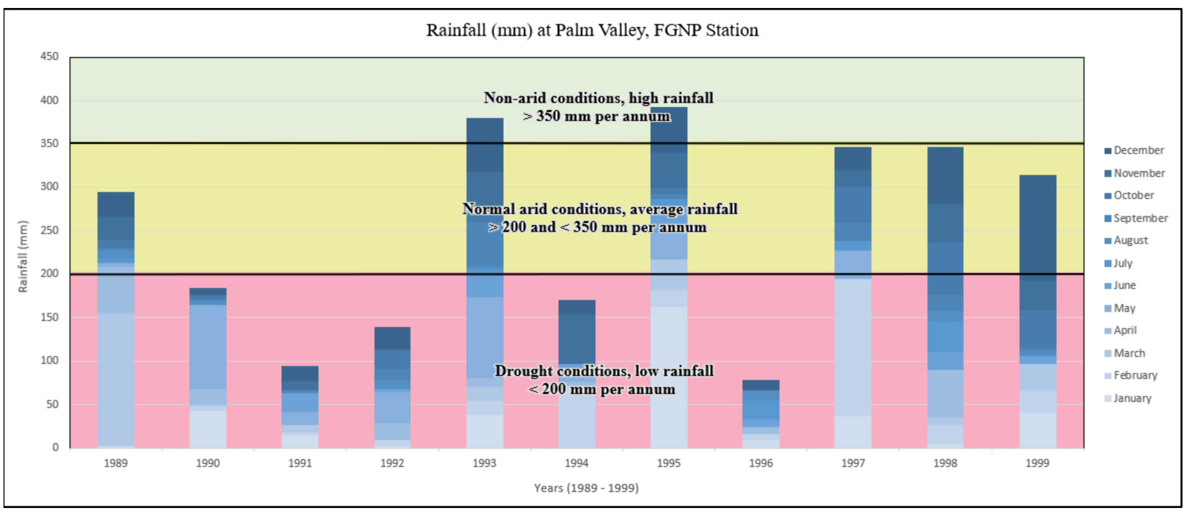


Figure 7 Rainfall data for Palm Valley Weather Station, located within the boundaries of FGNP. *Source*: Bureau of Meteorology, 2016

2.3.2 *Vegetation and Soil*

FGNP has over 680 plant species and a wide variety of habitats, soils and geographical features. At finer scales, soil texture and relief are important to understanding productivity responses, as well as the seasonal growth constraints of plant species (i.e. cool-season forbs) and attributes of their root structures (i.e. deep-rooted perennials over annuals) (Nano and Pavey, 2013). For example, relative frequent, small rainfall events can trigger a rapid and marked response in shallow-rooted species on course-textures (water-yielding) soils, whereas plant responses on clay-rich soils are comparatively rare and delayed. (Nano and Pavey, 2013).

Palm Valley, the most popular area at FGNP, lies in the Amadeus Basin aquifer and has a large population of red cabbage palms (Livistona mariae), a threatened species (Wischusen, Fifield, and Cresswell, 2004). The Hermannsburg sandstone beneath is a reliable source of water (Lau and Jacobson, 1991) for Palm Valley with bores over 50 m deep. Underground, low salinity water moves slowly through the sandstone below, causing favourable conditions (Wischusen, Fifield, and Cresswell, 2004) for the red cabbage palms in the arid zone. Red cabbage palm's closest relative, Mataranka palm (Livistona rigida), exists 1000 miles north in the tropical Mataranka region, where rainfall is abundant and other tropical plants are common (Wischusen, Fifield, and Cresswell, 2004). The unique hydrogeology of Palm Valley suggests that red cabbage palms have found a flora refuge at Palm Valley allowing these tropical plants to thrive in such arid conditions (Wischusen, Fifield, and Cresswell, 2004). This indicates that the response of these deep-rooted plants to the rainfall would be a stark contrast to shallow-rooted plant species. Figures 8a (Livistona rigida) and 8b (Livistona mariae) show mature Livistona palms thriving in two different areas. Figure 8a depicts Mataranka palms in tropical Rainbow Springs, Mataranka and Figure 8b depicts red cabbage palms in arid Palm Valley, FGNP.

(8a)

(8b)

Figure 8 Livistona palms. Figure 8a in tropical area and Figure 8b in arid area. *Photo credit:* Adlin Botkin

These broad-scale and fine-scale environmental drivers of primary productivity interact in complex ways on the vegetation to determine ground-cover dynamics in the park. In addition to the vegetation, geography and hydrogeology, land management efforts contribute to the complexity of assessments of relationship between plant species and a series of connected rain events.

2.3.3 Feral Horses

Feral horses are considered an environmental threat in central Australia and populations can increase by 20% each year if not managed (Csurhes, Paroz, and Markula, 2009). They can travel up to 50 kilometres from water sources in search of food, displacing native wildlife by competing for already scarce resources (Csurhes, Paroz, and Markula, 2009). Feral horse population in the NT was estimated at 50,000 in 1976 and not deemed a pest at such low population density (Graham and Johnson, 1986). However, when the brucellosis and tuberculosis eradication programme (BTEC) was developed to eliminate bovine tuberculosis from Australia (Gee, 1986), horses were viewed as a potential hindrance to the goal of the program (Graham and Johnson, 1986). A water buffalo survey conducted in 1982 (Graham and Johnson, 1986), collaterally estimated the population of feral horses in the NT at 76,000, a number considerably higher than accepted before.

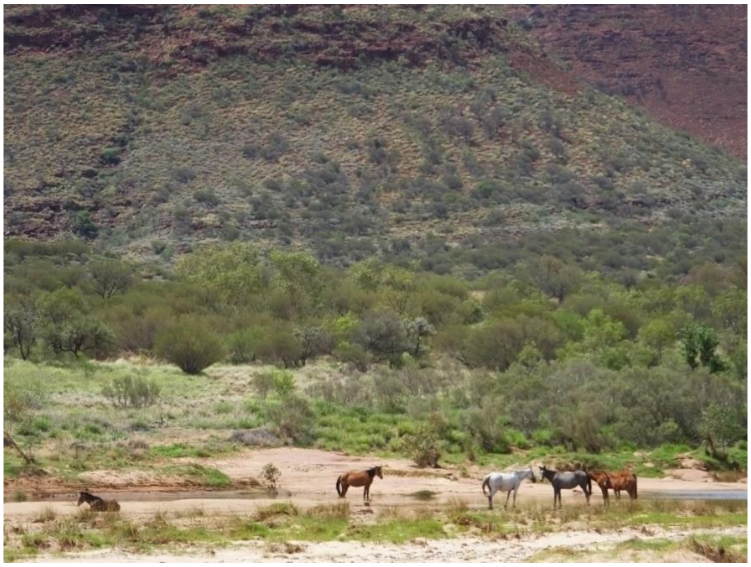


Figure 9 Wild horses in small numbers at FGNP, January 2016. *Photo credit*: Adlin Botkin

An increasing concern about the economic impact of horses on the BTEC and the conflicting reports of population totals led to further research. An ensuing aerial survey of horses, and other large animals, completed on May 1984 documented their distribution and abundance in known horse range areas. The survey found that the population of horses was much higher than originally estimated, with total population numbers surrounding Alice Springs at over 82,000 and population density at FGNP between 0.3 and 1 horse per square kilometre (Graham and Johnson, 1986).

Continued efforts to eradicate bovine tuberculosis in the area resulted in a perimeter fence project that began in 1986 and was completed in 1989 (Day, 1989). Through the multi-year project, feral horses caused severe damage to the fence, taking it down in some places (Day, 1989). In the months prior to the completion of the fence, the Finke Gorge Muster and Shoot was proposed, and approved, to mitigate further damages by removing horses and cattle from the park and from a 10-kilometre buffer around the park (Day, 1989). Between 1986 and 2001, a total of 32,881 horses were removed from FGNP and surrounding areas, the majority in the first three years of the program (Low and Hewett, 1990).

The removal of horses and cattle from the park and the placement of the fence resulted in an opportunity to monitor vegetation recovery in the area (Berman, 1990). A long-term vegetation monitoring program was funded to understand the environmental implications of removing the horses from the park by observing the vegetation.

2.3.4 Long-Term Vegetation Monitoring Program

After the major land management efforts were completed in 1990, the long-term vegetation monitoring project commenced in and around FGNP. The 'Environmental

Implications of Horse Removal in FGNP' project is documented in five reports between 1991 and 1998 (Low, Foster, and Berman, 1991; Low et al., 1992; Low et al., 1993; Cook et al., 1995; Miller, Low, and Matthews, 1998), and referred to as the Long-Term Vegetation Monitoring Program (LVMP) for the remaining of this thesis. It was led by Dr. W. A "Bill" Low at Low Ecological Services in Alice Springs. The project was intended to monitor the recovery of the vegetation in areas where animals were removed and the observations compared to vegetation in areas where they remained. LVMP was conducted in five phases (1991, 1992, 1993, 1995, and 1998) over eight years, collecting vegetation information such as herbage composition, species frequency, number of species per site, biomass, density of juvenile trees, canopy cover and some ecological indices.

The results of the LVMP were complex, and each site studied reflected its landscape and vegetation attributes (Low, Foster, and Berman, 1991; Low et al., 1992; Low et al., 1993; Cook et al., 1995; Miller, Low, and Matthews, 1998). The multi-year survey concluded that the sites inside the fence had greater biomass than the sites outside the fence when comparing the yield from 1991 to 1998 (Miller, Low, and Matthews, 1998). However, environmental effects, and more specifically rainfall, profoundly affected the vegetation changes at intervals between those years (Miller, Low, and Matthews, 1998). In addition to the seemingly recovery of native plants inside the park boundary, invasive grasses, such as couch and buffel grasses, increased in coverage (Miller, Low, and Matthews, 1998).

Dr. Low, who continues to provide services in Alice Springs, agreed to discuss the LVMP he and his colleagues conducted between 1991 and 1998. Dr. Low was enthusiastic about the use of GIS and satellite images looking back at the LVMP and provided as many details as possible.

The scope of the LVMP was extensive and included the examination of species composition, total biomass and trends for herbage, trees and shrubs, soil stability, water quality, rabbit activity, and mapping of land systems. The main goal of the LVMP was to monitor vegetation response and trends after the horses and cattle were nearly eradicated from FGNP and a strategic fence was emplaced to keep any remaining large animals entering the park. The LVMP is a loose model to define scope and scale in this thesis.

The original proposed schedule divided the LVMP into five stages, with the initial survey and site selection taking place July – August 1990, and the remaining four surveys occurring 12 months after the previous one. The project did occur in five stages, however, the time of sampling was altered due to drought, poor rainfall, and lack of funds. Surveys 1-5 were conducted on May 1991, May 1992, September/October 1993, February 1995, and March 1998, respectively. It is important to consider the implications of comparing data that has been collected in different seasons. Rainfall is another factor to be considered when comparing data in the surveys; if rainfall is lacking the vegetation can dry quickly in high temperatures, on the other hand, even a small amount of rain can quickly turn dry vegetation green. Seasonality and precipitation are the two most important elements affecting plant composition and productivity, followed by soil composition and grazing pressure (Foran, 1986).

Nine sites, shown in Figure 10, representing a wide range of landforms were selected for monitoring across the FGNP. Three sets of paired sites (1&2, 3&4, and 7&8) were selected to compare similar areas, inside and outside the park. The other three sites (5, 6, and 9) were representative of other landforms in areas known to have been heavily grazed within the park, but no comparable paired sites were found for any of them (Low, Foster, and Berman, 1991).

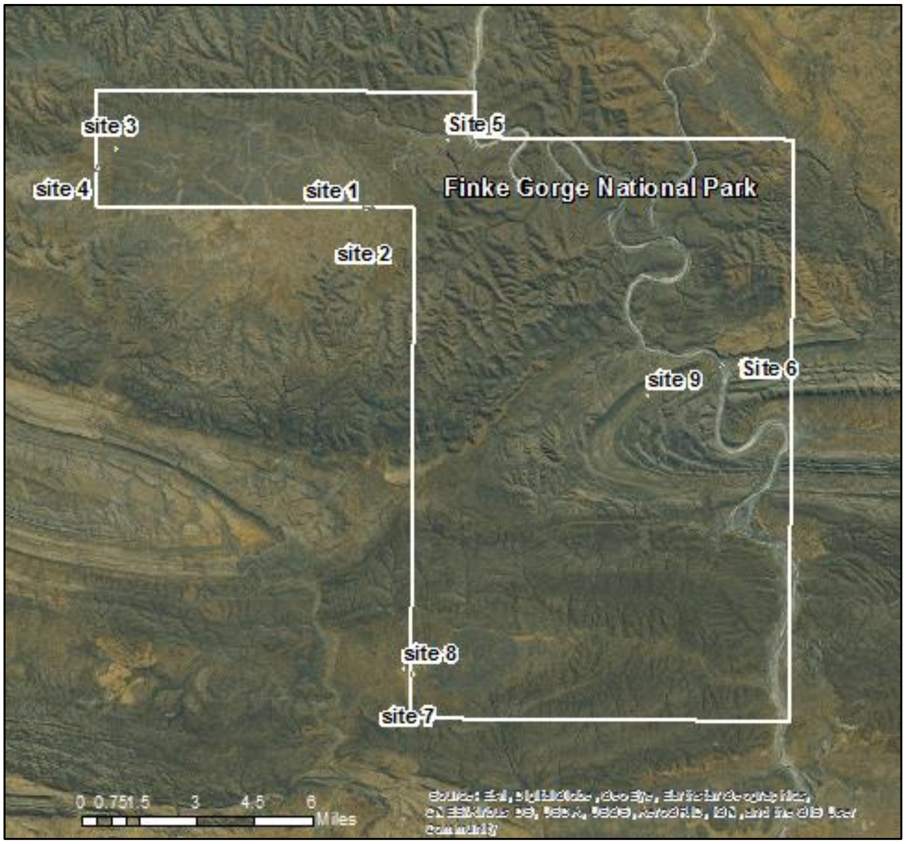


Figure 10 Location of LVMP survey sites

Table 1 Description of LVMP sites

Site Number	Location	Grazing
1 (Paired)	Palm Paddock – South Inside Park	Light
2 (Paired)	Palm Paddock – South Outside Park	Moderate
3 (Paired)	Palm Paddock – West Inside Park	Light
4 (Paired)	Palm Paddock – West Outside Park	Moderate
5	Junction of Palm Creek and Finke River	Heavy
6	Boggy Hole Waterhole	Heavy
7 (Paired)	Illbilla Dune Field - Inside Park	Light
8 (Paired)	Illbilla Dune Field - Outside Park	Light
9	Circle Gully	Heavy

2.4 Remote Sensing and Geographic Information Systems to Monitor and Manage Natural Resources

A study by Burns et al. (2014) investigating the extent of monitoring of Australia's ecosystems found that arid areas are insufficiently sampled and monitored, although they make up the majority of the country. Arid zones have limited resources, so the effects that fire, overgrazing, and introduced animals and plants can have on ecosystems may be felt for long periods of time after they occur, or even permanently.

Remotely sensed imagery is an important source of data in the monitoring of natural resources due to its practicality in Land Use and Land Cover (LULC) applications (Hussain et al., 2013). The differences in the spectral signatures between areas of LULC change and areas that have not changed can be identified with multi-band RS images. These differences may provide insight into the ongoing processes and how they behave and affect the area. Pixel-based, object-based, and spatial data mining change-detection techniques have been developed and continue to be developed (Hussain et al., 2013), as satellite images become finer and more accessible.

Most Landsat data became available free of charge to the public January 2009, facilitating user access to a retroactive archive of multi-spectral images with an 18-day or less coverage cycle (NASA, 2017). Single images of natural resources such as waterbodies, vegetation and mountain ranges, although important to understand spatial differences within the area imaged, do not provide comprehensive information about the ongoing processes when looked at individually. However, the analysis and comparison of two images of the same area at different times can yield comparative data to help understand the changes transpired in that period. Moreover, multiple images analysed over time can uncover trends or slower processes.

2.4.1 *Bitemporal Image Analysis*

Pairs of images are commonly used to detect changes on the landscape. The process, also known as bitemporal change detection, compares two images of the same geographic area taken at different times to detect and measure changes. Several RS methods have been established to identify bitemporal changes.

Celik (2009b) describes an unsupervised change detection method to extract feature vectors for each pixel so that it automatically considers the contextual information of the neighbourhood for each block. A related study also by Celik (2009a), outlines a similar method for paired images using k-mean clustering to calculate final change detection and PCA to reduce dimensionality and extract features. This method identifies significant changes irrespective of the nature of the image used as input (Celik, 2009a).

Collins and Woodcock (1996) describe several techniques for comparing pairs of images, including simple digital number (DN) matching, where two images are stacked one above the other and PCA is performed on the DN. Byrne, Crapper, and Mayo (1980) described a similar method overlaying a pair of Landsat MSS images of a coastal town to detect changes near the shore.

Bovolo, Marchsi and Bruzzone (2012) describes a number of techniques including Bayesian changes and PCA for quantifying the differences in two images of the same area. The study accounts for the difficulties of both, the collection of ground truth data and the possible loss of change information when using unsupervised methods; issues that continually arise when attempting to detect change in vast and unpopulated arid zones (Bovolo, Marchsi and Bruzzone, 2012). The technique presented is advantageous because it does not require previous knowledge of the changes occurred (Bovolo, Marchsi and Bruzzone, 2012).

Other bitemporal vegetation change detection studies have developed methodologies appropriate to the ecoregion of interest, such as coastal environment (Weismiller et al., 1977), wetland (Howarth and Wickware, 2007), and desert (Abuelgasim et al., 1999). Using bitemporal analysis is advantageous because it minimizes the atmospheric, sensor and environmental differences between multi-temporal images (Sun et al., 2016).

2.4.2 Multitemporal Image Analysis

At a lower temporal resolution, ecological dynamics requiring frequent measurements may be overlooked, requiring time-series image analysis. When images are collected at small enough intervals they can be used to detect changes and understand trends in highly variable ecoregions (Lawley, Lewis, and Ostendorf, 2016).

A study by Deng et al. (2008) uses PCA as a pre-classification spectral change-detection technique to transform a stack of hypertemporal images. The combined bands of the resulting image are transformed into components. It is further processed using a classified analytical method to produce labelled change-detection output. This is a type of “hybrid” analysis where more than one technique is used to process the images. Amiraslani and Dragovich (2013) presented a method to investigate vegetation changes in a degraded rangeland area. They considered a 42-year rainfall period and acquired images based on major rainfall or drought events. This method allowed enough time to understand the dynamics at a more appropriate temporal scale, minimizing drastic periods of change.

Sparrow, Friedel, and Stafford Smith (1997) developed a model to predict changes of chenopod vegetation in an area south of Alice Springs in Australia, considering the small amount of data available, climatic variability and vegetation heterogeneity. The changes in vegetation in the area of their study are most dependent on grazing effects and soil erosion. The study uses a plant cover index derived from Landsat images to test the model, resulting in a successful association of the index with the field data, except in highly eroded areas. Bastin et al. (2012) developed a successful method using 89 Landsat images over a tropical savannah to detect changes in ground cover relating to land management. Their study demonstrates the utility of this type of analysis at a paddock scale for those trying to monitor land cover changes.

In addition to the typical visualization of extent of herbage cover, Landsat's capability to record images in different bands of the electromagnetic spectrum provides information about the type and health of the vegetation. Graetz et al. (1976) used multi date and multi spectral imagery to assess rangeland type, condition and response to rainfall in arid central Australia. They found that the method was most useful where fenceline contrast in the vegetation condition were visible (Graetz et al., 1976). Matheson (1994) used multiple Landsat infrared images to analyse green vegetation cover relative to the background in arid area in the NT of Australia. Vegetation darkening enabled spectral separability of green vegetation in semi-arid rangelands and arid sandy areas.

2.5 Principal Components Analysis

Principal Components Analysis is a mathematical technique that reduces the number of correlated variables into a lesser number of uncorrelated factors. Each resulting component explains the variability independent of other components. That is, principal component 1, or PC1, will create a new variable in terms of a new axis and will have no correlation to PC2, which will present the next highest source of variability.

In earth and environmental sciences, PCA has traditionally been used for land cover change detection (Byrne, Crapper, and Mayo, 1980; Ingebritsen and Lyon, 1985), image enhancement (Deng et al., 2008; Alavi, 2012), and climate data analysis (Kelly et al., 1982;

Farhangfar et al., 2016). PCA has also been used in the search of less discrete changes that may provide more details of underlying factors responsible for localized variation across space and time.

Townshend, Goff, and Tucker (1985) used PCA as an exploratory tool to understand the relationships between multitemporal images in the continents of Africa and North America. They compared the resulting components from both continents and found significant similarities in the variation structures of underlying relationships. The first two principal components (PC) for each continent explain over 90% of the variation, with the first one following rain patterns and the second one seasonal variation.

Piwowar and Ledrew (1995) discuss PCA as one of three useful techniques for hypertemporal image analysis to identify connections between variables and to identify redundancy. The authors argue that PCA can assist in understanding polar climate changes due to the technique's capability to generalize a time-series of RS images. In his thesis, Piwowar (1996) uses PCA to isolate temporal and spatial variations to identify patterns in ice concentration over a nine-year time-series. Despite influence from interannual, regional and seasonal changes, Piwowar (1996) identified three new phase-shifted regionalisms in the area, evidencing the suitability of PCA to highlight underlying relationships and trends in melting ice that may begin and dissipate within the studied timeframe.

Bengraine and Marhaba (2003) used PCA to extract sources of variation and understand these in a temporal and spatial context to understand water pollution in the Passaic River, New Jersey. PCA was useful in explaining opposing patterns of organic, biological and chemical pollution. The authors were able to identify stations that affected the water quality, negatively and non-negatively.

A thesis written by Henderson (2010) used PCA to understand vegetation productivity changes and normal variation in areas of Grasslands National Park, Saskatchewan, Canada. She interpreted the components spatially by looking at each resulting image and temporally by plotting the loadings. Henderson (2010) chose to explore pixels with high spatial and temporal definition, resulting in the identification of types of changes in areas showing high variation. In her conclusion, she explains the possibility of predicting how the vegetation in the park will respond to climate change.

It is common to use change detection methods to measure how much the land has changed from time A to time B. But to understand patterns and trending over time, a multi-temporal set of images may be more appropriate. PCA can isolate the sources of variation (each as an orthogonal component), to assist in detecting patterns and trends, that are uncorrelated to other sources of variation. Although most of the variation can be explained with the first component, the subsequent higher components further identify other sources of variation that may be related to plant species, soil texture, specific rainfall events, or other indicators. The importance of the higher PCs, presenting increasingly smaller percentages of variation, may seem subjective because it is integrally dependent on the knowledge and ability of those interpreting the images (Davis, 2002).

3 Data and Methods

Chapter 3 describes the framework of this thesis, including the data used and the processes followed. Section 3.1 describes the seasonal fractional cover composites derived from Landsat images that were the principal source of remotely sensed data. Section 3.2 describes other data used, mainly rainfall data and information derived from the LVMP. Section 3.3 explains the methods used to process the data, including supervised classification and principal components analysis (PCA).

3.1 Seasonal Fractional Vegetation Cover Data

The main source of satellite images for this thesis were seasonal fractional vegetation cover (SFVC) composites with path number 103 and row number 77, published by the Terrestrial Ecosystem Research Network (TERN) with data from the Joint Remote Sensing Research Program (JRSRP) at the University of Queensland in Brisbane, Australia between the years 1989 and 1999. SFCV composites for those years were derived from images captured by Landsat 5 Thematic Mapper (TM) sensor (Terrestrial Ecosystem Research Network, 2013). Landsat 5 satellite and image characteristics and the radiometric characteristics of TM sensor are listed in Table 2 and Table 3.

Table 2 Landsat 5 Satellite and Image Characteristics. *Source*: Terrestrial Ecosystem Research Network, 2013

Characteristics	Description
Ground Sampling Interval (GSI)	30 x 30 m – for bands 1 – 5 & 7 120 x 120 m – for band 6
Swath width	185 km
Repeat coverage interval	16 days, 233 orbits in each 16-day interval
Altitude	705 km
Quantisation	B bits (256 levels)
On-board data storage	Magnetic tape failed

Orbit type	Sun-synchronous
Inclination	98.2
Equatorial crossing	Descending node at 10:10 AM
Image size	185 x 172 km
Number of bands	7

Table 3 Radiometric characteristics of TM sensor. *Source*: United States Geological Survey, 2017

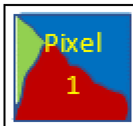
Band	Spectral Range	Electromagnetic Region
1	0.45 ~ 0.52	Visible blue
2	0.52 ~ 0.60	Visible green
3	0.63 ~ 0.69	Visible red
4	0.76 ~ 0.90	Near infrared
5	1.55 ~ 1.75	Middle infrared
6	10.40 ~ 12.5	Thermal infrared
7	2.08 ~ 2.35	Middle infrared

The SFVC images are time-serial composites of fractional, sub-pixel vegetation cover over Australia. They are regular time-series representative of each typical atmospheric season and capture the variability, whilst minimizing data gaps that may occur in single images (Flood, 2013). Each one is created by selecting representative pixels using the medoid (three-dimensional median) of a three-month period (seasons) of fractional cover of satellite images. Each year has four seasons; Summer (December to February), Autumn (March to May), Winter (June to August), and Spring (September to November), resulting in a maximum of four composites per year. The fractions for each pixel represent the portions of bare, green, and non-green cover. The Landsat images used to build the SFVC composites have been corrected for atmospheric effects, bi-directional reflectance and topographic effects using the methods described in Flood et al (2013). Images with over 80% cloud cover were excluded to reduce the possibility of extra noise (Terrestrial Ecosystem Research Network, 2013).

3.1.1 Model

The fractional cover of the bare soil, green and dry vegetation cover was assessed using models based on substantial sampling of more than 1,500 sites covering a wide variety of vegetation, climate, and soils in Australia (Terrestrial Ecosystem Research Network, 2013), following methods described in Muir et al. (2011). The values are calculated by inverting multiple linear regression estimates and a least squares non-mixing.

Values present a percentage of cover and range from 0 to 100 and, increased by 100 to allow for values under 0 and values over 100 (undershoots or overshoots of modelled values) (Terrestrial Ecosystem Research Network, 2013). Each pixel is categorized into three continuous variables representing the fraction of cover stored over three bands or layers; see Table 4 for band descriptions. A very simple example of such pixel is shown in Figure 11. A fourth band contains the root-mean-square error (RMSE) between the predicted and actual pixel value. For this thesis, 100 was subtracted from each value, and represented each pixel as a point in the percentage scale.



Example of values within a seasonal fractional vegetation cover pixel. All three values for Pixel 1 sum up to 100%.
Red (bare ground) - 42
Green (green vegetation) - 10
Blue (non-green vegetation) - 48

Figure 11 Example of a pixel in a SFVC composite

Table 4 Description of the four bands in the SFVC composites

Band	Category	Description
1	Bare (red)	Bare ground, rock face, disturbed soil
2	Green vegetation (green)	Live vegetation, green vegetation
3	Non-green vegetation (blue)	Dead plants, dead leaves, dry vegetation, dormant vegetation, branches, trash
4	Model fitting error	Error layer representing root-mean-square error

The construction of the perimeter fence and the initial large-scale horse removal effort at FGNP was completed by May 1990. The LVMP's last survey was completed in April 1998. So, the images considered for this thesis cover the timeframe between December 1989 and November 1999, slightly before and slightly after these two dates.

3.1.2 Pre-processing

The composites were derived from geometrically and radiometrically corrected Landsat images. Fractional cover of vegetation and bare soil were estimated using models based on extensive sampling of several hundred sites covering the variety of vegetation and climate types throughout Australia (Terrestrial Ecosystem Research Network, 2013) and applied retroactively to historical Landsat imagery to provide consistent classification of land cover over time. Each layer used in this analysis represents a summary (composite) of the land cover over a three-month period. As the methods used are sensitive to missing data, only complete or almost complete, cloud free composites were used. This gave a total of 27 images between the years of 1989 and 1999, out of the possible 40. List of available composites is shown in Table 5.

Table 5 SFVC Composites available from TERN with dates covered and quality of image

Composite	Dates covered	Data Quality
1	December 1989 to February 1990	Full Image
2	March 1990 to May 1990	Missing some data
3	June 1990 to August 1990	Missing some data
4	September 1990 to November 1990	Full Image
5	December 1990 to February 1991	Full Image
6	March 1991 to May 1991	Missing some data
7	June 1991 to August 1991	Missing some data
8	September 1991 to November 1991	Full Image
9	December 1991 to February 1992	Not enough coverage
10	March 1992 to May 1992	Full Image
11	June 1992 to August 1992	Not enough coverage

12	September 1992 to November 1992	Not enough coverage
13	December 1992 to February 1993	Not enough coverage
14	March 1993 to May 1993	Missing some data
15	June 1993 to August 1993	Missing some data
16	September 1993 to November 1993	Not enough coverage
17	December 1993 to February 1994	Not enough coverage
18	March 1994 to May 1994	Missing some data
19	June 1994 to August 1994	Missing some data
20	September 1994 to November 1994	Missing some data
21	December 1994 to February 1995	Full Image
22	March 1995 to May 1995	Not enough coverage
23	June 1995 to August 1995	Not enough coverage
24	September 1995 to November 1995	Missing some data
25	December 1995 to February 1996	Full Image
26	March 1996 to May 1996	Not enough coverage
27	June 1996 to August 1996	Missing some data
28	September 1996 to November 1996	Full Image
29	December 1996 to February 1997	Not enough coverage
30	March 1997 to May 1997	Not enough coverage
31	June 1997 to August 1997	Not enough coverage
32	September 1997 to November 1997	Missing some data
33	December 1997 to February 1998	Missing some data
34	March 1998 to May 1998	Missing some data
35	June 1998 to August 1998	Missing some data
36	September 1998 to November 1998	Not enough coverage
37	December 1998 to February 1999	Full Image
38	March 1999 to May 1995	Missing some data
39	June 1999 to August 1999	Missing some data
40	September 1999 to November 1999	Full Image

3.1.3 Possible problems with the model

The calibration and models were originally developed for agricultural land and rangelands in temperate and subtropical regions of Australia, with relatively little representation of calibration points in the Australian desert. So, the existing model is not perfectly suited for extrapolation into remote rangeland areas. For example, some fractional values were slightly smaller than 0%, or slightly larger than 100%.

The months covered in each composite align with typical atmospheric seasons. However, as discussed in section 2.2.1.1, the climate in the central Australian arid areas is unpredictable and highly variable causing anomalies such as the seemingly "skip over" a typical wet, summer season when there is a drought, possibly lasting years. Using composites that summarize each season, may introduce errors in the application of any of the methods as well as in the analysis part. However, due to the consistent classification criteria across time for the study area and given that they are still reasonably indicative of vegetation cover values, the model and images were suitable for this thesis.

The methods used to analyse the images are sensitive to missing data. 40 composite images were available for use, but only 27 had complete, or almost complete coverage over FGNP. The remaining images were not included in the analysis, introducing a level of error that may be difficult to measure as there is no way the data can be re-collected, and there are no other known sources of data, except for the LVMP. However, as one of the points of this thesis is to use what was available at the time, this is acceptable.

3.2 Rainfall and Temperature Data

Rainfall data was derived from the Palm Valley Bureau of Meteorology (BOM) Station, located within the boundaries of FGNP. Temperature data was not available at Palm Valley Station, so data from the Alice Springs Airport station was used, located about 200 km east of FGNP. The rainfall, minimum and maximum temperature has been recorded daily since the early 1980's and is available as bulk downloads from the BOM website. They are presented as averages in Figures 12a, 12b and 12c, each covering the three-month timeframe of a single SFVC composite.

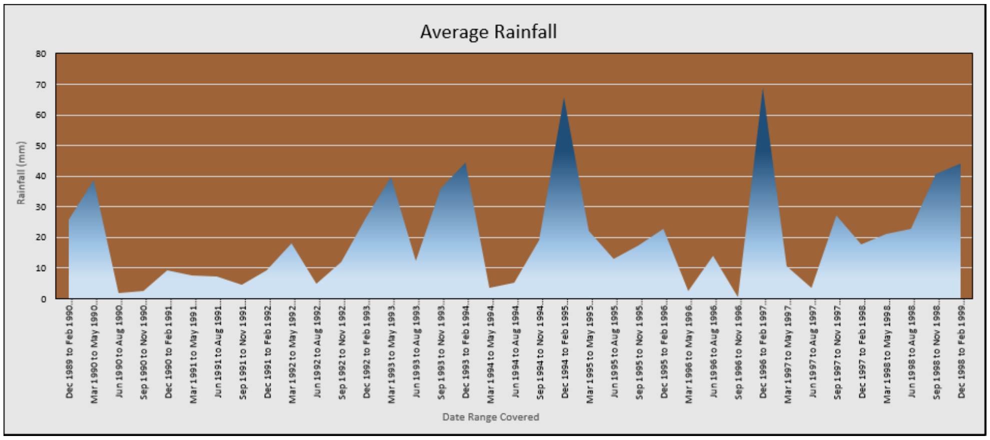


Figure 12a Average Rainfall chart, Palm Valley Station, 1989 – 1999. *Source*: Bureau of Meteorology, 2016

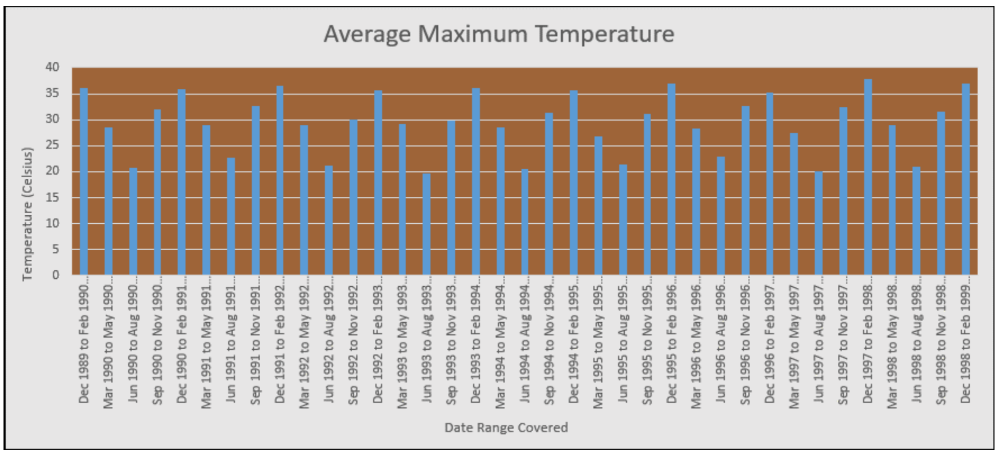


Figure 12b Average Maximum Temperature chart, Alice Springs Airport station, 1989 – 1999. *Source*: Bureau of Meteorology, 2016

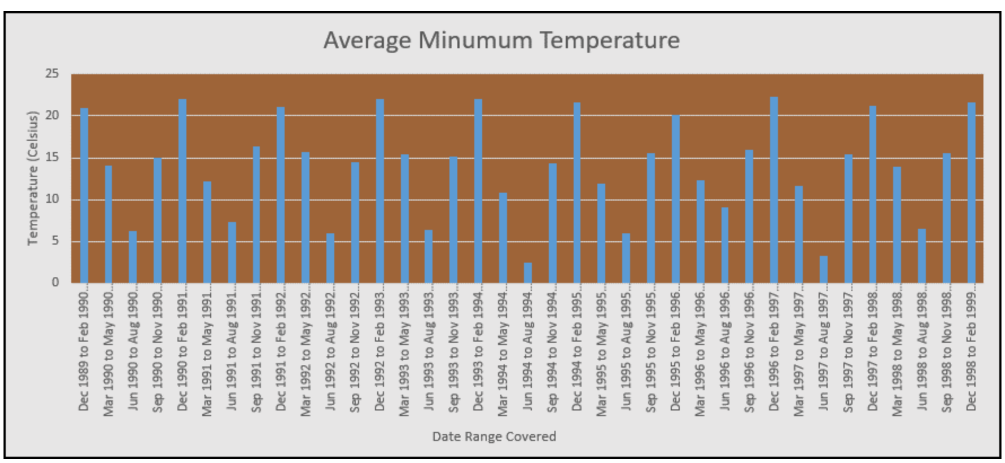


Figure 12c Average Minimum Temperature chart, Alice Springs Airport Station, 1989 – 1999. *Source*: Bureau of Meteorology, 2016

3.3 Field Survey Data from LVMP

The long-term vegetation monitoring project (LVMP) was conducted in five stages between June 1991 and April 1998 over nine field sites in FGNP. Paper maps from the initial survey's documentation were scanned, converted to Tiff file and georeferenced using land feature association. The paper maps provided soil unit, plant cover, and prominent features of the nine field sites surveyed in LVMP and surrounding areas. Additionally, conversations with ecologist Dr. Catherine Nano and Dr. Paul Box (Nano, 2014-2016; Box, 2014-2016) about the dominant plant species further enriched the classification.

3.3.1 Field Sites

The nine field sites were selected to represent distinct vegetation, topography, and soil composition, inside and outside of the park. In Table 6, vegetation, soil and landform data for each site was tabulated to understand what the area looks like in more detail. This data was derived from the field observation made by Low, Foster and Berman (1991).

Table 6 Description of nine survey sites of LVMP.

Location	Vegetation	Soil	Landform
1 – South Palm Paddock (Paired with 1, Located inside park)	Open Witchetty bush shrubland.	Light sandy clay loam, overlies weak, kaolinized sandstone.	Gently sloping hillslope plain of low relief.
2 - South Palm Paddock (Paired with 2, Located outside park)	Sparse Witchetty bush shrubland over Five Minute grass.	Light sandy clay loam, overlies weak, kaolinized sandstone.	Gently sloping hillslope plain of low relief.
3 - West Palm Paddock (Paired with 4, Located inside park)	Sparse Witchetty bush shrubland over Five Minute grass.	Platy, kaolinized sandstone, red sandy loam.	Hillslope within plain of low relief.

4 - West Palm Paddock (Paired with 3, Located outside park)	Sparse, witchetty bush shrubland. Other shrubs and grasses.	Calcrete substrate, sandy claim loam.	Hillslope within plain of low relief.
5 - Palm Creek (Not paired)	Sparse Senna with Witchetty bush over buffel and other grasses.	Light sandy clay loam. River gravel below.	Within pediment extending into flood plain.
6 - Boggy Hole Waterhole (Not paired)	Sparse Mulga shrubland over Senna, Buffel grass and other grasses. Sparse River Red gum woodland over Couch grass.	Yellowish red sandy loam and red light sandy clay loam.	Alluvial landform on channel bench within alluvial terrace. Bar plain.
7 - Illbilla Dunefield (Paired with 8, Located inside park)	Open Hummock grassland of Spinifex. Wattle, Ironwood and Blue Mallee.	Red sandy loam.	Wind-eroded sparse dunefield. No drainage features.
8 - Illbilla Dunefield (Paired with 7, Located outside park)	Open Hummock grassland of Spinifex. Mulga, Wattle, Ironwood and Blue Mallee.	Red sandy loam.	Wind-eroded sparse dunefield.
9 - Circle Gully (Not paired)	Sparse Acacia shrubland with Whitewood. Mulga, Fuschia bush and Senna.	Strong, brown sandy loam over strong brown sandy clay loam.	Gently sloping with low relief, within pediment. Erosion gullies present.

The location of each field site was confirmed with GPS in 2014 and an MXD file was created to denote each corner of each site. Although the location of each field site was identified in 1991 with markers in each corner, not all remain. Most points of the GPS-confirmed corners correspond closely to the georeferenced corners. However, sites 1 and 2, which have a fence as their common boundary, did not match exactly when georeferenced but were within approximately 15 meters. Site 5's markers were not found in 2014 and its exact location was also in question. It was found to have two possible, equally likely sites. After reviewing the images, the most likely location for Site 5 was identified using geographical features visible in the ArcMap World Imagery Basemap and slightly shifted it north-east.

3.3.2 Soil unit Data

The soil unit maps, like the one in Figure 13, were drawn by hand (exact date unknown), to 1: 50,000 scale, prior to the first survey in 1991. The land features used to classify the soil unit maps are described in Table 7. These soil units can vary slightly over time, especially in the areas where the Finke River can flood during heavy rainfalls and cause accumulation of sand in new areas or a wash away of previously existing sand bars. The soil unit data provides further insight into what the area looked during the LVMP. These maps were also used to identify the soil units in areas in the park.

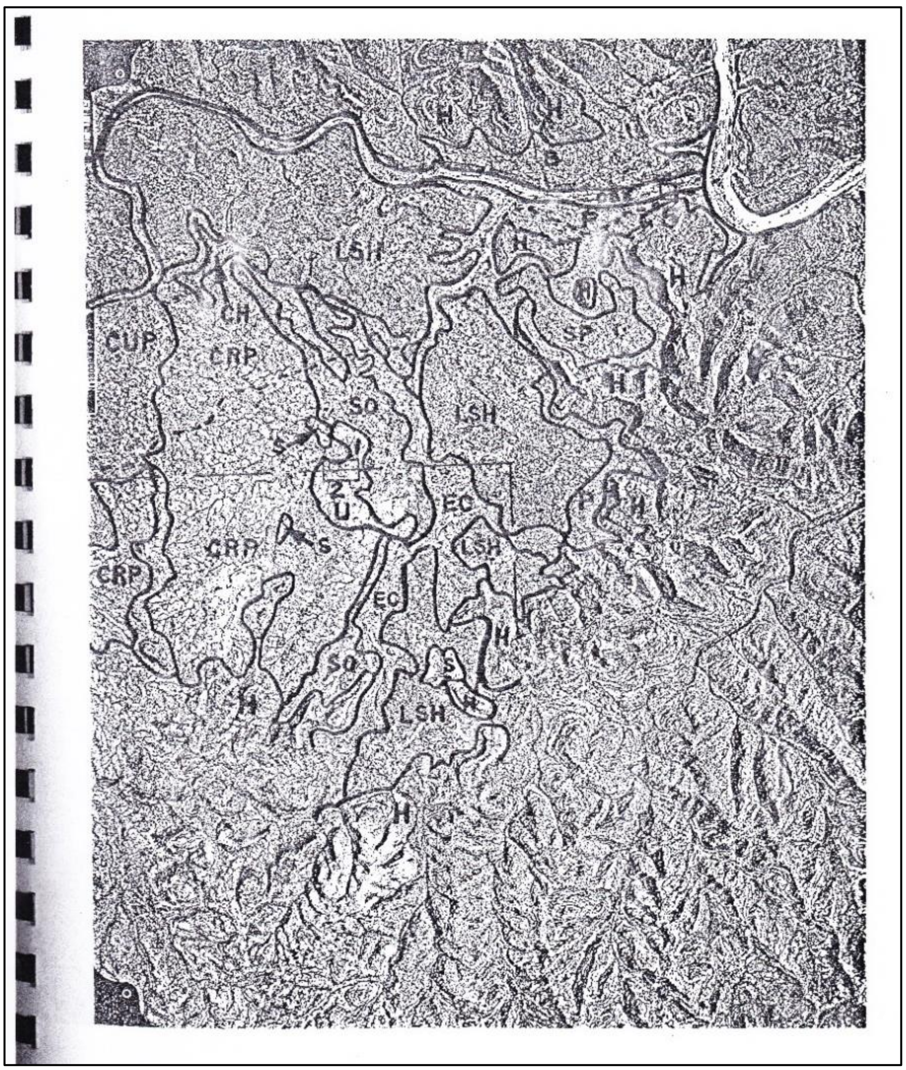


Figure 13 Soil Unit map. *Source*: Low, Foster and Berman, 1991

Table 7 Soil units in the immediate vicinity of each site. *Source*: Low, Foster and Berman, 1991

Abbreviation	Soil Unit
A	Alluvial plain
B	Bench
B+C	Bar plain plus channel in montane gully
BP	Back plain
CBE	Channel bench in floodplain
CBL	Calcareous badlands
CH	Calcrete hills
CRP	Calcareous rolling plain
CUP	Calcrete Undulating plain with spinifex
D	Dunefield with sparse dunes
EC	Creek valley
H	Hills
LSH	Low sandstone hills with sand veneer
MP	Meander plain
P	Pediment in EC, surrounding dunefield or montane valley
S	Sandhill or ridge
SO	Sandstone outcrop
SP	Sand plain
T	Terrace
U	Upper hill slope of eroded plain

3.3.3 Plant Species Data

The plant species present in each field site are depicted in site maps, like the one in Figure 14 for field survey site 3. These maps were also hand-drawn as the sites were initially surveyed in 1991. A significant photo record was found, one photo taken from each corner of each site looking in. Although these photos were not central in digitally identifying specific plants on the sites, it provided a visual of the area in terms of vegetation. Once georeferenced, these maps served to identify the vegetation/soil combinations. A complete list of plant species found during the LVMP can be found in Low, Foster and Berman (1991).

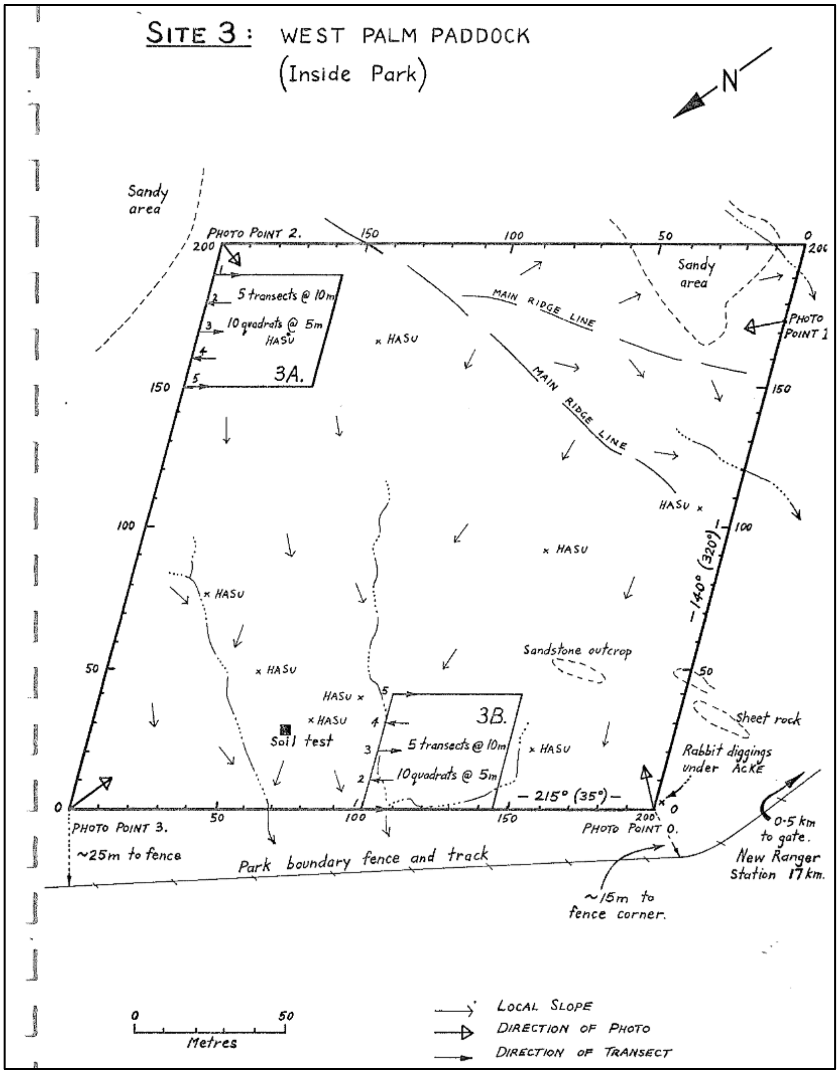


Figure 14 Field survey map for Site 3. *Source*: *Low, Foster and Berman, 1991*

3.4 Methods

Spatio-temporal analysis of satellite images is a common way to detect changes in the landscape. Satellite sensors record reflectance values on objects in the landscape (Lu et al., 2003). Changes in the reflectance indicate changes in the objects themselves, independent of changes in the atmosphere, illumination and viewing angles, and moisture in the soil (Lu et al., 2003). Change detection techniques help calculate these changes and assist in the understanding of the causes or factors in reflectance differences. The most frequently used detection techniques are described in Lu et al. (2003). Some methods, such as image differencing, provide mathematically simple but significant answers that can be used immediately. Other techniques, such as spectral mixture models, provide results that must be further analysed and examined to provide significant answers. Supervised classification and principal components analysis (PCA) are the main methods used in this thesis.

The main goal is to understand how the vegetation changed in FGNP during the years after large grazing animals were removed and a fence was placed in some areas to prevent them from returning. Supervised classification and PCA were used on a set of SFVC composites to interpret these changes. A supervised classification will help understand the vegetation and soil relationships and determine which combinations have the least and most variability. PCA is used as a method to enhance dissociation between the factors (or variables) with the intent to distinguish sources of variation. Lastly, the results are compared to the LVMP conclusions.

3.4.1 Classification

The first three bands of the seasonal fractional vegetation cover (SFVC) composites describe bare soil (B1), green vegetation (B2) and dry/dormant/dead vegetation (B3). These values are continuous, a function of each other and add up to 100. When B2 (green vegetation) values increase in a pixel, the values of B1 and/or B3 necessarily decrease. Due to this, it seemed acceptable to do a supervised classification only using green vegetation, with the understanding that as the values of B2 decrease the vegetation dries, dies or disappears from the area, leading to an increase in one or both other bands.

Training samples were created using the LVMP georeferenced maps (including the nine sites surveyed in the LVMP), knowledge of the area, and ArcMap World Imagery Basemap. B2 was separated from each of the final 27 SFVC composites. Using only these 27 B2 bands, a signature file was created and used to do a Maximum Likelihood Classification resulting in a classified vegetation map. Due to the harsh climatic conditions in the area, most plants are hardy and resilient, with the ability to flourish in multiple soil conditions, however unlikely. This means that the same plant species may appear dominant in two, or more different soil types.

The classification of these vegetation type/soil unit combinations allows analysis of the vegetation changes in the area after the land management efforts at FGNP and provide a baseline for the principal components analysis to examine possible sources of variation. Calculation for the mean. median, standard deviation, number of pixels per class, and percentage of class cover were calculated to further understand the vegetation in the area. Figure 15 show the process followed for the supervised classification.

- SFVC Composites - Download, Clip, Check for completeness
- Scan and georeferenced of paper maps
- Supervised classification
    - Create training samples
    - Create sig file for veg and for soil
    - Perform MLC for veg and soil
- Combine veg and soil classes to create combined class map
- Data export for each class to create 16 individual class layers
- Separate bands
- Test which B2 rasters have pixels with values > 25
- Using 16 layers as mask file extract all B2 values >25 (extract by mask)
- Convert raster to point
- Create summary statistics
- Append to main table
- Export to excel

Figure 15 Steps used in the supervised classification

3.4.2 Principal Components Analysis

Principal Components Analysis (PCA) is generally described as a data-reduction technique used to detect internal processes and significant events, as opposed to other hypertemporal analysis techniques that are concerned with larger, more general processes (Piwowar, 1996). The PCA algorithm works by looking at properties (or variables) of a larger set of variables (e.g. set of pixels across images over time) and finds the best way to describe them by reducing them into a smaller set of new variables. The reduction occurs when the properties are combined to enhance maximum variability between each item in the set. For example, properties such as temperature and evaporation may not enhance variability in arid zones such as FGNP because high temperatures typically deliver high evaporation. Thus, explaining the variability of vegetation growth in terms of temperature and evaporation as variables may yield similar results. In this case, PCA creates new property permutations, in the form of linear combinations, to describe the sets, effectively removing this type of redundancy.

New properties combinations are called principal components (PC), also found in the literature as eigenvalues. PCs show the significance of each relationships. A PCA will result in as many components as there are variables describing the set. The SFVC composites have four bands, with band 1 (red), band 2 (green) and band 3 (blue), each representing bare soil, green vegetation and dry/dead/dormant vegetation respectively. Band 4 represents the root-mean-squared error between predicted and actual pixel value and was not included in the PCA. A PCA analysis will result in three PCs for each composite used. This is because each composite is defined in three variables; red, green, and blue bands. The first principal component, or PC1, will show the most variance and least error, and if graphed, the linear combination representative of the new PC1 will best fit the data. The second principal component, or PC2, will show the next most variance, independent (or orthogonal) from PC1, and so on for the rest of the PCs. Each new component describes one "artificial" property created specifically to describe the set. In a multitemporal analysis, the new properties or PCs can be presented in a spatial relation (mapping the values), as well as a temporal relation (charting the PC loadings).

PCA may be calculated manually if the number of variables is low, but in this project the number of variables is high and the PCA function in ArcMap 10.5.1 was a better option. A tutorial on PCA by Smith (2002) was used to understand the mathematics of PCA.

Like standard deviation, variance is a measure of the spread of a data set in one dimension. Their equations, shown in Equation 1 and Equation 2, are very similar and expressed independently from other dimensions.

$$Standard\ Deviation = S = \sqrt{\sum_{i=1}^{n} \frac{(x_i - \bar{x})^2}{(n-1)}} \qquad (1)$$

$$Variance = S^2 = var(x) = \sum_{i=1}^{n} \frac{(x_i - \bar{x})^2}{(n-1)} \qquad (2)$$

Covariance is the spread of a data set from one dimension with respect to other dimensions. The covariance is always measured between two dimensions. Positive values indicate that the both dimensions increase together and are positively correlated (green vegetation and rainfall). Negative values indicate that one dimension increases as the other decreases and are negatively correlated (green vegetation and heavy grazing). Covariance values of zero indicate that the dimensions are independent of each other and uncorrelated (heavy grazing and rainfall). The formula for covariance for n dimensions, in this case two dimensions (x and y), is shown in Equation 3.

$$cov\ (x, y) = cov\ (y, x) = \sum_{i=1}^{n} \frac{(x_i - \bar{x})\ (y_i - \bar{y})}{(n-1)} \tag{3}$$

If there are more than two dimensions, more than one covariance will be calculated. For n dimensions, there are $\frac{n!}{(n-2)! \times 2}$ different covariance values. For convenience, covariance matrices can be created to view every possible covariance between every pair of dimensions. The equation for the covariance matrix with a data set of n dimensions is shown in Equation 4.

$$C^{m \times n} = (c_{i,j}, c_{i,j} = cov\big(Dim_i, Dim_j\big)) \tag{4}$$

The resulting covariances fed the loading for each PC in the charts. The loadings present relationships through time and help determine the strength between them (Piwowar, 1996). The PCA process followed is described in Figure 16. This process was automated using the ArcMap user interface, but it can also be coded with Python. Model Builder was used to automate some of the processes.

- Separate each band from all 27 SFVC Composites
- Subtract 100 from each band to display as percentage
- Combine all bands again
- Run PCA on all components using ArcMap 10.5.1
- Present each spatial association with a graphic and each temporal association with a chart.

Figure 16 Steps used in the PCA

4 Results

Chapter 4 describes the thesis results after the data was processed and analysed. Section 4.1 presents what was discovered about the vegetation and soil in and around FGNP after doing a supervised classification. The classification provides a baseline to understand the vegetation and soil, in terms of variability, representative of the park. Section 4.2 describes the results of a principal components analysis on the multitemporal set of composites. Selected components are described and analysed, spatially, temporally, and in terms of trends. In section 4.3, the results are compared to those in the LVMP.

4.1 Supervised classification

The supervised classification begins with the digitization of all the data available from the LVMP. The paper maps drawn at the initial stages of the LVMP surveys were scanned and georeferenced to provide a starting point. The composites have four bands, with Band 2 representative of the vegetation cover percentage for each pixel. During the classification process, only the values of Band 2 were used. The maps and charts show the green vegetation cover values (Band 2) over the 10-year period for each vegetation class. As stated in section 3.1.1, the values for all three bands in each pixel are correlated and add to 100. This means that when green vegetation increases in a pixel from one date to the next, the value of bare soil (Band 1) and/or the value of dry vegetation (Band 3) decreases because they will sum to approximately 100. For the purpose of showing variation in vegetation, only green vegetation was used.

Training samples of plant species and soil types were created using the georeferenced maps and recent personal conversations (Nano, 2014-2016; Box, 2014-2016; Brim Box, 2014-

2016) with experts and ecologists in the area. Using these training samples, two supervised classifications (using ArcMap 10.5.1) were done with the 27 SFVC composites, one for soil and one for vegetation. The classes reflect defined boundaries on the map, however they are the result of a Maximum Likelihood Classification based on the training samples. The soil and vegetation classes were derived from Low, Foster and Berman (1991). Both rasters were combined into a joint vegetation/soil classified image to understand the predominant classes.

4.1.1 Soil and Vegetation Classified Maps

The Soil classification map yielded 10 different classes of soil units, shown in Figure 17. The soil classes in the area represent a variety of land types. A full list of all the soil types used in the classification can be found in Table 7 (section 3.2.2.2). Meander plains and alluvial plains are visible, as well as ridges in between eroded hills. The class identified as calcrete undulating plains with Spinifex is a special class because it is not only a soil class. In this case, Spinifex grass covers such as significant amount of the area that it is listed as occurring with this type of soil. Spinifex is the most extensive vegetation type in australia, covering 22% of the continent (Alice Springs Desert Park, 2017). Despite its short, hummock appearance, Spinifex is a perennial grass that has deep roots and can survive in the most difficult areas of Australia's deserts. There were no samples available for this plant to train the classification, however, its presence is dominant over the southern area of FGNP.

The vegetation classification map yielded 11 different classes, shown in Figure 18. Although, there are only 11 vegetation classes, there is field record of dozens more. General characteristics, soil preferences and root-type are described for the 11 classes in Table 8. Some of these classes co-exist with several other dominant plant species, such as spinifex and invasive grasses like couch grass and buffel grass that spread and burn easily. However, the map produced is a good representation of plant coverage, and more specifically plant location among geographic features.

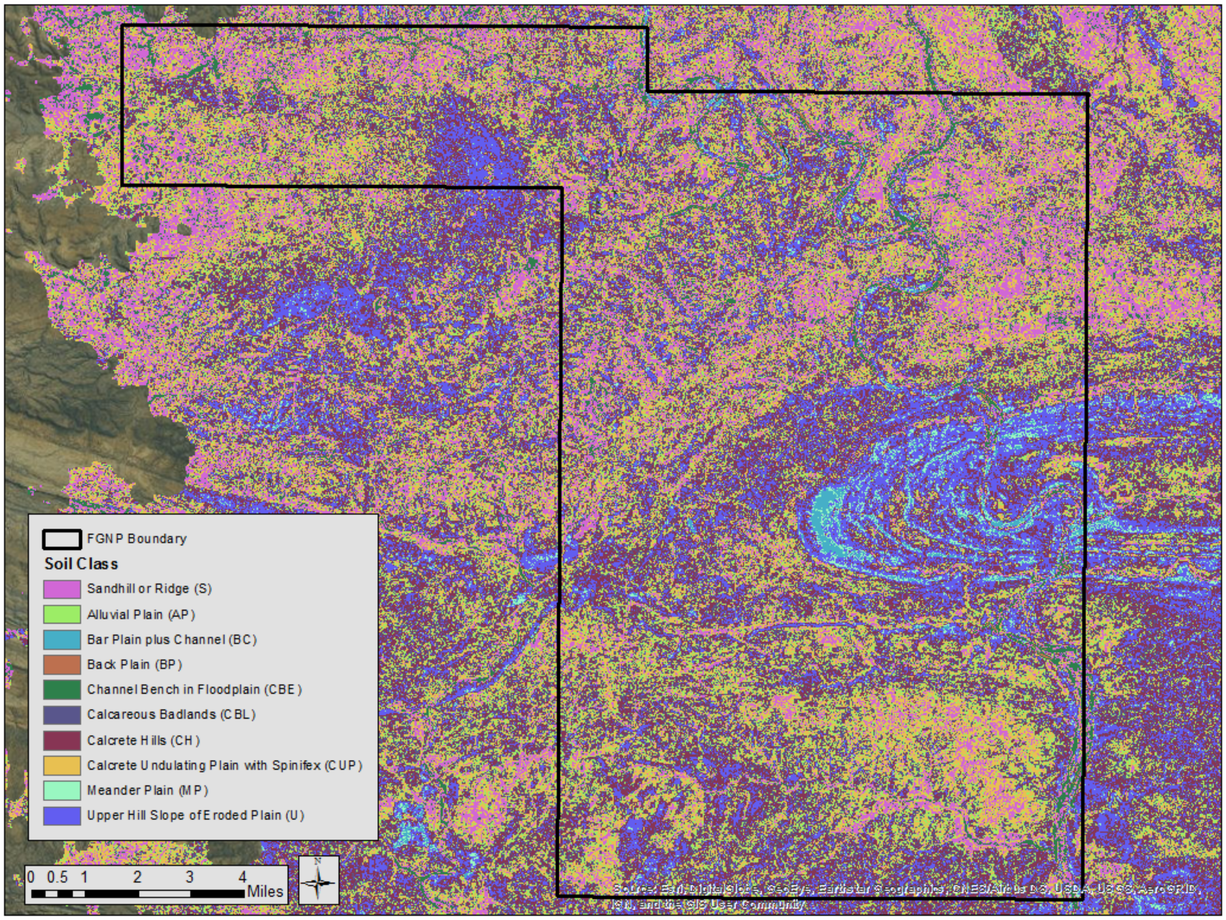


Figure 17 Soil classification map

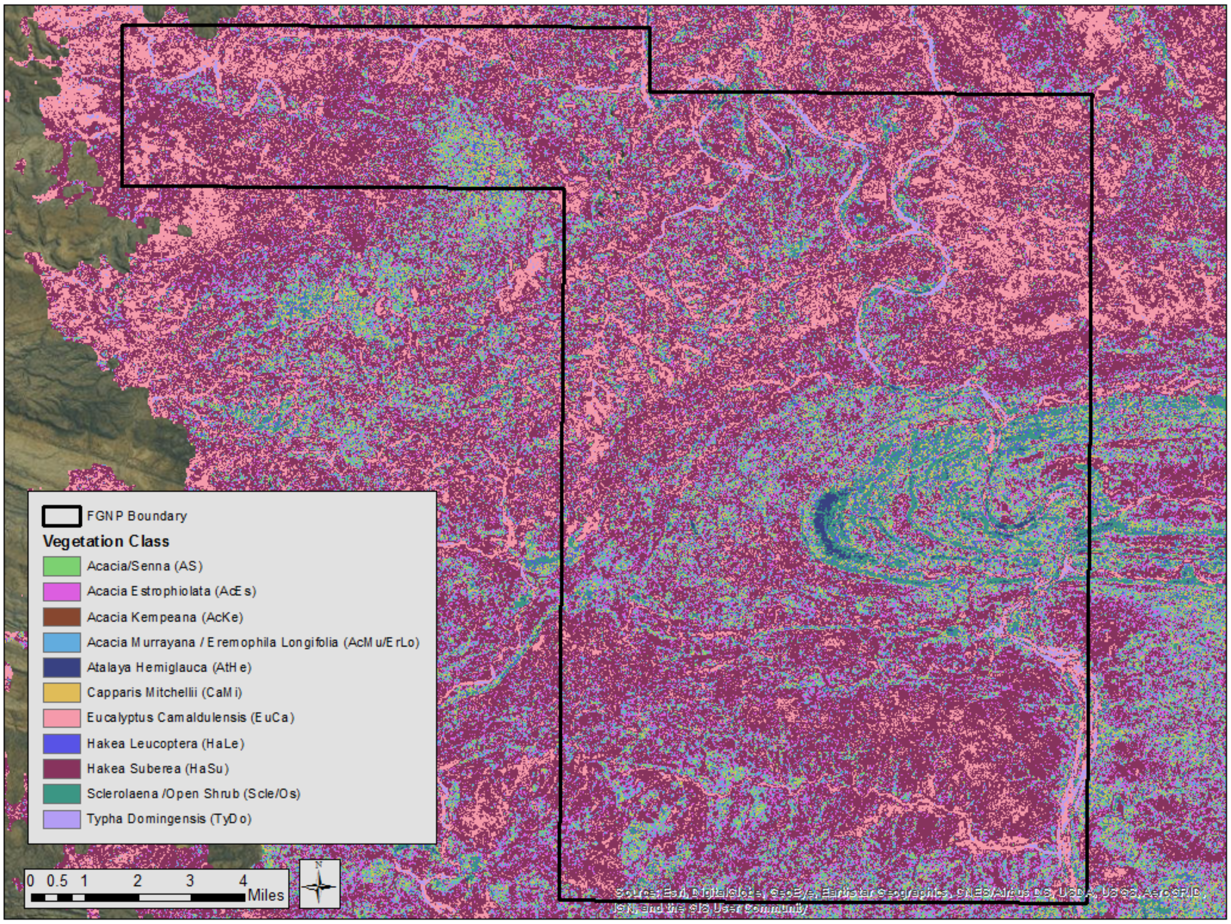


Figure 18 Vegetation classification map

Table 8 General characteristics, soil preferences and root-type of dominant vegetation.

Class	Scientific Name/ Abbreviation	Description
1	Acacia Kempeana (AcKe)	· **Acacia Kempeana** is a straggling shrub common in arid zones. · Common name: Witchetty Bush. · Soil: Stony loam or clay loam on hills, along seasonal watercourses, on decomposing granitic sandy soils.
2	Capparis Mitchellii (CaMi)	· **Capparis Mitchellii** is a thorny, slow-growing small tree. Frost and drought resistant. Requires good drainage. · Common name: Wild orange plant. · Soil: Wide range of soil types, including sand, sandy loam, clay loam and poor soil.
3	Atalaya Hemiglauca (AtHe)	· **Atalaya Hemiglauca** is a flowering, small tree. Drought tolerant. · Common name: Whitewood tree.

		· Soil: It occurs on sandy and clay soils, on flood plains, and sandy ridges.
4	Hakea Leucoptera (HaLe)	· **Hakea Leucoptera** is a small shrub or tree that re-sprouts from base. Occurs in arid and semi-arid Australia, grasslands, shrublands and woodlands. · Common name: Silver needlewood. · Soil: sandy to clay soil
5	Sclerolaena / Open Shrub (Scle/Os)	· **Sclerolaena** is a genus of annuals or short-lived perennials shrubs. Abundant Species in the area of FGNP include Sclerolaena convexula and Sclerolaena spinose. · Common name: Bindieyes.
6	Hakea Suberea (HaSu)	· **Hakea Suberea** is a small tree with thick, corky bark. Tolerant of arid conditions and frost. · Common name: Corkwood nectar tree. · Soil: Prefers moist, well-drained soils. Occurs in outcrops, rocky or stony soils, sand plains or flood plains.
7	Typha Domingensis (TyDo)	· **Typha Domingensis** is an erect, glasslike, perennial herbaceous plant. Grows along drains and edges of watercourses in slow moving water. · Common name: Bulrush, cumbungi or cattail. · Soil: Clay or sand substrate. Freshwater swamps, creeks or rivers.
8	Eucalyptus Camaldulensis (EuCa)	· **Eucalyptus Camaldulensis** is a perennial, single-stemmed, medium-sized to tall tree that could reach ages of 1000 years. deep sinker roots making them very effective in conducting water · Common name: River red gum. · Soil: Commonly grows on riverine sites, along river banks, on floodplains, preferring deep moist subsoils with clay content.
9	Acacia / Senna (AS)	· **Acacia** is a genus of shrubs and trees well adapted to hot climate and droughts, particularly prevalent in arid and semi-arid areas of Australia. Abundant Species in the area of FGNP include Acacia tetragonophylla (kurara), Acacia victoriae (gundabluie), Acacia kempeana (witchetty bush) and Acacia aneura (mulga). · Common name: Wattles or acacias. · Soil: Dry soil prone to bushfires, where they quickly grow over burned areas. · **Senna** is a species of flowering shrub adapted to a wide range of climatic conditions, although it is susceptible to frost, particularly when young. Common subspecies are Senna filifolia and Senna quadrifolia. · Common name: Silver senna, silver cassia or feathery cassia · Soil: Dry, well drained sites.

10	Acacia Estrophiolata (AcEs)	· **Acacia Estrophiolata** is a tall tree, usually found in areas with about 220–350 mm/year of average rainfall. · Common name: Ironwood or southern ironwood. · Soil: Sandy alluvial flats as scattered trees, but also in tall open shrubland and open woodland.
11	Acacia Murrayana / Eremophila Longifolia (AcMu/ErLo)	· **Acacia Murrayana** is an adaptable, fast-growing large shrub or tree. It is highly fire-tolerant and drought-adapted. · Common name: Murray's wattle. · Soil: Deep red sands but it may also occur on clay loams. It favours well-drained sites with access to run-on water such as the base of dunes, road verges and stream levees. · **Eremophila Longifolia** is an evergreen, small, rounded shrub distributed in arid and semi-arid regions suited to dry climates. It is a very hardy, drought tolerant plant and will tolerate moderate frost. · Common name: Berrigan emubush, dogwood, long-leaved eremophila. · Soil: Wide range of soil types and habitats. It generally grows in acacia or eucalyptus woodland but is also common on rocky hills, sand plains and sand dunes. It needs well-draining soil, not heavy clay.

4.1.2 Combined vegetation and soil classes

Both rasters in figures X and Y were combined to create a vegetation and soil map, shown in Figure 19. Each one of the 16 resulting classes was exported to create individual polygon features, and those used as a mask to extract the raster values from band 2 of the SFVC composite. B2 values represent the green vegetation, and can range from 0 to 100. Only values >= 25 were used. This ensured that each pixel used in the analysis had a significant amount (25% or more) of green vegetation for each class. Table 9 has description of these combined vegetation and soil classes.

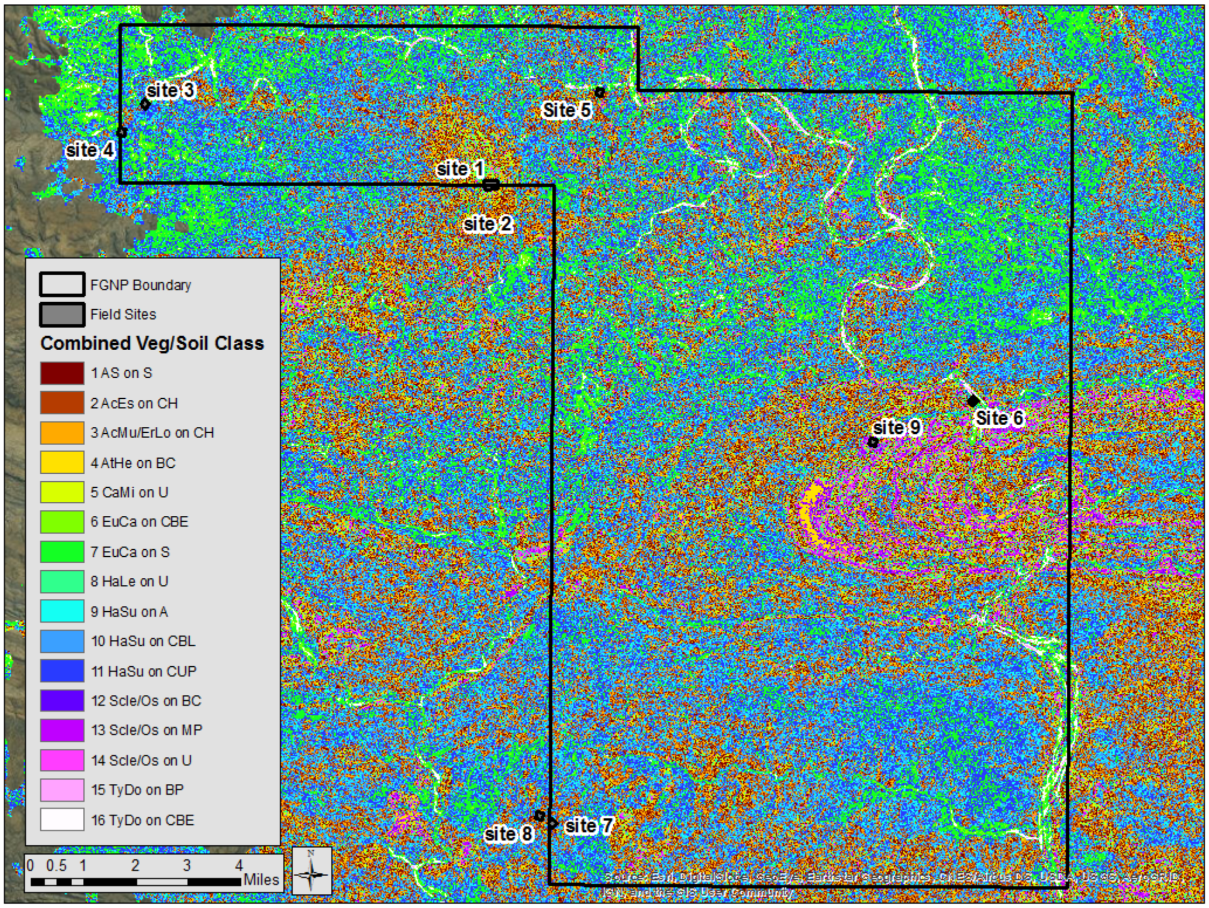


Figure 19 Vegetation and soil map

Table 9 Description of vegetation and soil classes

Class	Vegetation and Soil	Abbreviation	
1	Acacia/Senna on Upper hill slope of eroded plain	AS on U	Shrubs and trees growing in a slope of eroded plain.
2	Acacia Estrophiolata on Calcrete Hills	AcEs on CH	Tall tree preferring arid conditions in calcrete hills.
3	Acacia Murrayana / Eremophila Longifolia on Calcrete Hills	AcMu/ErLo on CH	Very hardy and drought-resistant shrubs in calcrete hills.
4	Atalaya Hemiglauca on Bar Plain plus Channel in Montane Gully	AtHe on BC	Drought-tolerant, small tree growing in elevated areas of a riverbed or a ditch in a hill.

5	Capparis Mitchellii on Upper Hill Slope of Eroded Plain	CaMi on U	Slow-growing, small tree growing in a slope of eroded plain.
6	Eucalyptus Camaldulensis on Channel Bench in Floodplain	EuCa on CBE	Deep-rooted trees in areas that flood and can collect and store water even during dry periods.
7	Eucalyptus Camaldulensis on Sandhill or Ridge	EuCa on S	Deep-rooted trees in areas that can collect and store water even during dry periods.
8	Hakea Leucoptera on Upper Hill Slope of Eroded Plain	HaLe on U	Small tree that likes sandy, clay soil growing in a slope of eroded plain.
9	Hakea Suberea on Alluvial Plain	HaSu on A	Small tree with thick, corky bark, drought and frost tolerant growing in alluvial, and subject to floods.
10	Hakea Suberea on Calcareous Badlands	HaSu on CBL	Small tree with corky bark, drought and frost tolerant, growing in badlands.
11	Hakea Suberea on Calcrete Undulating Plain with Spinifex	HaSu on CUP	Small tree with corky bark, drought and frost tolerant, in undulating plains with spinifex.
12	Sclerolaena/Open Shrub on Bar Plain plus Channel in Montane Gully	Scle/Os on BC	Shrubs of the family sclerolaena are annuals or short-lived growing in elevated areas of a riverbed or a ditch in a hill.
13	Sclerolaena/Open Shrub on Meander Plain	Scle/Os on MP	Shrubs of the family sclerolaena are annuals or short-lived in winding plain.
14	Sclerolaena/Open Shrub on Upper Hill Slope of Eroded Plain	Scle/Os on U	Shrubs of the family sclerolaena are annuals or short-lived growing in a slope of eroded plain.
15	TyDo on Back Plain	Typha Domingensis on BP	On the plan between a riverbed and a hill.
16	TyDo on Channel Bench in Floodplain	Typha Domingensis on CBE	Shallow-rooted, drought tolerant and typically found in areas that flood and can collect and store water even during dry periods.

Soil unit and vegetation cover regions can be recognized in Figure 19. The nine sites of the LVMP were selected to present distinct vegetation, topography, and soil composition so their location can be used as a representation of composition.

Short-lived tussock shrubs and grasses can be seen in the northwest of the park as well as some parts in the southeast and northeast (blue and green). These grasses grow in clumps or bunches and in Figure 19 exist in calcrete and sandstone hills and eroded plains. Sparse witchetty bush shrubland and five-minute grass are also found in the area. Sites 3 and 4 are in this area.

Annual short-lived grasses and forbs are a dominant species in the centre area of the park (pink and purple), including bindieyes, a favourite among native birds. Annual grasses can appear between hummock grasses, especially after rains but can quickly dry. Some of these softer plants are palatable and prone to being grazed, which is another reason they quickly disappear after rain. Sites 6 and 9 are located in this area. Site 6 sits on the alluvial plain next to the Finke river and has a good population of River Red gum trees as well as a significant population of Mulga shrubs over grasses. Site 9 is on a gentle slope with erosion gullies and its dominant vegetation appears to be sparse Acacia shrubs with other grasses.

Spinifex grasslands and hummock grasses are found in the south. Hummock grasses grow in mounds. Spinifex cover is as fundamental to the area as the land features because it is so prevalent. Sites 7 and 8 sit on wind-eroded dunefields within hummock grasslands. Other plant species found in these grasslands are mulga, wattle, ironwood and blue mallee.

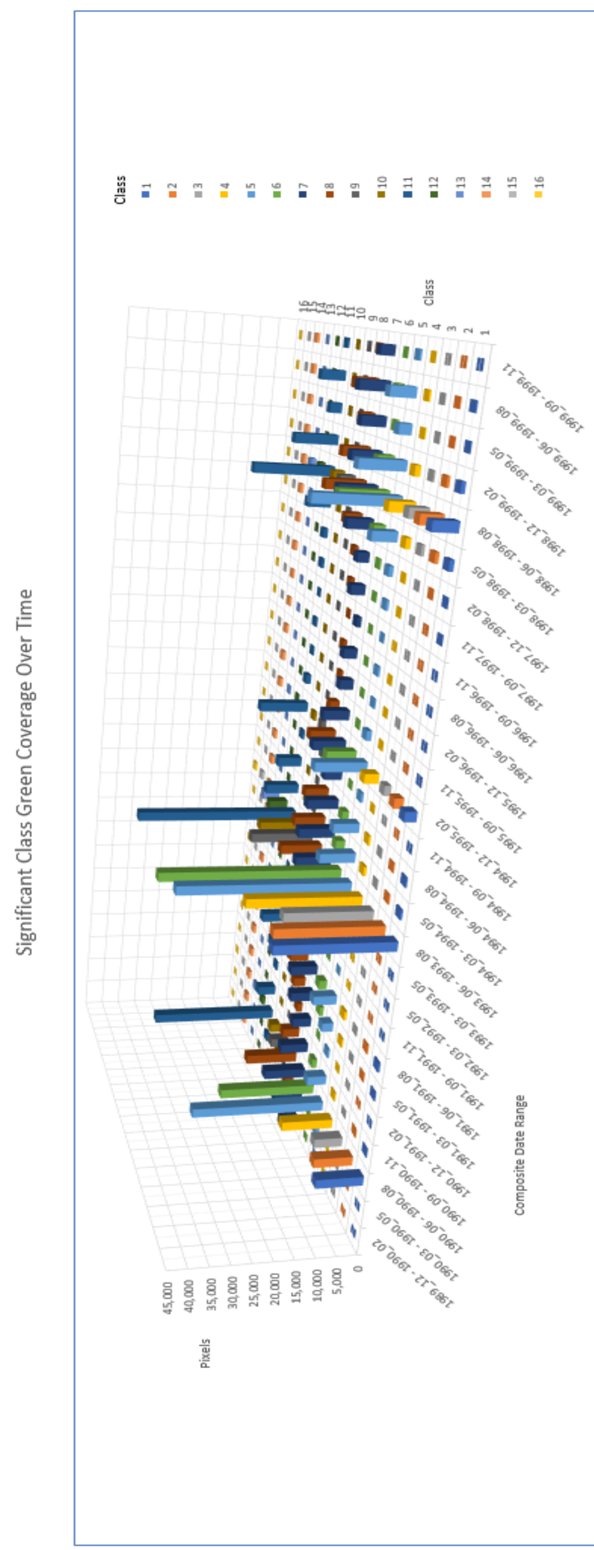
Sparse witchetty bush areas appear in the north centre of FGNP. Witchetty bushes are common in arid areas and provide cover for many grass species. Sites 1, 2, and 5 are located in this area. Sites 1 and 2 are in a gentle slope over sandstone and Site 5 is on a flood plain.

4.1.3 Variability of Classes through Time

Figure 20 shows the numbers of pixels with significant green vegetation cover in each class for each composite time frame. Out of the original 40 composites, each one covering an annual season over 10 years, only 27 were used because they showed complete, or almost complete, coverage over the park. The remaining composites were excluded. The temporal gaps left by the exclusion of incomplete composites can be seen in the chart, with the largest gaps between May 1992 and March 1993 and between November 1996 and September 1997. Although there are only 16 classes, it is understood that there are dozens more plant species that may not have occurred in significant numbers or that may be too similar to others.

Classes 5, 6, 7, 8, and 11 have the largest coverage of green vegetation. These classes consist of almost 74% of all significant green vegetation pixels. Most of the vegetation in these classes are frost and drought tolerant or deep-rooted trees. Classes 7 and 8 have the most consistent cover, only slightly increasing after rains and slightly decreasing during dry periods, suggesting a looser connection to rainfall than other plants. This type of vegetation, river red gum trees, have deep roots and can maintain green canopy cover even during droughts. Classes 1-4, 9-10, and 12-16 are classified as short-lived grasses or shrubs with short roots on floodplains or sloped areas. In these classes, rainfall is a more influencing factor of change. Some of the pixels may appear misidentified due to atypical plant behaviour after rain or during a drought.

The composites covering the spring seasons of 1990, 1993 and 1998, present the largest number of pixels with significant green vegetation. There is also a slight increase in the summer of 1994-1995. These higher values correspond to the increase in rainfall during the months of May 1990, May 1993, January 1995 and February 1997. The mean, median, standard deviation, number of pixels with significant (> 25% green vegetation cover), and the percentage of cover for each class are shown in Table 10.



Class	1989_12 - 1990_02	1990_03 - 1990_05	1990_06 - 1990_08	1990_09 - 1990_11	1990_12 - 1991_02	1991_03 - 1991_05	1991_06 - 1991_08	1991_09 - 1991_11	1992_03 - 1992_05	1993_03 - 1993_05	1993_06 - 1993_08	1994_03 - 1994_05	1994_06 - 1994_08	1994_09 - 1994_11	1994_12 - 1995_02	1995_09 - 1995_11	1995_12 - 1996_02	1996_06 - 1996_08	1996_09 - 1996_11	1997_09 - 1997_11	1997_12 - 1998_02	1998_03 - 1998_05	1998_06 - 1998_08	1998_12 - 1999_02	1999_03 - 1999_05	1999_06 - 1999_08	1999_09 - 1999_11
1	0	12	11401	213	9	264	469	0	1	32	27730	468	330	18	2744	51	25	36	5	78	95	1005	5635	892	138	278	23
2	0	13	9500	145	14	161	307	0	1	19	25432	307	227	11	2162	47	26	38	11	49	76	839	5136	597	124	196	17
3	0	8	6956	66	4	98	190	1	0	20	20987	204	162	8	1578	33	17	30	7	28	44	726	4477	351	85	118	11
4	0	24	12720	334	21	384	701	1	0	33	27513	705	504	24	3424	71	36	39	7	88	139	1177	5894	1275	222	413	40
5	0	944	33128	4843	512	2791	5867	13	13	507	41964	8672	6255	593	12459	1251	313	513	55	631	1054	5901	20147	10798	2893	5868	472
6	0	136	24157	1223	59	1002	2029	2	2	127	44509	2275	1604	73	7223	217	69	110	13	194	399	2720	11724	3737	673	1406	77
7	4843	7284	10713	7158	4794	6088	6916	1670	707	2285	8989	9050	7757	4366	8096	6375	3310	3275	1059	3384	2803	6193	9249	7008	5752	7195	3270
8	0	2223	13351	4361	1349	3081	4769	121	37	658	10495	7812	5921	1237	6452	2332	637	874	112	904	991	4057	9680	6481	3149	5440	778
9	0	5	4668	51	7	58	107	2	0	24	15940	156	117	2	1128	29	21	20	9	28	38	526	3698	250	66	79	18
10	0	1	2698	26	6	28	43	0	0	19	11647	109	75	3	674	16	11	14	5	15	29	328	2822	169	45	50	7
11	0	944	33128	4843	512	2791	5867	13	13	507	41964	8672	6255	593	12459	1251	313	513	55	631	1054	5901	20147	10798	2893	5868	472
12	0	5	902	6	1	8	12	0	0	17	4966	50	25	2	302	13	9	8	3	16	16	158	1403	58	29	31	9
13	0	0	802	5	4	7	12	2	0	13	4463	34	21	5	262	17	16	10	7	11	19	136	1252	71	34	33	19
14	857	816	806	836	776	757	676	546	427	485	802	807	712	647	824	836	707	596	460	740	639	774	809	801	780	762	697
15	0	0	136	3	2	2	5	0	0	1	779	8	4	0	41	3	4	4	4	3	5	22	171	13	10	10	7
16	0	0	133	5	2	4	4	2	1	4	576	21	11	3	20	7	8	6	9	7	13	18	88	27	12	20	11

Figure 20 Classified pixels with significant vegetation cover over time

Table 10 Data for each significant vegetation cover class

Class	Number of Pixels	Standard Deviation	Median	Mean	Percentage of Cover per Class
1	51952	5686.833117	95	1924.148148	5.40%
2	45455	5162.661392	76	1683.518519	4.73%
3	36209	4222.6943	44	1341.074074	3.76%
4	55789	5733.583787	139	2066.259259	5.80%
5	168457	10281.01543	1251	6239.148148	17.52%
6	105760	9564.434269	399	3917.037037	11.00%
7	149589	2695.591886	6088	5540.333333	15.55%
8	97302	3595.660048	2332	3603.777778	10.12%
9	27047	3187.339831	38	1001.740741	2.81%
10	18840	2306.906392	26	697.7777778	1.96%
11	168457	10281.01543	1251	6239.148148	17.52%
12	8049	983.9013918	13	298.1111111	0.84%
13	7255	883.1243407	16	268.7037037	0.75%
14	19375	121.5012691	762	717.5925926	2.01%
15	1237	151.9997563	4	45.81481481	0.13%
16	1012	111.3719929	8	37.48148148	0.11%
	961785				100.00%

4.2 PCA Results

A PCA performed on the multitemporal set of SFVC composites yielded 81 principal components (PC). Each of the 27 composites has 3 bands, representing bare soil (Band 1), green vegetation (Band 2) and dry vegetation (Band 3); 27 x 3 = 81. The first PCs account for most of the variance, with the first three representing more than 85%. The higher the percentage the more variation it explains and the lower the percentage, the less variation it explains. Table 11 shows all 81 PCs and the percentages associated with each.

Table 11 Data for each significant vegetation cover class

PC1	76.0964%	PC18	0.3222%	PC35	0.1329%	PC52	0.0373%	PC69	0.0019%
PC2	6.2308%	PC19	0.2985%	PC36	0.1238%	PC53	0.031%	PC70	0.0019%
PC3	2.7607%	PC20	0.2912%	PC37	0.1092%	PC54	0.0278%	PC71	0.0019%
PC4	1.7174%	PC21	0.2794%	PC38	0.1063%	PC55	0.0026%	PC72	0.0019%
PC5	1.4412%	PC22	0.2716%	PC39	0.1%	PC56	0.002%	PC73	0.0019%
PC6	0.8736%	PC23	0.2548%	PC40	0.0952%	PC57	0.002%	PC74	0.0019%
PC7	0.7635%	PC24	0.2451%	PC41	0.0859%	PC58	0.0019%	PC75	0.0019%
PC8	0.7171%	PC25	0.2376%	PC42	0.0791%	PC59	0.0019%	PC76	0.0019%
PC9	0.6698%	PC26	0.2282%	PC43	0.0749%	PC60	0.0019%	PC77	0.0019%
PC10	0.5481%	PC27	0.2188%	PC44	0.07%	PC61	0.0019%	PC78	0.0019%
PC11	0.5049%	PC28	0.1951%	PC45	0.0666%	PC62	0.0019%	PC79	0.0019%
PC12	0.4651%	PC29	0.1885%	PC46	0.0628%	PC63	0.0019%	PC80	0.0018%
PC13	0.4315%	PC30	0.1747%	PC47	0.0614%	PC64	0.0019%	PC81	0.0016%
PC14	0.4032%	PC31	0.1662%	PC48	0.054%	PC65	0.0019%		
PC15	0.3831%	PC32	0.1505%	PC49	0.0456%	PC66	0.0019%		
PC16	0.3472%	PC33	0.1469%	PC50	0.0435%	PC67	0.0019%		
PC17	0.3387%	PC34	0.1368%	PC51	0.0421%	PC68	0.0019%		

A visual inspection of the components was performed to identify significant PCs. Most of the higher PCs are included and most of the PCs with lower variation are excluded. Although this decision seems arbitrary, the inclusion/exclusion of PCs is based on thorough visual analysis of the components significance. This seemingly subjective process requires knowledge of the area and an understanding of the processes, soils and vegetation composition.

Each component shows processes happening to the entire image area. They are presented spatially and temporally using map images and component loading charts. The component map images present spatial relationships graphically for each PC and are shown in the map images for

Figures 21 – 24. The red areas (more negative values) and blue areas (more positive values) represent areas of strong association. The beige areas (values closer to zero) represent weaker relationships and less significant variation.

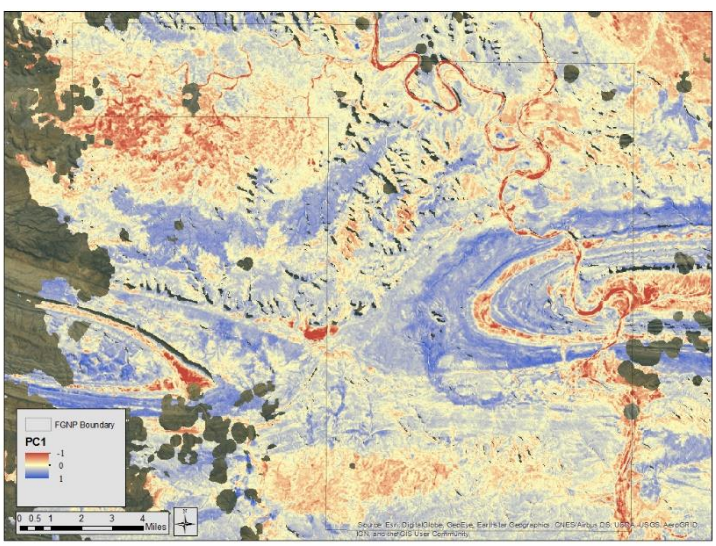
The PC loadings graphs, shown in the charts for Figures 21 - 24, represent the temporal relationship. The Y-axis plots the covariance between each input band and each component. The three lines denote bare soil (red), green vegetation (green), and dry vegetation (blue). The X-axis represents the time in three-month periods corresponding to each SFVC composite. The positive values indicate that they increase together or decrease together. The negative values indicate that the dimensions are inversely correlated. Values of zero indicate variables are independent.

The first four principal components were selected for review an analysis. The remaining components did not seem to have had visible patterns, however they may explain other smaller sources of variation.

4.2.1 Principal Component 1 (PC1) – 76.1%

Principal Component 1 (PC1) in Figure 21 represents most of the variation through time at 76.1% and shows broad-scale processes in the area. The high value of PC1 can be explained by the regional processes that often dominate ecological dynamics. The darker red areas highlight river beds, meander and sloped plains, and sandy plains, typical areas that could collect and hold water. The darker blue areas represent hilltops, rocky outcrops, and other areas where rainfall run off is common. As the colours lighten and get closer to yellow, the areas vary the least, with some obvious depressions and outcrops seen in the images.

PC1 is indicative of processes that occur over the area simultaneously, such as a drought, a freeze, or any other environmental affects. The loadings for PC1 show consistent values, a characteristic of typical conditions. These typical differences are very representative of the geography and vegetation and map out different ecological zones in the area. PC1 explains how they share the same rates of variation; how they rise and fall through time.



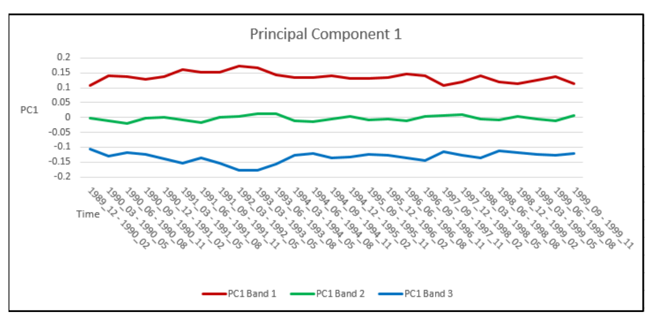


Figure 21 Image and Loadings for Principal Component 1. The figures represent spatial variation of PC1 at 76.1% over FGNP, and surrounding areas.

4.2.2 Principal Component 2 (PC2) – 6.2%

Principal Component 2 (PC2) in Figure 22 represents the second most variation through time at 6.2%, independent of variation caused by broad-scale proccesses accounted for by PC1. The dark blue areas support persistently green, photosynthesizing vegetation over time, such as riverbeds or channel benches. Deep-rooted trees in these areas can access underground water and maintain leaf canopies even during periods of drought. Most of the dark red areas are classified as rocky hills, calcareous rises or sloped plains with perennial, short-lived grasses and sparse woody vegetation. These plants with shallow root systems have limited or no access to underground water. Their growth and reproduction are closely linked to sporadic rainfall events.

PC2 shows the difference between persistently green vegetation and rainfall-dependent vegetation. The loadings present higher values of dry cover and bare ground when compared to green coverage. There is a large gap in the input composites between the winter of 1992 and the winter of 1993, where a shift in the composites can be seen between dry vegetation cover and bare soil.

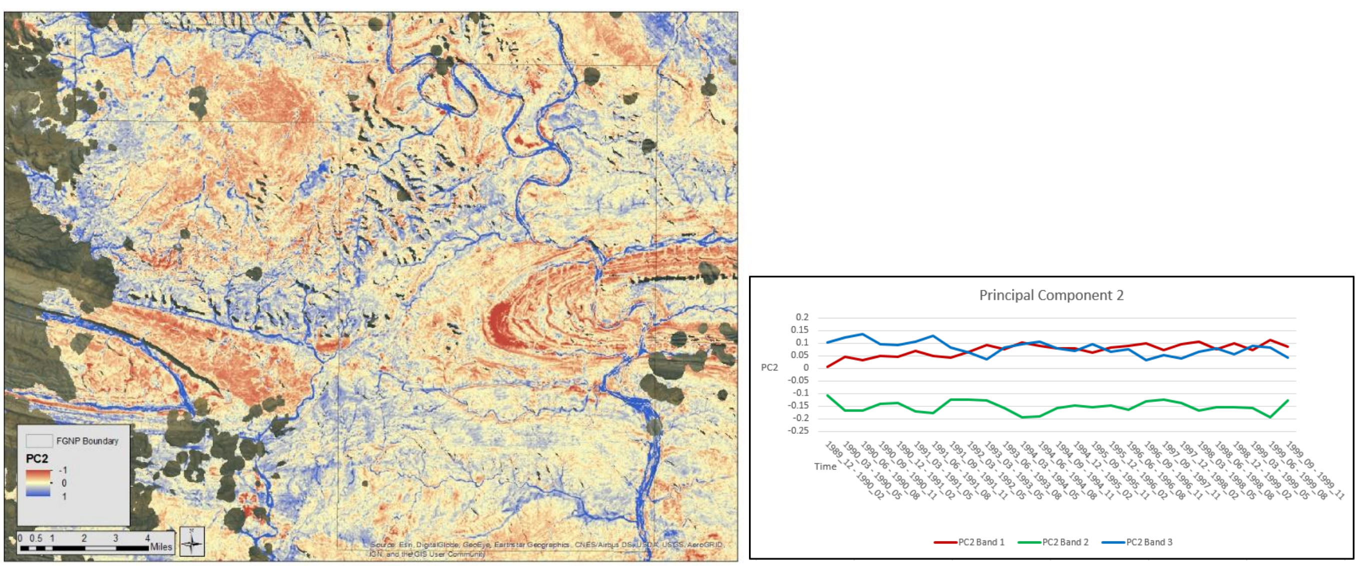


Figure 22 Image and Loadings for Principal Component 2. The figures represent spatial variation of PC2 at 6.2% over FGNP, and surrounding areas.

4.2.3 Principal Component 3 (PC3) – 2.8%

Principal Component 3 (PC3) in Figure 23 represents 2.8% of the variation in the area and shows some fine-scale processes. There is a visible change corresponding to a fenceline on the west side of the park (Palm Paddock) bisecting a red area. The dark red colour above the fence correspond to an increase in vegetation. The lighter red colour below the fenceline corresponds to a slower increase in the vegetation, indicating a difference between growth inside and outside the fence. The same colour pattern is seen towards the center of the east boundary, where the sandy portions near the river with a sigificant population of deep-rooted trees show dark red and the surrounding meandering plain with small trees and shrubs show a lighter shade of red.

PC3 components represents localized changes over time. In the loadings, Band 2 showing green cover increases just after the first significant high rainfall periods, in winters of 1990 and1993, and summer 1994, following land management efforts. Band 1 bare soil cover loadings show a decline as band 3 dry vegetation cover shows a steady increase.

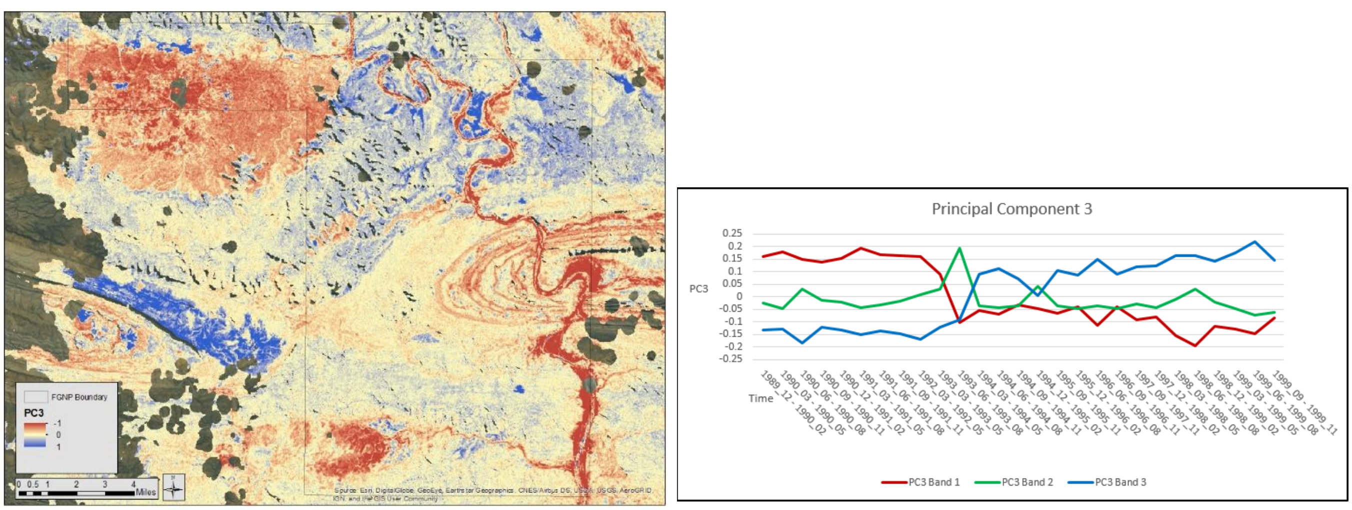


Figure 23 Image and Loadings for Principal Component 3. The figures represent spatial variation of PC3 at 2.8% over FGNP, and surrounding areas.

4.2.4 Principal Component 4 (PC4) – 1.7%

Principal Component 4 (PC4) in Figure 24 represents 1.7% of the variation in the area and shows other finer-scale processes. The dominant spatial pattern on the map, shows intense red colours in the area where the Finke River splits into Palm Creek to the the west and Ellery Creek towards the north. This area is mostly surrounded by blue zones made up of sandy hills and calcareous rolling plains. Many of these blue zones may reflect abrupt changes in the area's vegetation cover. These abrupt changes can represent fires burning quick through dry foliage or floods clearing the river vegetation as it floods. Another area of dark red colour appears on calcrete undullating hills at Palm Paddock, predominantly covered by hummock grasses like spinifex, with some blue areas representing the riverbed and floodplain.

The loadings for the PC4 explain some of the spatial pattern where localized changes occurred. The rains in 1990 and 1993 are represented with high values for the green vegetation cover and low value for the dry vegetation cover. The rains of 1995 and 1997 were not visible, however the rainfall during those years was consistently low.

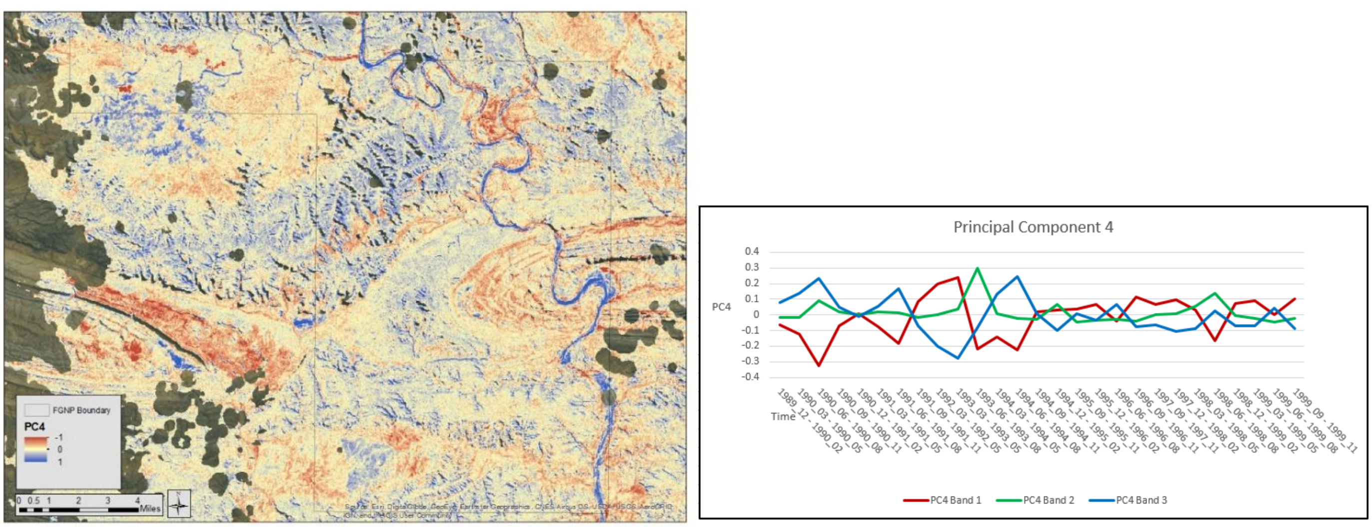


Figure 24 Image and Loadings for Principal Component 4. The figures represent spatial variation of PC4 at 1.7% over FGNP, and surrounding areas.

4.2.5 Area of Interest – Palm Paddock

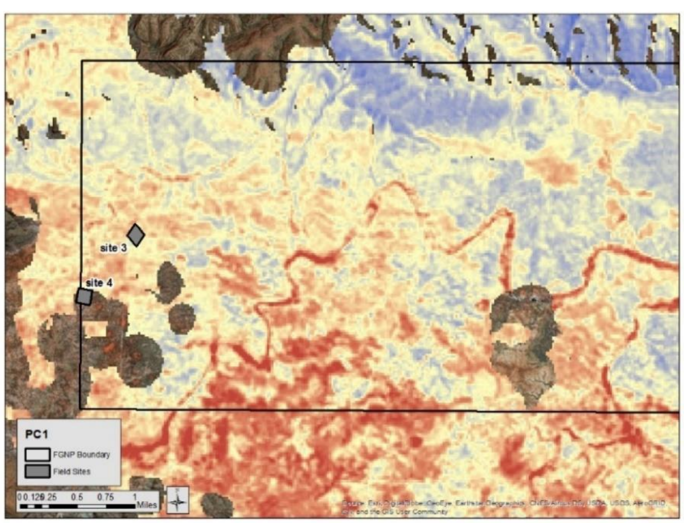
During a close analysis of all the components, the area of Palm Paddock seemed to provide interesting patterns and were used it as a case study to further understand the changes in vegetation at a more appropriate scale. Palm Paddock is located at the far northwest section of FGNP and was an area fenced during the land management efforts in the late 1980's and early 1990's. Principal components show the strength of the spatial association with the really high and really low values represented as dark blue and dark red.

PC1 (Figure 25a) depicts broad scale processes under average conditions in the area. Arid zones like FGNP are strongly dependent on environmental effects like rain, temperature, fire, etc. Some features of the landscape are defined spatially and visible but this image and its loadings provide a picture of that the average conditions look like. A PCA with the spatial scale of only Palm Paddock would yield different results and the spatial relationship strength would be more obvious.

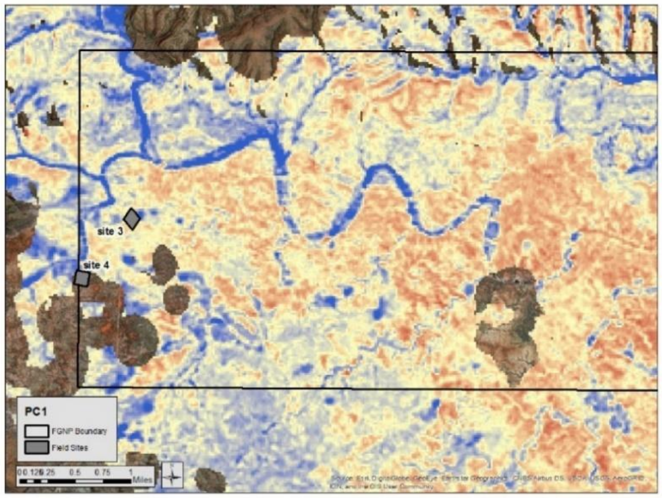
A significant portion of the blue areas in PC2 (Figure 25b) are in a dry river beds, which typically collect moisture and favour persistent ground water collection long after rainfall. One dominant plant species present in the dry riverbeds in the Finke River and its tributaries is River red gum tree. These and other deep-rooted trees can access water underground, maintaining the green leaf canopies, even during dry periods. A second type of dominant vegetation in these areas is cattail. Cattail is shallow-rooted, fairly tolerant to drought and typically found near water sources. Their growth and reproduction are closely synched to sporadic rainfall events, resulting in quick green vegetation bursts following even a small amount of rain. Both types of vegetation respond differently to rainfall, but dominate the same area. The red areas in PC2 are classified as hilly and sloped areas with perennial, short-lived grasses and sparse woody vegetation. These shallow-rooted grasses and forbes (Acacia, Senna, Ironwood, Corkwood) have restricted access to underground water sources and quickly respond to drought or any amount of rainfall.

PC3 (Figure 25c) represents an increase in woody vegetation in areas where horses were removed to cease grazing and a fence was emplaced to prevent more large herbivores to enter the area; most of the work was completed by 1989. This type of land management was drastic and encouraged quick recovery of the vegetation. Other environmental threats remained, however, the effects of the horse removal can be seen in PC3 as the fence can be outlined in the image.

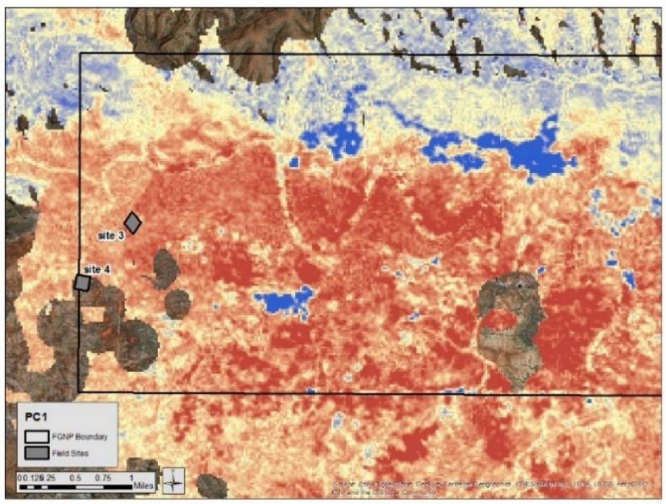
The localized variation in PC4 (Figure 25d) highlights some areas in the south part of Palm Paddock that may have underwent fires and areas where river currents can clear the vegetation with its force after a flood. Controlled fires are set to prevent wild fires from spreading out of control. Additionally, wild fires are difficult to document in isolated areas because they can start and die down without notice. Some of the remaining components could represent significant features of the landscape or meaningful spatial patterns but, their increasingly insignificant values make their importance difficult to assess.



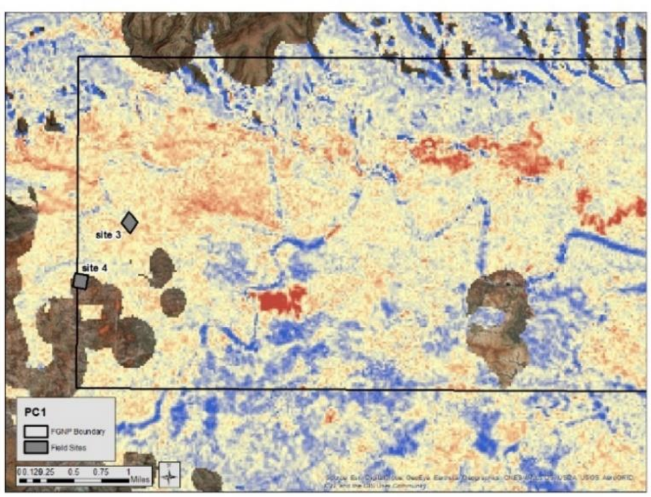
(a)



(b)



(c)



(d)

Figure 25a-d Images for Principal Components 1-4 for the area of Palm Paddock

5 Discussion and Conclusions

This chapter discusses classification and PCA results in the context of previous work conducted as well as how the methods were applied to FGNP. The research questions are also addressed and conclusions are presented, based on analysis results. Limitations encountered during the thesis process are considered and possible future research options area identified.

The two main methods used to conduct the thesis were supervised classification and PCA. The supervised classification used LVMP field data collected in the 1990's at FGNP. This was mainly due to not having the capability to collect training samples. It also made sense to use data matching temporal range to the SFVC composites used in the PCA. The classification helped in creating a baseline to understand the vegetation and soil of the park.

Many pixels in the 16 resulting classes representing combinations of soil forms and vegetation were identifying plants that were similar or behaved similarly as one class. Environmental effects could cause some of the pixels to be misrepresented in a supervised classification, particularly rainfall. Rainfall in this arid area is unpredictable and vegetation may behave atypically. Some invasive or drought-resisting plants can invade an area occupied by a dry and dormant species. Non-native invasive species like couch grass and buffel grass are notorious for spreading quickly in central Australia and thus changing the plant composition.

Upon closer inspection, a general pattern of plants with similar characteristics was seemingly present. The patterns were tightly connected with the land forms in the areas but groups of short-lived tussock shrubs and grasses in the northwest, annual short-lived grasses and forbs in the centre, spinifex grasslands and other hummock grasses in the south, and sparse witchetty bushland in the north centre were apparent. The general characteristics for each vegetation class represent a large number of other plants with a similar footprint. In addition, it was common to see similar plants behaving differently as they grow in different soil forms (i.e. acacia short bush growing on the riverbed as well as on the eroded side of a hill). Heavy and consistent rains during the year 1993, and the summers of 1994 and 1996 are reflected as an increase of green vegetation cover for most classes. The supervised classification results provided a greater understanding of the vegetation changes in the area based on rainfall, vegetation characteristics and land forms. These findings were essential to the understanding of the resulting PCs of the PCA.

The first four PCs were selected for further analysis. PC1 accounts for most of the variation at 76% and represents broad-scale processes, typical of the area. Areas that can typically collect water, either due to soil composition or land form, have reverse values to areas where water typically runs off, such as hilly area or areas where the soil is sandy and water can quickly seep through. Common conditions at FGNP are a persistent drought with periodic rainfall that may be significant or in short bursts. Rainfall occurs mostly during the summer months but also during the other seasons and can take years to fall at a rate that can significantly affect the area. Studies by Piwowar (1996) and Henderson (2010) had similar results. Piwowar (1996) found that PC1 showed "a generalized perspective of the northern ocean's ice cover." His study of the area is pertaining to ice and lacks the vegetation component, however, much of the literature on PCA agrees that PC1 will represent the most variation and therefore, when looking at a large enough temporal range will show average, or the most common conditions. In his study, Piwowar (1996) compared the differences of areas with constant ice cover and areas with no ice cover. In her study, Henderson (2010) found that PC1 reflects conditions that would typically occur in the area, with dry areas showing opposite values to wet areas, as well as protected areas showing opposite values to cultivated areas.

PC2 accounts for 6.2% of the variation and presents a more defined pattern in vegetation. It shows the difference between persistently green vegetation and rainfall-dependent vegetation. Areas that are persistently green, like deep-rooted trees that can access underground water tables, have opposite values of areas that are not persistently green, such as annual grasses or shallow-rooted plants that have no access to underground water and can turn green or dry quickly. It is understandable that PC2 corresponds to vegetation attributes because most plants in central Australia have adapted to live in extremely harsh conditions. In Henderson's study of Grasslands National Park in Saskatchewan, Canada, the second most important source of variation seems to be tightly related to temperature. She found more localized changes showing strong spatial patterns in years that had either very high or very low temperature readings (Henderson 2010). This shows that it is possible to have very different results when PCA is applied to two similar areas. Grasslands National Park and FGNP are both protected arid and semi-arid zones with drastic temperature changes between seasons.

PC3 shows 2.8% of the vegetation and shows finer-scale, localized processes. It is apparent that this component highlights differences between areas inside and outside the fence placed around the Palm Paddock area in the northwest portion of FGNP. The difference in the colour of the areas above and below the fence indicate a difference in growth between vegetation inside and vegetation outside the fence. The relatively small Palm Paddock area is affected similarly by rainfall, temperature and other environmental factors. Human-introduced effects, however, have allowed the vegetation inside the fence to recover while the area outside this boundary remain available to grazing and trampling by horses and other large herbivores. The lighter red colour below the fenceline suggests a slower increase in the vegetation, corresponding to the land management efforts.

PC4 shows 1.7% of the vegetation and shows other fine-scale processes. The dominant spatial pattern on the map shows blue colours over dry areas, specially dry riverbeds and creeks. The spatial pattern can be further scrutinized by looking at the Palm Paddock area alone where blue zones could represent areas of rapid vegetation changes, such as the burning of dry plants or clearing of vegetation by flooding river waters.

As expected, rainfall was a pivotal factor that drove much of the variation occurred at FGNP. High rainfall years directly influenced some of the vegetation growth in the area, but did not explain all. PCA showed that some of the variation was independent from rain. This is particularly visible in the PC3 with differences inside and outside of the park fence. The supervised classification and PCA in this thesis support the findings of Miller, Low and Matthews (1998) that there was a general vegetation recovery in areas of FGNP that underwent land management methods.

Miller, Low and Matthews (1998) also concluded that a number of invasive species benefited from these changes and increased in the area. This conclusion was not apparent in the PCA, and may require a PCA of a smaller spatial scale and/or large temporal scale, or a further review of the smaller components over the entire park after field work determines the extent of cover of these plant species.

The use of classification using existing non-digital maps was necessary for this thesis. General knowledge of vegetation cover and land forms in the area was necessary but no recent field samples were available. The data collected during the LVMP and documented in Low, Foster, and Berman, (1991); Low et al., (1992); Low et al. (1993); Cook et al., (1995); Miller, Low, and Matthews, (1998) filled a portion of this knowledge gap, however, it was a limiting factor which introduced errors in pixel categorization. Uncharacteristic plant response to rainfall and unpredictable rainfall patterns also accounted for some of the pixel misclassification. Future research in this topic or this area will improve with the use of more current information about vegetation type, vegetation cover, soil composition, erosion and grazing animals in the area. This will allow for a more reliable quantification of change and therefore a better classification.

The PCA rested on the use of seasonal fractional vegetation cover composites that represented typical annual seasons. These composites were derived from geometrically and radiometrically corrected Landsat images. Composites minimize data loss from individual images, however, when looking at large areas these same composites can introduce gaps as well. Only 27 composites out of the possible 40 were used due to completeness, leaving large gaps in the temporal scale. Landsat 5 was the only source of satellite images available during that time. These issues limited trend analysis because some annual season composites were not included in the PCA. Future research using PCA in this area should include a more complete set of regular time-series images or composites. Multiple sources of data are now available and the possibility of using one or more of these sources will minimize the gaps in the coverage and maximize the detection of trends.

Future work should also include a study of smaller, paddock-sized areas. When doing a PCA at a smaller scale the variations are more apparent, and so are trends. Preliminary work conducted over only the area of Palm Paddock shows stronger trends, not visible when doing a PCA over the entire park. The methodology created to process the data in this thesis should be revised to ensure that it is most effective in determining how sources of variation have affected the vegetation.

This thesis presents a novel use of PCA as a tool to understand and explore changes in managed areas in remote central Australia. The method described in this thesis can be used as an exploratory way to identify areas that may not be obviously threatened, but due to its particular signature should be evaluated. This kind of research is significant because it uses an established and accepted, relatively simple and cost-effective method to understand changes occurred in remote areas. Land managers can use this kind of analysis as a viable alternative to initially assess the value of their efforts.

This thesis supports the claim that the vegetation in managed areas at FGNP has seen some recovery, as the field survey has stated. The conclusion was reached through the analysis of the results of a supervised classification and PCA whereas previous work concluded the same with the collection of field data over a period of eight years. This thesis did not have a fine enough temporal scale to identify trends in individual plants species as the LVMP was able to capture. However, at the larger spatial scale used, this research showed how some dissimilar land forms in the areas presented similar trends in variation and how some comparable land forms presented variation in different ways. With currently available, finer images, the PCA would have been more efficient at recognizing some trends, as the ground sampling interval is smaller. Products from any modern suite of satellite systems can provide better resolution than the Landsat 5. Another option would be the use of unmanned aerial vehicles or drones to regulate and improve the spectral and temporal resolution. This technology allows full control of image collection, far outweighing its marginal cost. These differences occur due to either natural effects, such as vegetation species or soil composition, or due to human or animal action. The natural effects were associated with the classification of plants and soil in the area. The human and animal effects were due to land management practices and heavy grazing and soil compacting. PCA was used as a tool to help separate and understand the variation. Of interest in the PCA results, was the area of Palm Paddock, where most land management efforts were focused at. This method provides an alternative for land managers to study other remote parts of central Australia, where field surveys may not be cost-effective, and to more appropriately allocate efforts to protect vulnerable areas.

6 References

Abuelgasim, A., W. D. Ross, S. Gopal, and C. Woodcock. "Change Detection Using Adaptive Fuzzy Neural Networks: Environmental Damage Assessment after the Gulf War." *Remote Sensing of Environment* 70, no. 2 (May): 208-223.

Alavi, N. 2012. "Land Use and Land Cover Change Detection in Isfahan, Iran Using Remote Sensing Techniques." Master's thesis, University of Ottawa. Accessed June 10, 2016. ProQuest Dissertations and Theses.

Alice Springs Desert Park. 2017. "Nature Notes: Spinifex." Accessed March 8. http://www.alicespringsdesertpark.com.au/kids/nature/plants/spinifex.shtml

Al-Jawarneh, R. 2004. "Spatial Analysis of Land Cover and Land Use in Evaluating Land Degradation in Northwestern Al-Mafraq City, Jordan." Master's thesis, Yarmouk University. Accessed September 11, 2016. ProQuest Dissertations and Theses.

Amiraslani, F., and D. Dragovich. 2013."Image Acquisition for Detection of Vegetation Change Based on Long-term Rainfall in an Arid Rangeland in Western NSW, Australia." *Environmental Earth Sciences* 70, no. 1 (November): 83-95.

Australian Bureau of Statistics. 2016. "Population." ABS Statistics. Last modified December 12. Accessed February 15, 2017. http://www.abs.gov.au/Population.

Bastin, G, P. F. Scarth, V. Chewings, A. Sparrow, R. J. Denham, M. D. Schmidt, P. J. O'Reagain, R. Shepherd, and B. N. Abbott. 2012. "Separating Grazing and Rainfall Effects at Regional Scale Using Remote Sensing Imagery: A Dynamic Reference-cover Method." *Remote Sensing of Environment* 121 (March): 443-457.

Bengraine, K., and T. F. Marhaba. 2003. "Using Principal Component Analysis to Monitor Spatial and Temporal Changes in Water Quality." *Journal of Hazardous Materials* 100, no. 1 (March): 179-195.

Berman, D. 1990. "Monitoring Vegetation and Rabbits at FGNP by Rangers After Removal of feral Horses. File A/89/200." Minute Paper, Alice Springs, December 19.

Bovolo, F., S. Marchesi, and L. Bruzzone. 2012. "A Framework for Automatic and Unsupervised Detection of Multiple Changes in Multitemporal Images." *IEEE Transactions on Geoscience and Remote Sensing* 50, no. 6 (June): 2196-2212.

Box, J. B., A. W. Duguid, R. E. Read, R. G. Kimber, A. Knapton, J. A. Davis, and A. E. Bowland. 2008. "Central Australian Waterbodies: The Importance of Permanence in a Desert Landscape." *Journal of Arid Environments* 72, no. 8 (August): 1395-1413.

Box, P. 2014-2016. Interviews by Adlin Botkin. Alice Springs.

Brim Box, J. 2014-2016. Interviews by Adlin Botkin. Alice Springs.

Bradshaw, C. J. A. 2012. "Little Left to Lose: Deforestation and Forest Degradation in Australia since European Colonization." *Journal of Plant Ecology* 5, no. 1 (March): 109-20.

Bureau of Meteorology. 2016. "Climate Data Online." Accessed February 10. http://www.bom.gov.au/climate/data.

Burns, E., D. Lindenmayer, A. Lowe, and N. Thurgate. 2014. *Biodiversity and Environmental Change: Monitoring, Challenges and Direction*. Victoria: CSIRO Publishing.

Byrne, G., P. F. Crapper, and K. Mayo. 1980. "Monitoring Land-cover Change by Principal Component Analysis of Multitemporal Landsat Data." *Remote Sensing of Environment* 10 (November): 175-184.

Celik, T. 2009a. "Multiscale Change Detection in Multitemporal Satellite Images." *IEEE Geoscience and Remote Sensing Letters* 6, no. 4 (October): 820-824.

------. 2009b. "Unsupervised Change Detection in Satellite Images Using Principal Component Analysis and K-Means Clustering." *IEEE Geoscience and Remote Sensing Letters* 6, no. 4 (October): 772-776.

Collins, J. B., and C. E. Woodcock. 1996. "An Assessment of Several Linear Change Detection Techniques for Mapping Forest Mortality Using Multitemporal Landsat TM Data." *Remote Sensing of Environment* 56, no. 1 (April): 66-77.

Cook, J., A. Grattidge, W. A. Low, D. Schunke, and D. Matthews. 1995. The Environmental Implications of Removal of Horses from Finke Gorge National Park. Stage 4: Fourth Vegetation Monitoring and Progress Assessment. Alice Springs, NT: Arid Zone Research Institute Library.

Csurhes, S., G. Paroz, and A. Markula. 2009. "Pest Animal Risk Assessment: Feral Horse Equus Caballus." Queensland Primary Industries and Fisheries, Queensland.

Davis, J. C. 2002. *Statistics and Data Analysis in Geology*. 3rd ed. New York: Chichester: Wiley.

Day, C. 1989. "Feral Animal Muster and Cull – FGNP. File A/89/186." Minute Paper, Alice Springs, May.

Deng, J. S., K. Wang, Y. H. Deng and G. J. Qi. 2008. "PCA-Based Land-Use Change Detection and Analysis Using Multitemporal and Multisensor Satellite Data." *International Journal of Remote Sensing* 29, no. 16 (July): 4823-4838.

Department of the Environment and Energy. 2016. “Plan for a Cleaner Environment.” Accessed December 16. http://www.environment.gov.au/cleaner-environment/plan-2016.

Department of the Environment and Energy. 2017. “Australia’s Bioregions (IBRA).” Accessed January 20. http://www.environment.gov.au/land/nrs/science/ibra.

Farhangfar, S., J. Kambouzia, R. Deihimfard, S. Soufizadeh, and B. Mirbagheri. 2016. "Introduction of an Index for Drought Evaluation Using Principle Components Analysis." *Agricultural Ecology* 5, no. 4 (2016): 452-461.

Fischer, W. A., W. R. Hemphill, and A. Kover. 1976. "Progress in Remote Sensing /1972-1976/." *Photogrammetria* 32 (August): 33-72.

Flood, N. 2013. "Seasonal Composite Landsat TM/ETM plus Images Using the Medoid (a Multi-Dimensional Median)." *Remote Sensing* 5, no. 12 (December): 6481-6500.

Flood, N., T. Danaher, T. Gill, and S. Gillingham. 2013. "An Operational Scheme for Deriving Standardised Surface Reflectance from Landsat TM/ETM plus and SPOT HRG Imagery for Eastern Australia." *Remote Sensing* 5, no. 1 (January): 83-109.

Foran, B. D. 1986. "The Impact of Rabbits and Cattle on an Arid Calcareous Shrubby Grassland in Central Australia." *Vegetatio* 66, no. 1 (April): 49-59.

Gee, R.W. 1986. “Bovine Tuberculosis Eradication in Australia.” World Organization for Animal Health, 1985. Accessed November 22, 2016. http://www.oie.int/doc/ged/d8570.pdf.

Geoscience Australia. 2016. “National Local Information.” Australian Government Geoscience Australia. Accessed November 15, 2016. http://www.ga.gov.au/scientific-topics/national-location-information.

Graetz, R. D., D. M. Carneggie, R. Hacker, C. Lendon, and D. G. Wilcox. 1976. “A Quantitative Evaluation of Landsat Imagery of Australian Rangelands.” *The Rangeland Journal* 1, no. 1 (1976): 53-59.

Graham, A., and K. Johnson. 1986. “An Aerial Survey of Horses and Other Large Animals in the Alice Springs and Gulf Regions.” Alice Springs, NT: Arid Zone Research Institute Library.

Griffin, G. F., and M. H. Friedel. 1984. “Effects of Fire on Central Australian Rangelands. II Changes in Tree and Shrub Populations.” *Australian Journal of Ecology* 9, no. 4 (December): 395-403.

Henderson, J. A. 2010. “A Study of the Response of the Northern Mixed-grass Prairie in Grasslands National Park, Saskatchewan to a Changing Climate.” Master’s thesis, University of Regina. Accessed January 8, 2016. ProQuest Dissertations and Theses.

Howarth, P. J., and G. M. Wickware. 2007. "Procedures for Change Detection Using Landsat Digital Data." *International Journal of Remote Sensing* 2, no. 3 (April): 277-291.

Hussain, M., D. Chen, A. Cheng, H. Wei, and D. Stanley. 2013. "Change Detection from Remotely Sensed Images: From Pixel-based to Object-based Approaches." *ISPRS Journal of Photogrammetry and Remote Sensing* 80 (June): 91-106.

Ingebritsen, S. E., and R. J. P. Lyon. 1985. "Principal Components Analysis of Multitemporal Image Pairs." *International Journal of Remote Sensing* 6, no. 5 (1985): 687-696.

Kelly, P. M., P. D. Jones, C. B. Sear, B. S. G. Cherry, and R. K. Tavakol. 1982. "Variations in Surface Air Temperatures: Part 2, Arctic Regions, 1881-1980." *Monthly Weather Review* 110, no. 2 (February): 71-83.

Kluger, J. 2013. “Earthrise on Christmas Eve: The Picture That Changed the World.” Time, December 24. Accessed November 15, 2016. http://science.time.com/2013/12/24/earthrise-on-christmas-eve-the-picture-that-changed-the-world/photo/earthrise1/.

Landsberg, J., and G. Crowley. 2004. "Monitoring Rangeland Biodiversity: Plants as Indicators." *Austral Ecology* 29, no. 1 (February): 59-77.

Lau, J. E., and G. Jacobson. 1991 “Aquifer characteristics and groundwater resources of the Amadeus Basin.” Bureau of Mineral Resources, Australia, Bulletin 236 (1991): 563-580.

Lawley, E. F., M. M. Lewis, and B. Ostendorf. 2016. "A Remote Sensing Spatio-temporal Framework for Interpreting Sparse Indicators in Highly Variable Arid Landscapes." *Ecological Indicators* 60 (January): 1284-1297.

Low, W. A. and M. R. Hewett. 1990. “Aerial Survey of Horses and Other Large Animals in the Central Ranges of the Alice Springs District, October 1988.” Consultancy Report to the Conservation Commission of the Northern Territory.

Low, W. A., E. Foster, and D. McK. Berman. 1991. *The Environmental Implications of Removal of Horses from Finke Gorge National Park. Stage 1: Site Selection, Ranger Training and First Vegetation Monitoring.* Alice Springs, NT: Arid Zone Research Institute Library.

Low, W. A., N. de Preu, D. Schunke, D. Matthews, and D. McK. Berman. 1992. *The Environmental Implications of Removal of Horses from Finke Gorge National Park. Stage 2: Second Vegetation Monitoring and Continued Ranger Training.* Alice Springs, NT: Arid Zone Research Institute Library.

Low, W. A., R. Dunlop, M. Kanter, D. Matthews, and D. McK. Berman. 1993. *The Environmental Implications of Removal of Horses from Finke Gorge National Park.*

Stage 3: Third Vegetation Monitoring and Progress Assessment. Alice Springs, NT: Arid Zone Research Institute Library.

Low, W. A. Bill. 2016. Interview by Adlin Botkin. Alice Springs. March.

Lu, D., P. Mausel, E. Brondízio, and E. Moran. 2003. "Change Detection Techniques." *International Journal of Remote sensing.* 25, no. 12 (April): 2365-2401.

Matheson, W. 1994. "The Use of Landsat MSS Imagery to Determine Plant Characteristics and Community Spectral Separability from Sub-tropical to Arid Zones in Northern Australia." *Geocarto International* 9, no. 2 (June): 5-13.

Morton, S., D. M. Stafford Smith, C. R. Dickman, D. L. Dunkerley, M. H. Friedel, R. R. J. Mcallister, J. R.W. Reid, D. A. Roshier, M. A. Smith, F. J. Walsh, G. M. Wardle, I. W. Watson, and M. Westoby. 2011. "A Fresh Framework for the Ecology of Arid Australia." *Journal of Arid Environments* 75, no. 4 (April): 313-329.

Miller, C., W. A. Low, and D. Matthews. 1998. The Environmental Implications of Removal of Horses from Finke Gorge National Park. Stage 5: Fifth Vegetation Monitoring and Progress Assessment. Alice Springs, NT: Arid Zone Research Institute Library.

Muir, J., M. Schmidt, D. Tindall, R. Trevithick, P. Scarth, and J. Stewart. 2011. "Guidelines for Field Measurement of Fractional Ground Cover: A Technical Handbook Supporting the Australian Collaborative Land Use and Management Program." Technical Report, Queensland Department of Environment and Resource Management for the Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra.

Nano, C. E. M., A. E. Bowland, T. J. Nano, S. Raghu, and C. R. Pavey. 2012. "Demographic Hurdles to Persistence in Acacia Peuce (F. Muell.): Effects of Resources, Fire and Browsing on a Threatened Keystone Tree Species from Arid Australia." *Journal of Arid Environments* 80 (May): 17-26.

Nano, C. E. M., and C. R. Pavey. 2013. "Refining the 'pulse-reserve' Model for Arid Central Australia: Seasonal Rainfall, Soil Moisture and Plant Productivity in Sand Ridge and Stony Plain Habitats of the Simpson Desert." *Austral Ecology* 38, no. 7 (February): 741-753.

Nano, C. 2014-2016. Interviews by Adlin Botkin. Alice Springs.

NASA. 2017. "Landsat." Last modified August 3. Accessed November 15, 2016. https://www.nasa.gov/mission_pages/landsat/main/index.html.

Parks and Wildlife Commission. 2011. "Finke Gorge National Park Joint Management Plan." Last modified October. Accessed May 15, 2016. https://dtc.nt.gov.au/__data/assets/pdf_file/0010/249148/finke-gorge-national-park.pdf.

Piwowar, J. M. 1996. “Hypertemporal Image Analysis of Arctic Sea Ice Concentrations as an Index of Climate Change and Variability.” PhD thesis, University of Waterloo. Accessed January 8, 2016. ProQuest Dissertations and Theses.

Piwowar, J. M., and E. F. LeDrew. 1995. "Hypertemporal Analysis of Remotely Sensed Sea-ice Data for Climate Change Studies." *Progress in Physical Geography* 19, no. 2 (June): 216-242.

Smith, L. I. 2002. “A Tutorial on Principal Components Analysis.” Last Modified February 26. Accessed January 25, 2016. https://klevas.mif.vu.lt/~tomukas/Knygos/principal_components.pdf.

Smyth, A. K., and C. D. James. 2004. "Characteristics of Australia's Rangelands and Key Design Issues for Monitoring Biodiversity." *Austral Ecology* 29, no. 1 (2004): 3-15.

Sparrow, A. D., M. H. Friedel, and D. M. Stafford Smith. 1997. "A Landscape-scale Model of Shrub and Herbage Dynamics in Central Australia, Validated by Satellite Data." *Ecological Modelling* 97, no. 3 (April): 197-216.

Story, R., G. A. Yapp, and A. T. Dunn. 1976. "Landsat Patterns Considered in Relation to Australian Resources Surveys." Remote Sensing of Environment 4, no. C (1976): 281-303.

Strahler, A. H., C. E. Woodcock, and J. A. Smith. 1986. "On the Nature of Models in Remote Sensing." *Remote Sensing of Environment* 20, no. 2 (October): Sun, Danfeng, Xiaoqian Yu, Xiaona Liu, and Baoguo Li. 2016. "A New Artificial Oasis Landscape Dynamics in Semi-arid Hongsipu Region with Decadal Agricultural Irrigation Development in Ning Xia, China." *Earth Science Informatics* 9, no. 1 (March): 21-33.

Terrestrial Ecosystem Research Network. 2013. “Seasonal fractional cover - Landsat, JRSRP algorithm, Australia coverage.” Last Modified April 2017. Accessed April 15, 2016. http://data.auscover.org.au/xwiki/bin/view/Product+pages/Landsat+Seasonal+Fractional+Cover.

Thackway, R., and I. D. Cresswell, eds. 1995. *An Interim Biogeographic Regionalisation for Australia: a framework for establishing the national system of reserves, Version 4.0.* Australian Nature Conservation Agency, Canberra.

Townshend, J. R.G., T. E. Goff, and C. J. Tucker. 1985. "Multitemporal Dimensionality of Images of Normalized Difference Vegetation Index at Continental Scales." *IEEE Transactions on Geoscience and Remote Sensing* Ge-23, no. 6 (November): 888-895.

Tueller, P. T. "Remote Sensing Science Applications in Arid Environments.” 1987. *Remote Sensing of Environment* 23, no. 2 (November): 143-154.

United States Geological Survey. 2017. "Landsat 5 History." Last Modified June 22. Accessed September 20, 2016. https://landsat.usgs.gov/landsat-5-history.

Van Etten, E. J. B. 2009. "Inter-annual Rainfall Variability of Arid Australia: Greater than Elsewhere?" *Australian Geographer* 40, no. 1 (March): 109-120.

Wardle, Glenda M., Chris R. Pavey, and Chris R. Dickman. 2013. "Greening of Arid Australia: New Insights from Extreme Years." *Austral Ecology* 38, no. 7 (July): 731-740.

Weismiller, R. A., S. J. Kristof, D. K. Scholz, P. E. Anuta, and S. A. Momin. 1977. "Change Detection in Coastal Zone Environments." *Photogrammetric Engineering and Remote Sensing* 43, no. 12 (December): 1533-1539.

Wischusen, J. D. H., L. K. Fifield, and R. G. Cresswell. 2004. "Hydrogeology of Palm Valley, Central Australia; a Pleistocene Flora Refuge?" *Journal of Hydrology* 293, no. 1 (June): 20-46.

Woodcock, C. E., A. H. Strahler, and J. Franklin. 1983. "Remote Sensing for Land Management and Planning." *Environmental Management* 7, no. 3 (May): 223-237.

World Wildlife Fund. 2016. "Ecoregions." Accessed July 15. https://www.worldwildlife.org/biomes