



University of the Witwatersrand

School of Animal Plant and Environmental Science

**Spatial and temporal changes of greenness metrics in Kruger National Park
from 2000-2010**

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requirements for the degree of Master of Science

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DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the Degree of Master of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

A handwritten signature in dark ink, consisting of a large, stylized 'W' followed by a horizontal line and a small flourish.

31st day of August 2012

Abstract

The spatial and temporal changes in vegetation patterns and heterogeneity of savannas has become important as the biodiversity of savannas are expected to respond to the predicted climate variability and change. The spatial and temporal changes in vegetation greenness patterns observed in Kruger National Park (KNP) between 2000 and 2010 using productivity phenometrics, the sum of EVI ($\sum \text{EVI}$) and the maximum EVI value (EVI_{max}), derived from Enhanced Vegetation Index (EVI) time series data from MODIS were characterised. Underlying substrate did not determine vegetation greenness but followed KNP's rainfall gradient. Vegetation structure possibly determined vegetation greenness as the presence of woody vegetation in the far north of KNP was evident. KNP got greener over the study period with an increase in variability and heterogeneity of vegetation greenness. The results have important implications for savanna management under climate change conditions and show the potential of vegetation indices being used to monitor biodiversity changes.

Key words: EVI, vegetation, productivity, photosynthesis, rainfall, geology, KNP

Dedication

To Michael, Dad, Mum and the siblings

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Glossary

AVHRR: Advanced Very High Resolution Radiometer

Ba: Basalt

BLUE: Blue Reflectance

BRDF: Bidirectional Reflectance Distribution Function

C: Central

ENSO: El Niño-Southern Oscillation

EVI: Enhanced Vegetation Index

Σ **EVI:** Summation of total EVI for year

EVI_{max}: Maximum EVI value of the year

FN: Far North

Gr: Granite

KNP: Kruger National Park

LAI: Leaf Area Index

MODIS: Moderate Resolution Imaging Spectroradiometer

N: North

NASA: National Aeronautics and Space Administration

NDVI: Normalized Difference Vegetation Index

NIR: Near Infrared Reflectance

NOAA: National Oceanic and Atmospheric Administration

NPP: Net Primary Productivity

RED: Red Reflectance

S: South

SPOT-VGT: Satellite Pour l'Observation de la Terre-Vegetation

1 Introduction

The predicted human induced climate change and its impacts on terrestrial ecosystems has become of great concern to terrestrial ecologists. Long-term mean annual and inter-annual rainfall, and the frequency and intensity of rainfall are expected to change in the 21st century (Richard *et al.* 2001). This in turn is predicted to affect primary productivity of vegetation in space and time as studies have shown a strong link between rainfall variability and vegetation patterns (Prince and Tucker 1986; Nicholson *et al.* 1990; Goward and Prince 1995; Richard and Pocard 1998). Spatial and temporal heterogeneous distribution of resources have been proven to affect animal population dynamics in semi-arid savannas (Levin 1992; Griffith *et al.* 2002; Hurlbert and Haskell 2003; Saino *et al.* 2004; Pettorelli *et al.* 2005; DeKnecht *et al.* 2011), which are predicted to be affected by the impacts of climate change (Pettorelli *et al.* 2005; Walther *et al.* 2002). Climatic changes and variation in rainfall, which affects timing of plant growth, are likely to be of importance to the reproductive success of herbivores in highly seasonal environments like savannas (Ogutu and Owen-Smith 2003; Post *et al.* 2008). Southern Africa has a range of climate zones which exhibit extensive variability as the timing and amount of rainfall in these seasons is variable year after year (Richard *et al.* 2001). Availability of green forage in winter, which is influenced by the period when late summer rainfalls occur, in semi-arid savannas has been shown to have an effect on herbivores population dynamics (Ogutu and Owen-Smith 2003). A migratory strategy shown by large herbivores in seasonal environments, allows them to follow the spatial front of the

most digestible and highly nutritious vegetation as it emerges, prolonging the time they consume the best vegetation available (Andersen *et al.* 2004; Boone *et al.* 2006).

Plant phenologies both at intra-annual and inter-annual scales have been used as biological indicators to monitor plant responses to climate variability and climate change (Reed *et al.* 1994; Chen *et al.* 2000). Plant phenophases give an indication of the start and end of growing season of terrestrial vegetation. Some studies have shown an earlier arrival of growing season in the northern hemisphere (Zhou *et al.* 2001; Schwartz *et al.* 2006; Zhang *et al.* 2007); with long-term phenological data showing an increase of 1- days per decade in the start of growing season (Scheffinger *et al.* 2002). A shift in date phenometrics affects the length of the growing season. This again affects animals sensitive to the start of vegetation growth for their survival, migratory patterns, resource dynamics and their reproductive potential (Levin 1992; Griffith *et al.* 2002; Hurlbert and Haskell 2003; Saino *et al.* 2004; Pettorelli *et al.* 2005; De Knecht *et al.* 2011). Most of these studies have been carried out in the northern hemisphere, with little being done in the southern hemisphere.

Phenophases have an impact on global carbon dynamics; hence the growing season has become an important period that can be used in modeling the global terrestrial carbon-cycle and net primary productivity (Lieth 1975; Baldocchi *et al.* 2001). Savannas come second to forests in their rates of carbon flux and storage hence a strong understanding of their vegetation patterns and phenology is important as they have huge impact on global carbon cycles (Archibald and Scholes 2007).

They form part of the world's major biomes, with tropical savanna and woodlands covering about 20% of terrestrial landscapes in the world and covering 40% of Africa (Scholes and Walker 1993). These are ecosystems composed of a mix of trees, shrubs and grasses which contributes to their highly heterogeneous nature (Scholes and Walker 2003). The process behind the co-dominance between trees and grasses in savanna ecosystems still poses a challenge to ecologists (Scholes and Walker 1993; Sankaran *et al.* 2005). Herbivory and fire, together with rainfall are the main factors that determine savanna vegetation structure (Eckhardt *et al.* 2000).

Satellite imagery has become an important tool in analyzing patterns and greenness of terrestrial vegetation and its inter-annual and seasonal variability over large geographical areas. This has made it possible to analyse large-scale spatial patterns of vegetation greenness in relation to climatic change. Vegetation indices like the Enhanced Vegetation Index (EVI) use the visible and near-infrared bands and blue band of the electromagnetic spectrum, from remote sensing measurements to provide an indication of vegetation dynamics (Jiang *et al.* 2008). Vegetation indices have become one of the few techniques that can be used to match vegetation, climate and animal distribution at large temporal and spatial scales (Pettorelli *et al.* 2005).

1.1 Problem Statement

Biodiversity in savanna ecosystems is expected to be affected by predicted climate changes, with a great uncertainty on how vegetation will respond to the

impact of seasonal and inter-annual variability in rainfall patterns (Goward and Prince 1995). There is limited understanding on the spatial and temporal changes in vegetation heterogeneity of savannas. Several vegetation studies have been carried out in homogenous ecosystems for example the temperate regions where factors such as temperature and photoperiod control phenology (Zhou *et al.* 2003; Schwartz *et al.* 2006) but fewer have been carried out in tropical savanna ecosystems (Richard and Pocard 1998; Chamaille-Jammes *et al.* 2006), which tend to be heterogeneous and water, rather than temperature and photoperiod among other factors limit plant growth (Scholes and Walker 1993; Botta *et al.* 2000; Morellato 2003). Inter-annual and intra-annual spatial variability of vegetation greenness has been studied using EVI metrics from satellite data to measure vegetation changes in ecosystems like savannas (Jiang *et al.* 2008). Changes in vegetation greenness help give an indication on the impact of the predicted climate change on vegetation of terrestrial ecosystems like savannas as long term changes in rainfall patterns affect vegetation greenness patterns over time (Chen *et al.* 2000; Chamaille-Jammes *et al.* 2006; Park 2008). Long term spatial and temporal patterns of vegetation greenness in Kruger National Park (KNP) have already been presented for the years 1985-1999 (Parrini and Erasmus 2009). The study of vegetation patterns using vegetation greenness indices of KNP from 2000 extending to 2010 would shed light on changes in vegetation greenness and heterogeneity of KNP over an extended period of time, allowing for a comparison with the previous study and for a further understanding of the relationship between climatic variables and vegetation greenness. The aim of this report is therefore to assess whether KNP has been getting greener or browner.

Furthermore, the report assesses whether KNP is becoming more or less heterogeneous and looks into the potential of using EVI indices for predicting and monitoring biodiversity changes.

1.2 Purpose statement

The purpose of the research is to characterize the spatial and temporal changes in vegetation greenness patterns observed in KNP between 2000 and 2010 using EVI time series from Moderate Resolution Imaging Spectroradiometer (MODIS). The spatial and temporal changes of maximum EVI (EVI_{max}) and the sum of EVI ($\sum EVI$) for each year are assessed for this period to give a measure of change in vegetation greenness and heterogeneity of KNP, which can be used to monitor changes in biodiversity of southern Africa savanna ecosystems.

1.3 Aim

For the period 2000-2010, the aim of the study is to investigate changes in vegetation greenness by analyzing large-scale temporal and spatial changes in the EVI metrics (EVI_{max} and $\sum EVI$), in order to assess whether KNP has become greener or browner and increasing or decreasing in the amount of vegetation produced over this period.

1.4 Objectives

1. To assess the spatial variation of the EVI metrics (EVI_{max} and $\sum EVI$) in KNP for each year.
2. To assess temporal changes in vegetation greenness by analysing the temporal changes in spatial distribution of the EVI metrics (EVI_{max} and $\sum EVI$).

2 Literature Review

2.1 Terrestrial Remote Sensing

Remote sensing is the instrumentation, techniques and methods used to observe the Earth's surface at a distance and to interpret the images or numerical values obtained in order to acquire meaningful information of particular objects on earth (Buiten and Clevers 1993). It allows earth to be viewed from different satellites providing a variety of imagery covering wide surfaces applicable to different fields (Zhang and Kerle 2008), which is a quicker and economical method of collecting data.

The quality of images captured by remote sensors are characterised by the spatial, spectral, radiometric and temporal nature of sensor-platform systems. These characteristics are further classified by their coverage (extremes that are observed) and resolution (smallest units that can be distinguished) (Janssen and Baker 2004). The spectral coverage is the total wavelength range observed by the sensor, whilst the spectral resolution refers to the number and width of the portions of the electromagnetic spectrum measured by the sensor (Janssen and Baker 2004, Smith 2012). The total area covered by one image is the spatial coverage of a sensor, which is also equal to the total field of view (FOV) in multispectral scanners which determines the swath width (Janssen and Baker 2004). The amount of spatial detail in an image is determined by its spatial resolution and may be described as a measure of

the smallness of objects on the ground that may be distinguished as separate entities in the image (Janssen and Baker 2004; Smith 2012). The smallest differences in levels of energy that can be distinguished by the sensor determines its radiometric resolution. The more sensitive a sensor is in detecting small differences in reflected or emitted energy, the finer the radiometric resolution (Janssen and Baker 2004). The temporal resolution (revisit time) is the minimum time between two successive image acquisitions over the same location on earth (Janssen and Baker 2004).

A sensor is said to have low spectral resolution if it captures a small number of wide bands in a portion of the electromagnetic spectrum but high spectral resolution if it captures many smaller bands in same portion of the electromagnetic spectrum (Janssen and Baker 2004; Smith 2012). Data is available from either multispectral or hyperspectral sensors (Vogel *et al.* 2008). Most multispectral satellite systems measure between three and six spectral bands within the visible to middle infrared region of the electromagnetic spectrum in each pixel of images they produce (Vogel *et al.* 2008). Landsat, and Spot satellites are well-known satellite sensors that use multispectral sensors. Multispectral remote sensing allows for the discrimination of different types of vegetation, rocks and soils, clear and turbid water (Smith 2012). Hyperspectral sensors on board satellites or airborne hyperspectral imagers are used to obtain data of a higher spectral resolution compared to multispectral data. Hyperspectral sensors measure energy in narrower and more numerous bands throughout the visible, near infrared, mid-infrared, and thermal infrared portions of the electromagnetic spectrum than multispectral sensors, producing images that

contain up to 200 or more contiguous spectral bands (Janssen and Baker 2004).

Images produced from hyperspectral sensors contain much more data than images from multispectral sensors and have a greater potential to detect differences among land and water features (Janssen and Baker 2004; Smith 2012).

The different spatial, temporal and spectral resolutions are the limiting factor for the utilization of the remote sensing data for different applications. Satellite sensors like MODIS, Advanced Very High Resolution Radiometer (AVHRR) and Satellite Pour l'Observation de la Terre-Vegetation (SPOT Vegetation) make it possible to access satellite imagery at different spatial resolution, with pixel sizes ranging from between 250 m to 1 km, with data spanning as much as three decades (Vogel *et al.* 2008; Zhang and Kerle 2008). These are provided regularly and with high temporal frequency depending on type of sensor and cloud cover (Pettorelli *et al.* 2005; Vogel *et al.* 2008; Zhang and Kerle 2008). An inverse relationship exists between spatial and temporal resolution. Hypertemporal environmental satellite data have lower spatial resolutions and shorter return visits (Vogel *et al.* 2008; Zhang and Kerle 2008). National Oceanic and Atmospheric Administration's (NOAA) AVHRR provides daily hypertemporal satellite data with five to six spectral bands, whilst National Aeronautics and Space Administration's (NASA) MODIS has 36 spectral bands, which improves the quality of images captured by MODIS (Pettorelli *et al.* 2005; Vogel *et al.* 2008). Regional, long-term, spatial and high frequency measurements of the Earth's surface are possible due to the availability of these low resolution sensors (Vogel *et al.* 2008) Time series data made available by these

coarse resolution sensors is valuable as researchers use it to identify environmental patterns, trends, detect changes and forecast future trends from the Earth's surface year in and out (Vogel *et al.* 2008). Vegetation phenological events, drought monitoring, crop monitoring, disaster management and fire early warning systems become possible with the availability of hypertemporal data (Vogel *et al.* 2008).

2.2 Enhanced Vegetative Index (EVI)

Remote sensing data has been used to formulate vegetation indices, with Park (2008) defining them as, “dimensionless, radiometric measures that indicate biophysical parameters of green vegetation, which include leaf area index (LAI), percent green cover, biomass, chlorophyll content, and absorbed photosynthetically active radiation”. From LAI, terrestrial plant biomass can be calculated and converted to leaf area per unit ground surface area (Running 1990). The EVI is a vegetation index which was developed to counter the shortcomings of Normalized Difference Vegetation Index (NDVI) as it optimizes the vegetation signal with improved sensitivity to high biomass and vegetation monitoring (Liu and Huete 1995, Huete 2002; Park 2008). Aerosol influence on the red band reflectance is minimized, making it a better indicator of vegetation greenness (Kaufman and Tanré 1992; Jiang *et al.* 2008). EVI is known as a better vegetation index, compared for example to NDVI, because it is not saturated by higher LAIs. It is more sensitive to chlorophyll content changes compared to canopy structural variations such as leaf area index

(LAI), canopy type, and canopy architecture (Liu and Huete 1995). The EVI is expressed as:

$$EVI = G \frac{N-R}{N + C_1R - C_2B + L}$$

Where the near-infrared, red and blue surface reflectance bands which have been atmospherically corrected are represented by N, R, and B respectively, with the coefficients of the aerosol resistance terms, which use the blue band of the magnetic spectrum to correct the effects of aerosol in the red band represented by C_1 and C_2 ; G is a gain factor; and the soil adjustment factor is represented by L (Liu and Huete 1995).

Several studies have used vegetation indices as a proxy for productivity, biomass and biodiversity (Aragon *et al.* 2011) and phenology (Reed *et al.* 1994; Zhang *et al.* 2007). Vegetation indices have also been related to climatic variables like rainfall making it possible to make predictions on vegetation based on climatic variables (Richard and Pocard 1998; Richard *et al.* 2001; Walker *et al.* 2003; Wang *et al.* 2003). Fluctuations and variability in climatic variables like precipitation give rise to variability in vegetation greenness and patterns picked up by vegetation indices like EVI (Richard and Pocard 1998).

2.3 Greenness metrics

Vegetation greenness metrics have been used to predict and monitor vegetation phenology (Reed *et al.* 1994; Zhang *et al.* 2007). Leith (1974) defines phenology as 'the study of the timing of recurring biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species'. Vegetation phenology describes the seasonal cycle of leaf functioning such as bud burst, flowering and leaf senescence and is important for the better understanding of how the climate, biogeochemical cycles and the biosphere interact (Reed *et al.* 1994; Schwartz and Reed 1999; Botta *et al.* 2000; Menzel 2000; Schwartz 2003). Vegetation phenology is greatly associated with climatic factors together with land cover change (Botta *et al.* 2000; Heumann *et al.* 2007). Studies in vegetation phenology analyse the effect of seasonally, which alters environmental conditions such as temperature, day length, water availability and its effect on the timing of plant phenological stages which include germination, bud burst, flowering, and senescence (Lloyd 1990). Hence ecological and biophysical processes are dependent on the phenological growing season (Prasad *et al.* 2007). Vegetation parameters such as green leaf biomass, LAI, percent green cover, green biomass production and annual net primary production (ANPP) can be captured from vegetation metrics like EVI (Jiang *et al.* 2008). EVI time series bring out the seasonality of vegetation from capturing the photosynthetic activity of vegetation (Wagenseil and Samimi 2006) and can be used to calculate phenology metrics. This makes it possible to produce vegetation maps from vegetation indices like EVI and NDVI using their metrics (Justice *et al.* 1986).

Several studies have concluded that vegetation indices can be used as a climatic recorder, and in the tropics, mainly a rainfall recorder with the relationship being stronger on seasonal scales than inter-annual scales (Nicholson 1990; Richard and Poccoard 1998; Chamaille'-Jammes *et al.* 2006). Savanna plant species responses to seasonal change are closely linked to their structure and function. Several tree species are known to put on leaves in the dry season, one to three months before the start of the growing season whilst the growth of grasses occurs in the growing season as it is limited by water availability (Archibald and Scholes 2007; Delgado-Carty *et al.* 2010). According to Delgado-Carty *et al.* (2010), three phenological events exist in savannas. These are early-flushing trees, late-flushing trees and late flushing grasses. Both responses of trees and grasses need to be incorporated in phenology models of savanna ecosystems (Archibald and Scholes 2007; Delgado-Carty *et al.* 2010). Vegetation strongly influences animal distribution and dynamic and hence information on vegetation phenology is of prime importance to ecologists (Ogutu and Owen-Smith 2003; Pettorelli *et al.* 2005). Studies on the relationship between vegetation indices and vegetation productivity have been carried out extensively, concluding that a strong relationship exists.

2.4 Mechanisms that determine vegetation greenness in savanna ecosystems

To shape the heterogeneous structure of savanna ecosystems, many drivers act at multiple spatio-temporal scales (Scholes and Walker 1993). These occur at continental, regional, landscape and local scales, interacting with climatic, topo-

edaphic and disturbances like fire, herbivory and human activities to create the variable nature of savannas (Sankaran *et al.* 2005). At the continental scale, climatic patterns determine the extent of savanna biomes (Coughenour and Ellis 1993). At regional scales vegetation cover is determined by rainfall with a linear relationship existing between the two (Coughenour and Ellis 1993; Sankaran *et al.* 2005). Availability of water determines the period at which vegetation can grow with other factors like soil nutrients and temperature affecting the rate of primary production of vegetation (Scholes 1993). The above ground primary production of vegetation, hence vegetation greenness is linearly related to annual rainfall (Goward and Prince 1995; Chammille-Jammes *et al.* 2006) with variability of mean annual rainfall resulting in variability in vegetation greenness (Nicholson *et al.* 1990) regulated by disturbances like fire and herbivory (Eckhardt *et al.* 2000). Climatic heterogeneity and the spread of rainfall in semi-arid African savannas ecosystems are the greatest predictors of the vegetation growth form diversity and species richness hence vegetation greenness. Therefore the functional ecology of ecosystems is better understood by interpretation of vegetation greenness patterns (Cowling *et al.* 1994).

Vegetation patterns then tend to vary at landscape scales depending on geologic substrate and topographic position (Venter *et al.* 2003). Large herbivores and fire then become major mediators of vegetation properties, possibly acting at both landscape and regional scales in savannas (Higgins *et al.* 2000) and thought to be crucial in observed transformation of a number of African savannas from woodland savannas to shrubland/grassland savannas (Bond and van Wilgen 1996; Bond and

Keeley 2005). Given the importance of these drivers (fire and herbivory), they are difficult to quantify as feedbacks exist between them and they rarely occur without the other (Eckhardt *et al.* 2000).

3 Hypotheses

3.1 Hypotheses related to objective one

Greenness and number of pixels in EVI metrics clusters will differ depending on geographical and geological regions within KNP with the following differences:

- a) EVI_{max} and $\sum EVI$ clusters will have greener and more pixels on basaltic plains as compared to the granite rock derived soils (due to fertile clay basaltic soils compared to sandy granite soils).
- b) EVI_{max} and $\sum EVI$ clusters will have greener and more pixels in the southern and central regions of KNP than the northern and far north regions of KNP (due to more rainfall in the dry and wet season in the south and central regions compared to the north and far north regions).

3.2 Hypotheses related to objective two

- a) KNP will become greener during 2000-2010 as shown by an increase in the greenness and number of pixels in EVI_{max} and $\sum EVI$ clusters over time.
- b) KNP will be highly heterogeneous shown by:
 - i. High variability in EVI_{max} and $\sum EVI$ pixel greenness and numbers between 2000- 2010.
 - ii. A low spatial overlap of EVI_{max} and $\sum EVI$ clusters between years as measured by the frequency of re-occurrence of pixels in the clusters.

4 Methodology

4.1 Study Area

The study was undertaken in Kruger National Park (KNP) located in the northeast lowveld of South Africa, bordering Mozambique in the east and Zimbabwe in the north (Figure 1). The park has an area of ~20 000 km², with an average width of 60 km, stretching 350 km from north to south. The Limpopo and Luvuvhu River in the north, the Crocodile River in the south, the communal areas and parks in the west and the Lembobo hills in the east form the boundaries of KNP. The Limpopo, Olifants, Luvuvhu, Crocodile, Letaba and Sabie are the six perennial rivers that run from west to east (Figure1). Mean annual rainfall is higher in the south (average 530mm) than the north (average 440mm) (Eckhardt *et al.* 2000; Mabunda *et al.* 2003; Venter *et al.* 2003). KNP experiences hot wet summers and mild dry winters, receiving rainfall from October to March, with April to September being dry (Venter *et al.* 2003; Wessels *et al.* 2006). Temperature increases from south to north of KNP (Venter *et al.* 2003). Because of this rainfall and temperature gradient which impacts on vegetation patterns, two climatic transitional zones can be defined in KNP, the arid bushveld zone in the north and central part, and the lowveld bushveld zone in the

centre and south of KNP (Mabunda *et al.* 2003; Venter *et al.* 2003).

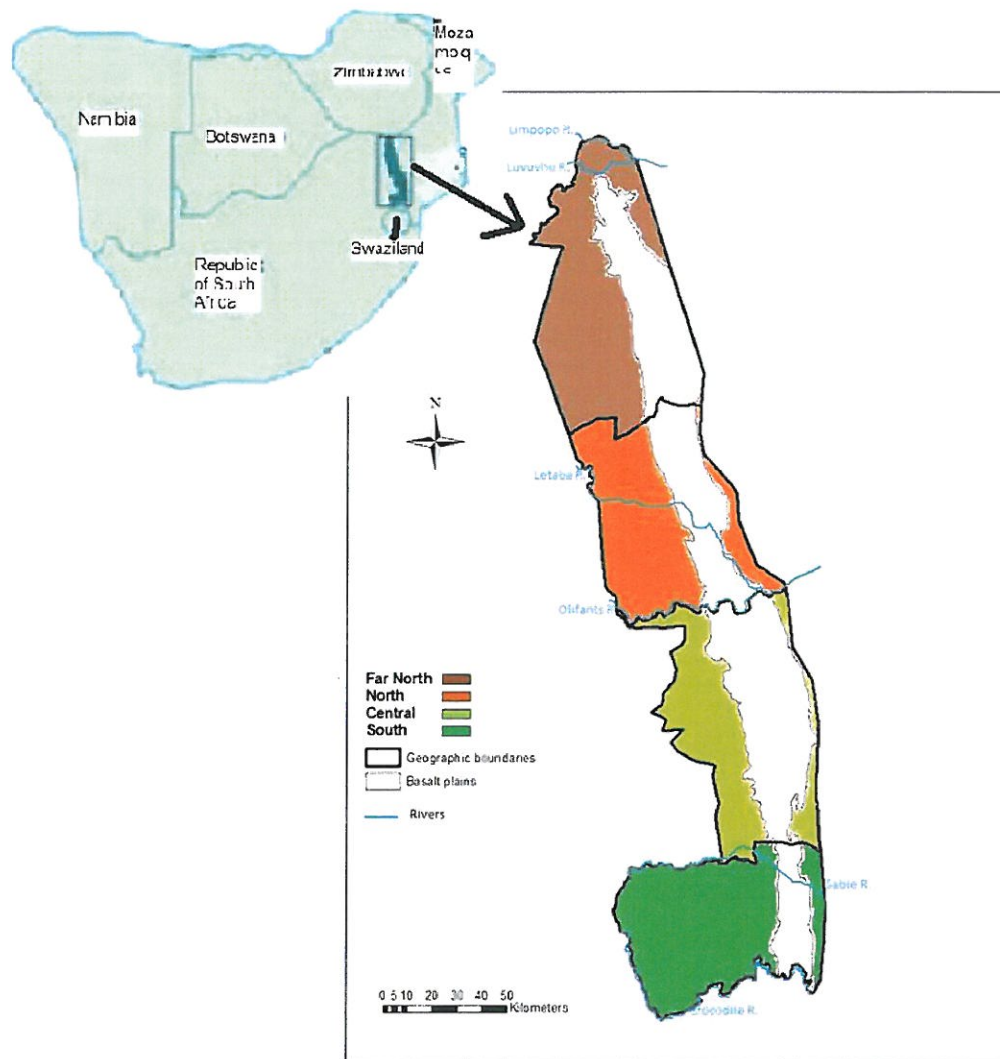


Figure 1: Regions, geology and rivers of Kruger National Park.

The geology of KNP is characterized by level basaltic plains dominated by clayey fertile soils in the east and undulating granite plains in the west (Figure 1), with a strip of sedimentary rocks separating the two (Mabunda *et al.* 2003; Venter *et*

al. 2003). Soil profiles become shallower from south to north as rainfall decreases, especially in the coarse-grained soils derived from granite rock, resulting in a decrease in soil diversity with decreasing rainfall (Venter *et al.* 2003). Drought years have up to 25 % less rainfall, resulting in decrease of grass cover and increased occurrence of fires. This has an effect on animal population dynamics and movements as changes in the amount and type of grasses in one particular area forces grazers to move to favourable vegetation cover as grazers favour different types of grasses (Venter *et al.* 2003).

The vegetation distribution of KNP reflects the climatic zones and the underlying geology described above. Frequent fires occur in the dry winter season, when dry grass fuel is present (Trollope 1993; Venter *et al.* 2003). Fires are more intense on basalt plains in the east, where the savanna is open and grass production is higher (Venter *et al.* 2003; van Wilgen *et al.* 2003). Trees from the families Caesalpinaceae and Combretaceae dominate in the areas with nutrient poor soils derived from granite or sandstone rocks in the west. These are broad leaved deciduous trees with fewer thorns. The grasses in these areas are sparse wiry and unpalatable such as *Pogonarthria squarrosa* and *Aristida* spp. Mimosaceae especially *Acacia* species, dominate the fertile soils in the east. These are deciduous, thorny trees with fine compound leaves. These trees are abundant in high nitrogen soils, hence preferred by herbivores. High bulk grasses such as *Panicumcoloratum* and *Themeda triandra* are found in these fertile soils. Mopane (*Colophospermum mopane*) a member of the Caesalpinaceae family dominates woody vegetation on soils with

more than 15 percent clay and annual rainfall below 500 mm in the north (Eckhardt *et al.* 2000; Venter *et al.* 2003).

4.2 Data Acquisition

For the period 2000 to 2010, MODIS MCD43 EVI time series satellite data, for South Africa was sourced and processed by the Remote Sensing Research Unit of the Meraka Institute in the Council for Scientific and Industrial Research (CSIR), Pretoria and used as a measure of vegetation greenness. The data was produced from NASA; at a resolution of 500 m, with 8 day composites, where the highest EVI value per pixel every 8 days is used as the greenness measure of vegetation, limiting the effects of disturbances like cloud cover. The data was also corrected for Bidirectional Reflectance Distribution Function (BRDF) which minimizes reflectance variability from the sun to the target and finally the sensor geometry, limiting noise in the EVI time series data (Huete *et al.*, 2002). The EVI values were scaled by a factor of 10 000 in all years and available as geotiff files that are freely downloadable from the Meraka Institute's website (www.afis.meraka.org.za/wamis/products/long-term-time-series).

4.3 Data Analysis

4.3.1 Data preparation

For each year from 2000 until 2010, each of the 8 day composite tiles were prepared and analysed in ArcGIS 9 Arcmap version 9.3. From the multiple rasters

contained in each year, the following two metrics were calculated; for each pixel, the max annual EVI (EVI_{max}) representing the highest EVI value for that pixel out of the 45 rasters in each year; for each pixel, the annual sum of EVI ($\sum EVI$) representing the cumulative EVI values for that pixel across all 45 images for the year. The final output was one raster per year for each metric. The EVI_{max} (absolute vegetation greenness) and $\sum EVI$ (total vegetation greenness) as vegetation indices can be used as a proxy for highest photosynthetic activity and above ground ANPP each year respectively (Reed *et al.* 1994; Pettorelli *et al.* 2005).

The EVI_{max} and $\sum EVI$ rasters were converted into point feature files, with each pixel being represented by its middle point given ArcGIS's ability to cluster raster data using Local Indicators of Spatial Association (LISA), a statistical analysis explained in the next section. Only the area pertinent to KNP was extracted, by clipping out KNP using a KNP shapefile. This meant that for each year, KNP point shapefiles for the EVI_{max} and $\sum EVI$ were created.

4.3.2 Analyses for objective one

4.3.2.1 Creating clusters

Local Indicators of Spatial Association (LISA) using Anselin Local Moran's I similarity index was used for the clustering analysis. A LISA is any statistic that satisfies the two following requirements: 1) For each observation it gives an

indication of the extent of significant spatial clustering of similar values around that observation; 2) The sum of LISAs for all observations is proportional to a global indicator of spatial association (Anselin 1995; Jacquez 2008). A local Moran statistic for an observation i may be defined as

$$I_i = z_i \sum_j w_{ij} z_j,$$

Observations z_i and z_j are deviations from the mean, w_{ij} is a weight denoting the strength of connection between areas i and j ensuring only neighbouring values of z_i are included in the statistic and weights standardized for the number of neighbours, hence nearest neighbours are included (Anselin 1995). In other words it is the propensity of neighbouring values in a matrix to be similar. So each value or point in a location or study area is given a measure of how similar it is to the surrounding points (autocorrelation) and based on this similarity, clustered.

The Cluster and Outlier Analysis application in ArcGIS which uses Anselin's Moran I similarity index used the Inverse distance to conceptualize spatial relationships and the Euclidean distance method to specify how distances are calculated when measuring spatial autocorrelation. Clusters and outliers of the EVI metrics were mapped. The application locates features where high or low values cluster spatially ("the clusters"), and features with values that are very different from surrounding feature values ("the outliers"). The output of the cluster and outlier

analysis is a Local Moran's I index value, Z score, p -value and cluster type field for each observation. Clusters are areas that are statistically more similar (0.05 level) than others as given that each observation had a p -value, which was used to determine significance of an observation to belong to a cluster. The cluster type code (COTypes) was only given for statistically significant clusters (Table 1).

Table 1: Cluster types codes given to statistically significant clusters grouping similar values.

COType	Type of Clustering
HH	Clusters of high values
LL	Clusters of low values
LH	Low feature surrounded by high values(Outliers)
HL	High feature surrounded by low values(Outliers)

Maps of clusters with high values were then created separately for each year. This was done by exporting points from the statistically significant KNP point shapefiles that had attributes of COTypes HH. These point shapefiles were converted to raster with one point and its value representing one pixel of the same dimensions as the original EVI pixel to create separate spatial distribution raster maps with clusters of high greenness values (HH).

4.3.2.2 Basalt versus Granite and North versus South

The HH clusters were spatially classified based on their occurrence in either basalt or granite geology or north versus south geography. This was done using a KNP shapefile with geological regions, basalt and granite or geographic regions far

north, north, central and south and selecting points from the HH clusters that fell into the different geological and geographic regions.

For each region, the area covered by the pixels that made up the clusters each year was calculated by multiplying the size of one pixel (500 m x 500 m) by the number of points making up the cluster. This gave an indication of the total extent of clusters. The number (area covered) of pixels making up the HH clusters was compared between the two geological regions and amongst the four geographic regions. The geographic regions were further classified based on which geological type (basalt or granite) they fell into.

Differences in the greenness (EVI) for both metrics between the two geologies and amongst the geographic regions were compared using the EVI values of the pixels that made up the HH clusters each year. Two sample t-tests were used to test the difference in greenness between granite and basalt geologies for EVI_{max} and $\sum EVI$ each year, with $H_0: \mu_{Ba} = \mu_{Gr}$ using a random sample of 20% of the data points within geology. The difference in greenness amongst the geographic regions (far north, north, central and south) was compared using the EVI values of pixels that made up the HH clusters for EVI_{max} and $\sum EVI$. One way ANOVA was used to test the differences in greenness amongst the geographic regions, with the $H_0: \mu_{FN} = \mu_N = \mu_C = \mu_S$ using a sample of 20% of the data points. Tukey's post hoc multiple comparison

tests were used to identify where the differences in greenness amongst the regions for EVI_{max} and $\sum EVI$ occurred. All differences were calculated using SAS (SAS Enterprise Guide 4.2) with $\alpha = 0.05$ as the confidence level.

4.3.3 Analyses for objective two

The changes over time of the HH clusters was analysed by performing frequency calculations pixel by pixel, mean-variance analysis and calculating the changes in number and mean greenness of the pixels making the clusters from 2000 to 2010.

For both EVI_{max} and $\sum EVI$ metrics, the number of pixels (area) making up the clusters was presented for each year. To determine the vegetation greenness shifts in KNP, following Washington-Allen *et al.* (2009), EVI_{max} and $\sum EVI$ variances of pixels making up the clusters for each year were plotted against EVI_{max} and $\sum EVI$ mean values of pixels making up the clusters of the same year. Mean greenness is an indication of vegetation cover and variance an indication of the degree of landscape heterogeneity (Figure 2).

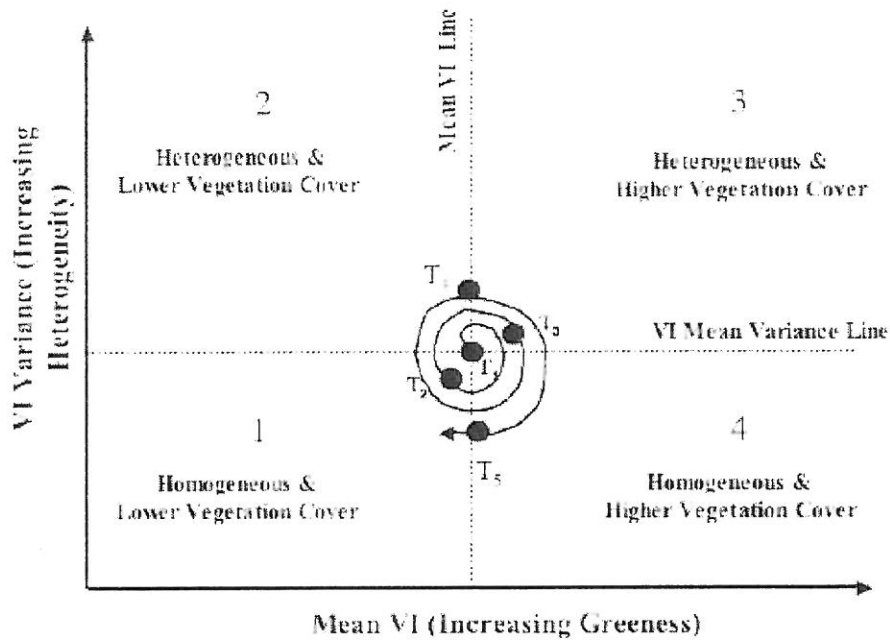


Figure 2: Potential vegetation states of inter-annual mean-variance dynamics in a landscape's vegetation index (VI). T= time (After Washington-Allen *et al.* 2009).

To determine if the spatial location of pixels making up the clusters changed in time, for each pixel, it was calculated how many times the same pixel reoccurred throughout the 11 years in the clusters created each year. The frequency of reoccurrence of individual pixels in the clusters created each year was calculated using The Equal to Frequency of Spatial Analyst. This tool counts the number of times multiple rasters are equal to an input raster on a cell by cell basis. In this case the input raster was created by using a KNP point shapefile with all points that make up the whole of KNP and converted it to raster using its point ID which becomes the pixel ID. Hence the raster file had all the pixels, with their IDs that make up KNP.

The pixel ID is what is used to identify the reoccurrence of individual pixels in the multiple rasters of HH, year by year (Figure 3).

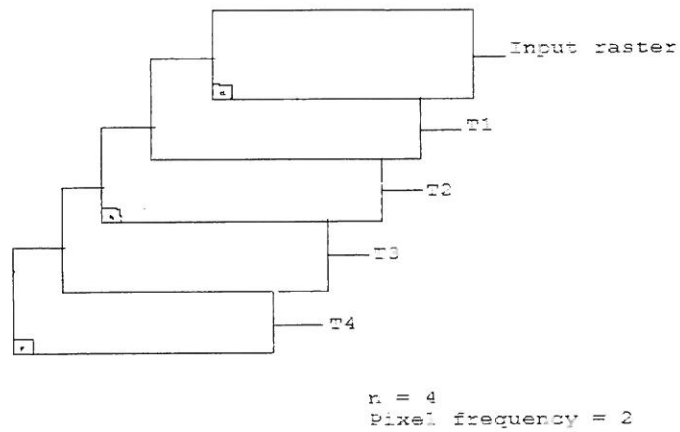


Figure 3: Schematic representation of the pixel frequency reoccurrence calculation.

5 Results

The results for the vegetation patterns observed in KNP using EVI metrics are reported by dividing them into their objectives and then presenting the metrics separately.

5.1 Geographic and geological cover of KNP

Of the four geographical areas of KNP, the far north covers the greatest area while the south covers the smallest area. Central KNP has the most basalt geology of the four regions and the south has more granite and less basalt when compared to all the other regions (Table 2).

Table 2: The size of each of the subdivisions used in the comparative analyses, expressed as a percentage of the total size of KNP by geographic region; Far North (FN), North (N), Central (C), South (S) and geology; Basalt (Ba), Granite (Gr).

KNP	FN		N		C		S	
	Ba	Gr	Ba	Gr	Ba	Gr	Ba	Gr
100%	10%	18%	8%	16%	13%	13%	3%	19%

5.2 Objective one: To assess the spatial variation of the EVI metrics (EVI_{max} and $\sum EVI$) in KNP for each year.

For objective one, the metrics are reported separately beginning with the EVI_{max} followed by $\sum EVI$. For each metric the mean location of the clusters created between 2000 and 2010 is presented by a map. Next is the annual spatial distribution

maps of the pixels forming the HH clusters from 2000 to 2010. The area covered by (number of) pixels in the HH clusters in the different geological and geographical regions of KNP is then presented for each year. Next are the results for the difference in greenness (EVI) between the regions and amongst the geographic regions using EVI values of the pixels that made the HH clusters for each year. The t test results are reported for the difference in the greenness between basalt and granite geologies and the ANOVA test results for the difference in the greenness amongst the far north, north, central and southern regions of KNP. The Tukey multi-comparison results show where the differences in greenness lay amongst the different regions each year.

5.2.1 EVI_{max}

5.2.1.1 Location and number (area) of pixels making up the clusters.

On average, the greenest pixels making up the clusters were mainly located in the south and the far north, on granite geology (Figure 4). In each year, the pixels making up the HH clusters were spatially located in the south, central and far north of KNP. The north had very few if any pixels classified as belonging to a HH cluster in all the years (Figure 5a to k). Hence the north was the driest region of KNP as we had expected but surprisingly the far north was not as dry as expected. The pixels fell mainly on granite geology than basalt in most of the years.

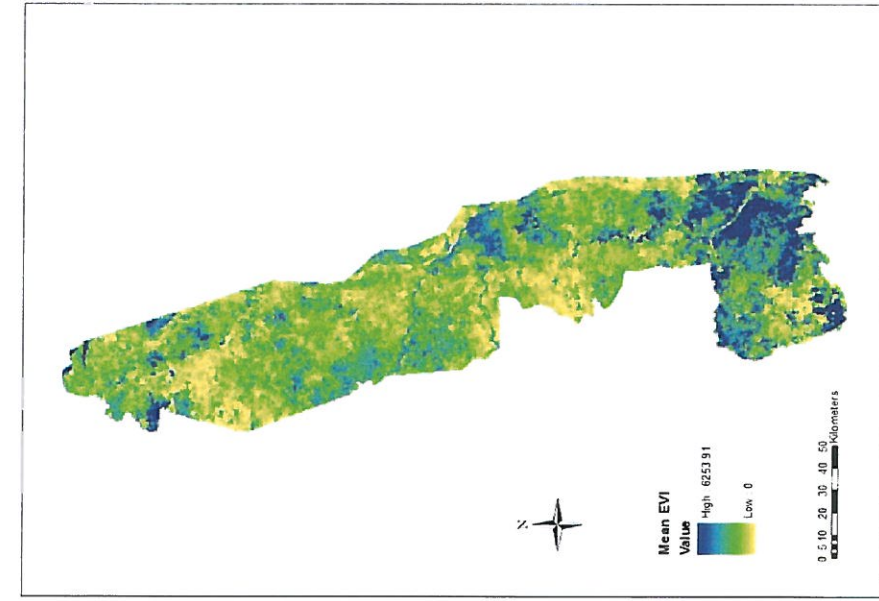


Figure 4: Mean spatial distribution of clusters for the EVI_{max} metric for the period 2000-2010 in KNP

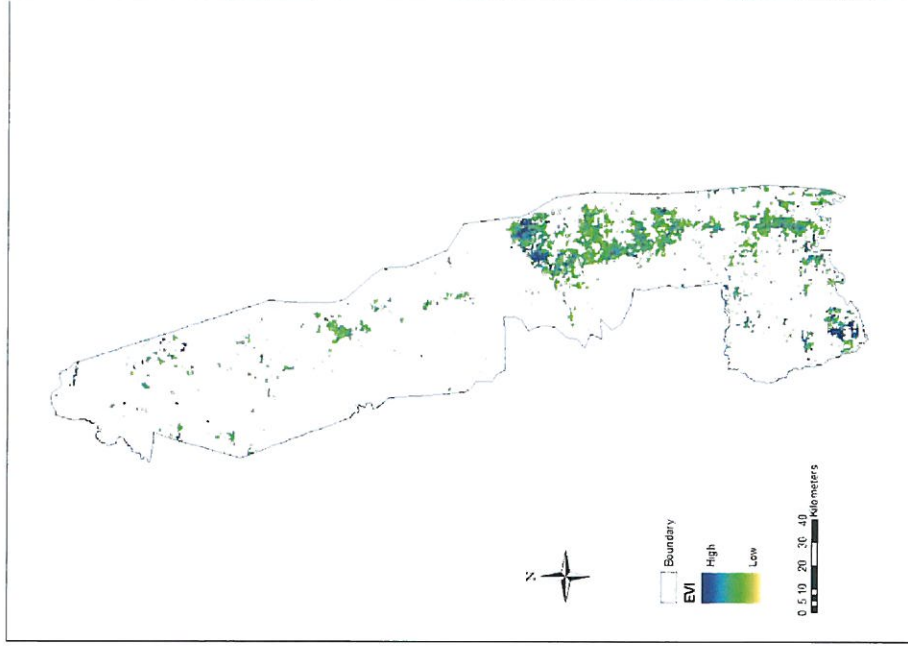


Figure 5(a): Annual spatial distribution of EVI_{max} pixels belonging to the greenest (HH) clusters in KNP (2000)

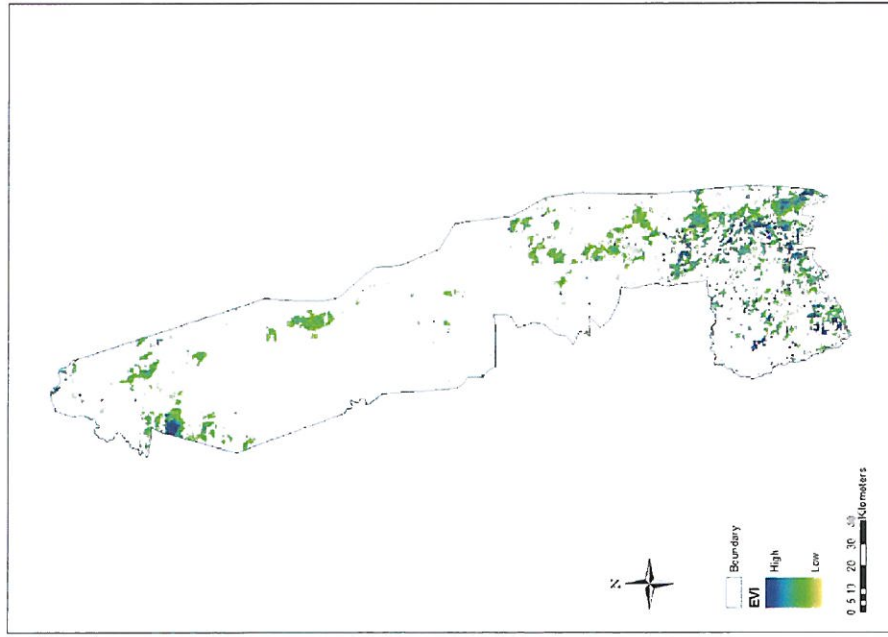


Figure 5(b): Annual spatial distribution of EVI_{max} pixels belonging to the greenest (HH) clusters in KNP (2001).

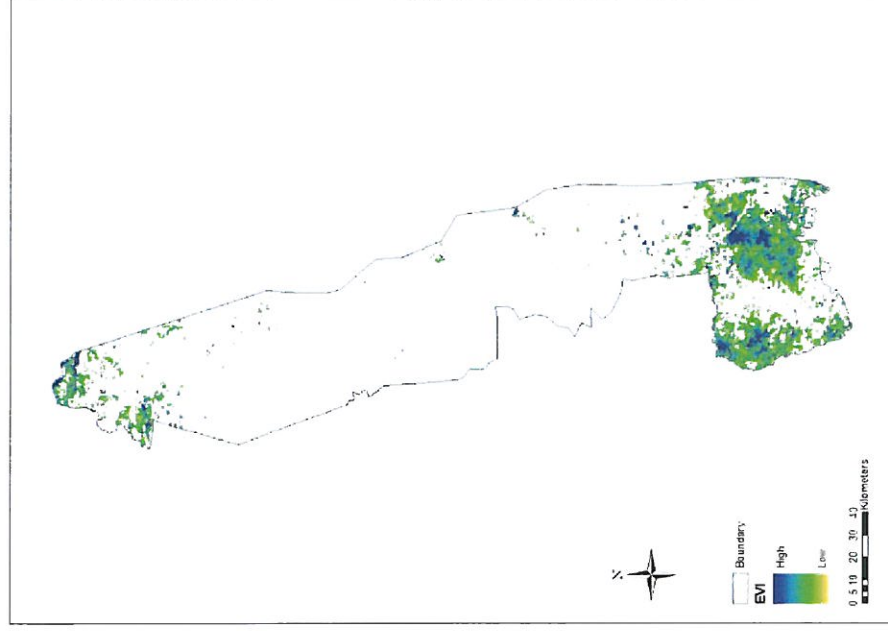


Figure 5(c): Annual spatial distribution of EVI_{max} pixels belonging to the greenest (HH) clusters in KNP (2002)

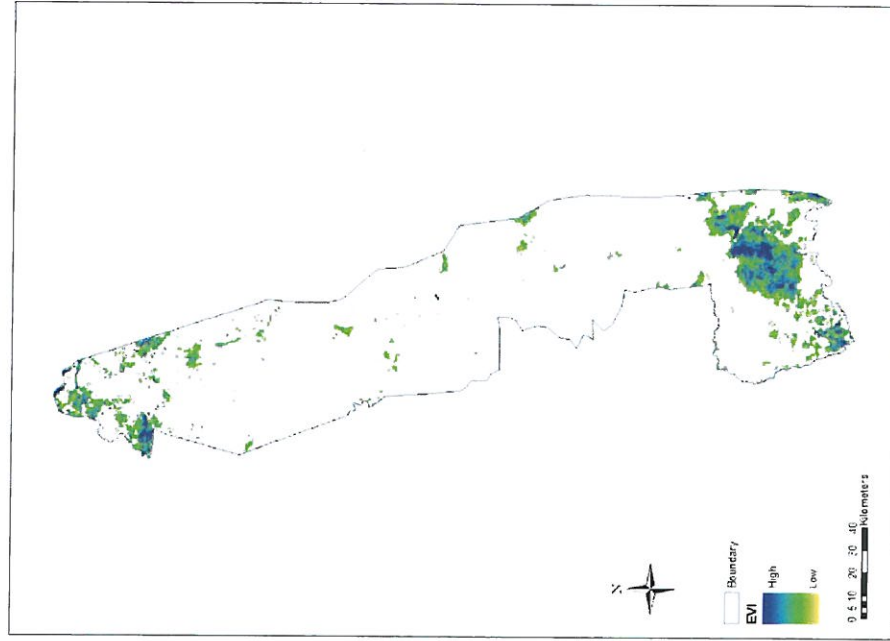


Figure 5(d): Annual spatial distribution of EVI_{max} pixels belonging to the greenest (HH) clusters in KNP (2003)

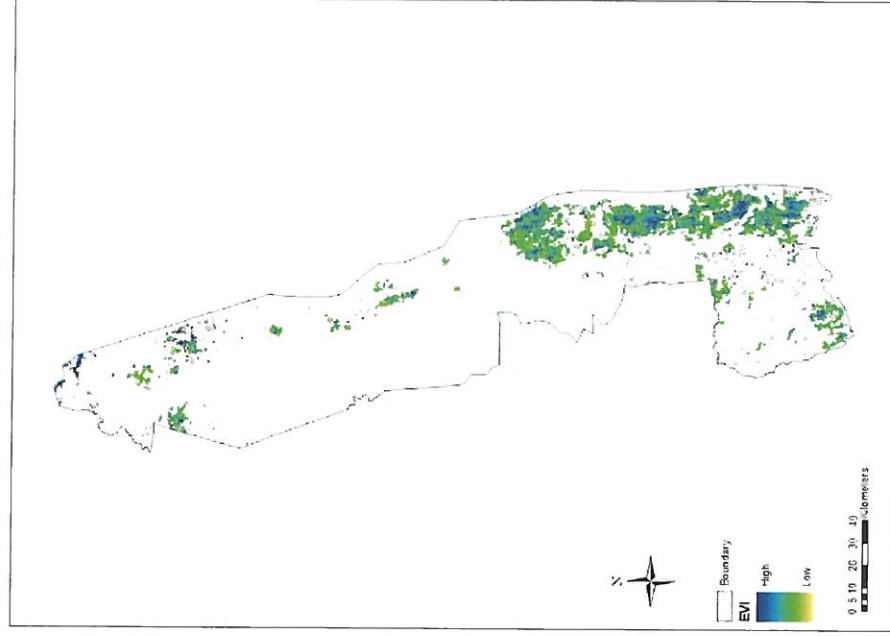


Figure 5(e): Annual spatial distribution of EVI_{max} pixels belonging to the greenest (HH) clusters in KNP (2004).

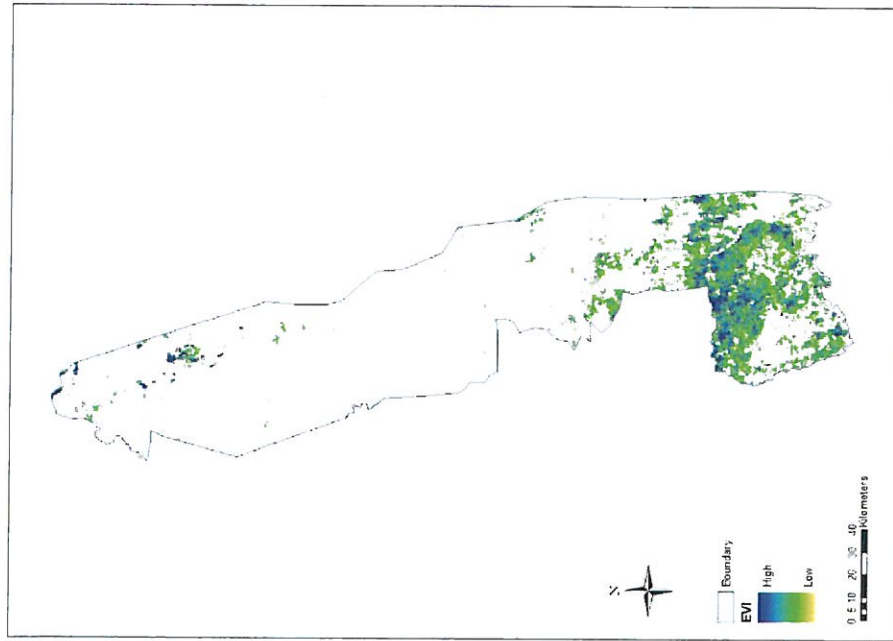


Figure 5(f): Annual spatial distribution of EVI_{max} pixels belonging to the greenest (HH) clusters in KNP (2005)

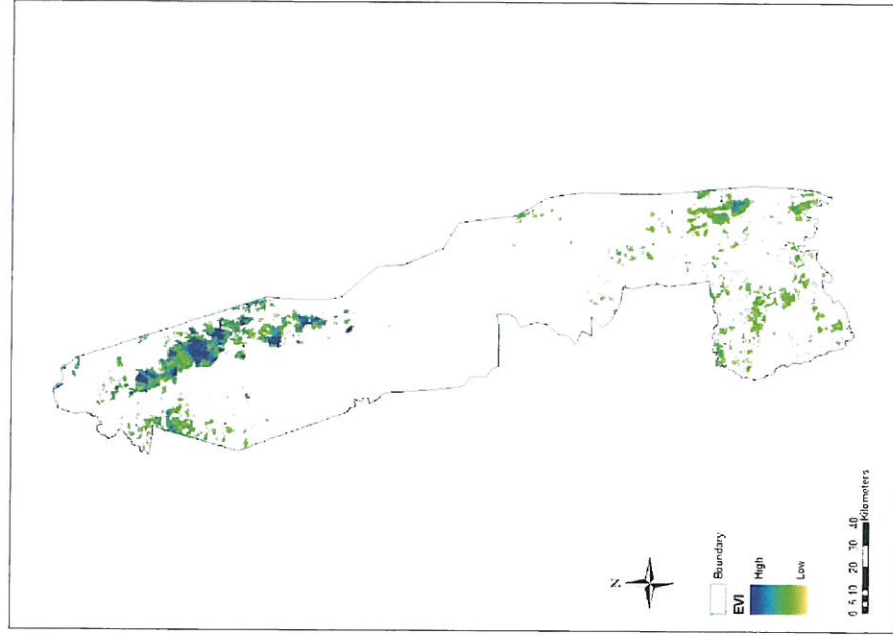


Figure 5(g): Annual spatial distribution of EVI_{max} pixels belonging to the greenest (HH) clusters in KNP (2006).

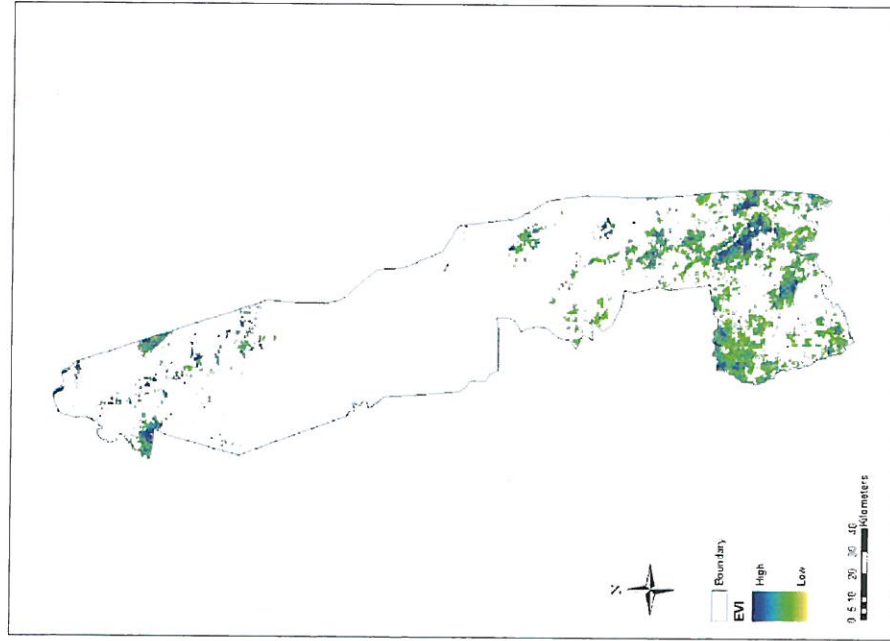


Figure 5(h): Annual spatial distribution of EVI_{max} pixels belonging to the greenest (HH) clusters in KNP (2007).

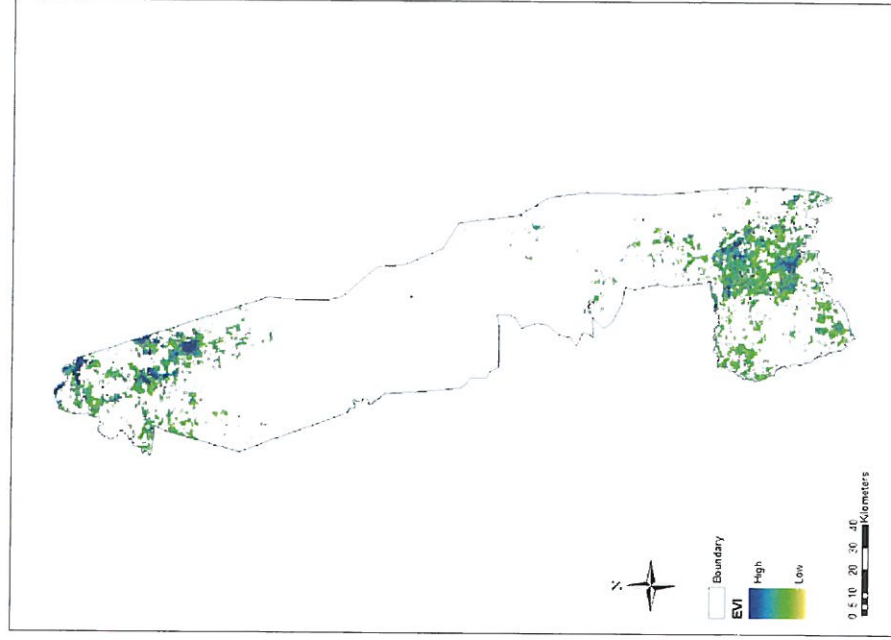


Figure 5(i): Annual spatial distribution of EVI_{max} pixels belonging to the greenest (HH) clusters in KNP (2008).

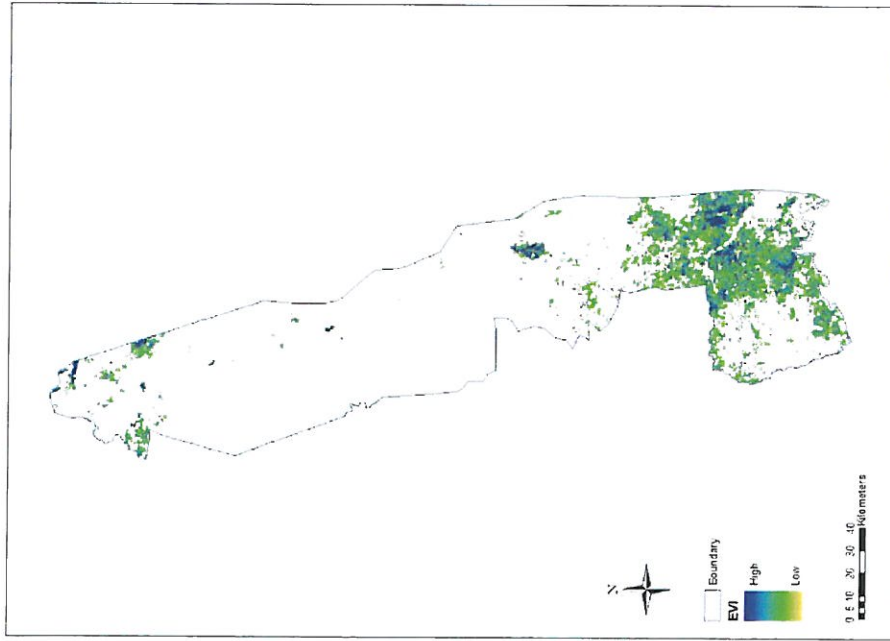


Figure 5(j): Annual spatial distribution of EVI_{max} pixels belonging to the greenest (HH) clusters in KNP (2009).

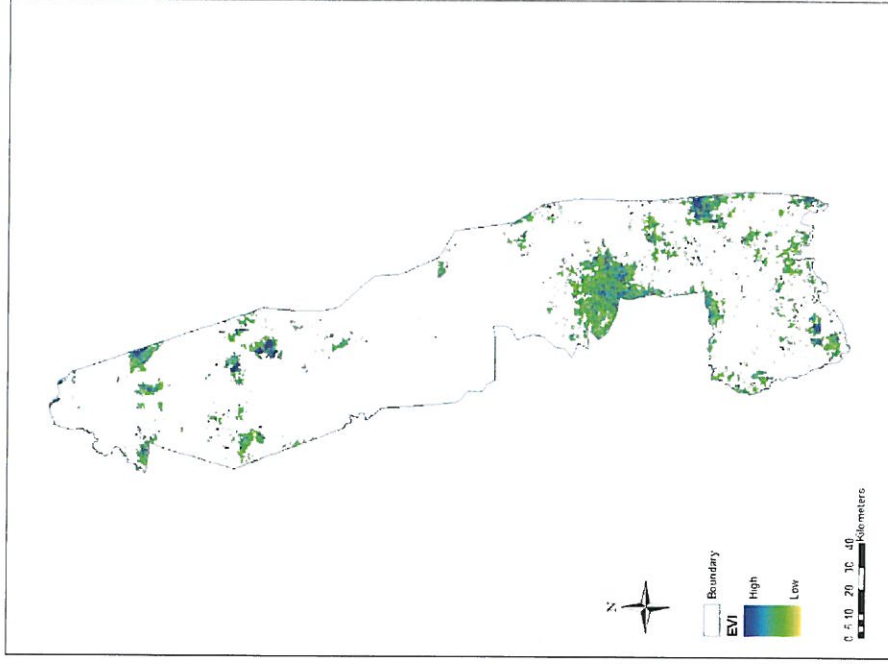


Figure 5(k): Annual spatial distribution of EVI_{max} pixels belonging to the greenest (HH) clusters in KNP (2010).

Pixels from the HH clusters fell more on granite than basalt geology throughout the 11 years with exceptions for 2000, 2004 and 2006 (Figure 6), and on average 78% fell on granite with 22% on basalt geology. Hence the greenest vegetation covered a greater area on granite geology than that on basalt geology on most years, contrary to what was hypothesized.

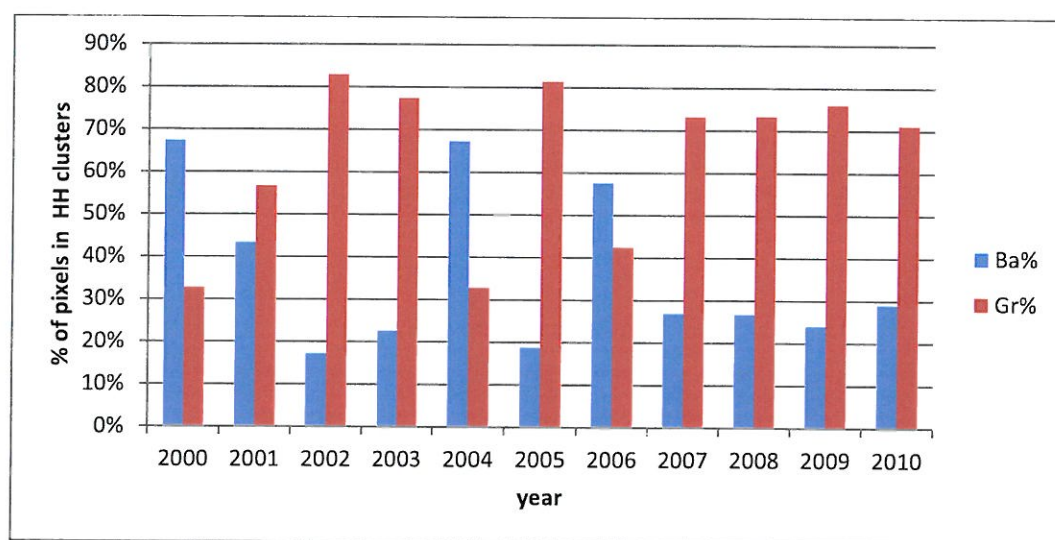


Figure 5: The % of EVI_{max} pixels belonging to the greenest (HH) clusters that fell either on basalt or granite geology between 2000 and 2010 in KNP.

The number of pixels from HH clusters were variable in terms of the geographic boundary they fell in throughout the 11 years in KNP. Pixels fell in the south in most of the years except 2000, 2004, 2006 and 2010. In 2000, 2004 and 2010 more pixels fell in the central region of KNP. Throughout the 11 years, the north had the least number of pixels falling in that region (Figure 7). On average 53% of the pixels fell in the south, 23% in the central, 21% in the far north and 3% in the north

of KNP. In terms of vegetation greenness, the south covered a bigger greener area, with the north having the smallest green area as hypothesised. However the far north had a significant number of pixels in that region which was unexpected.

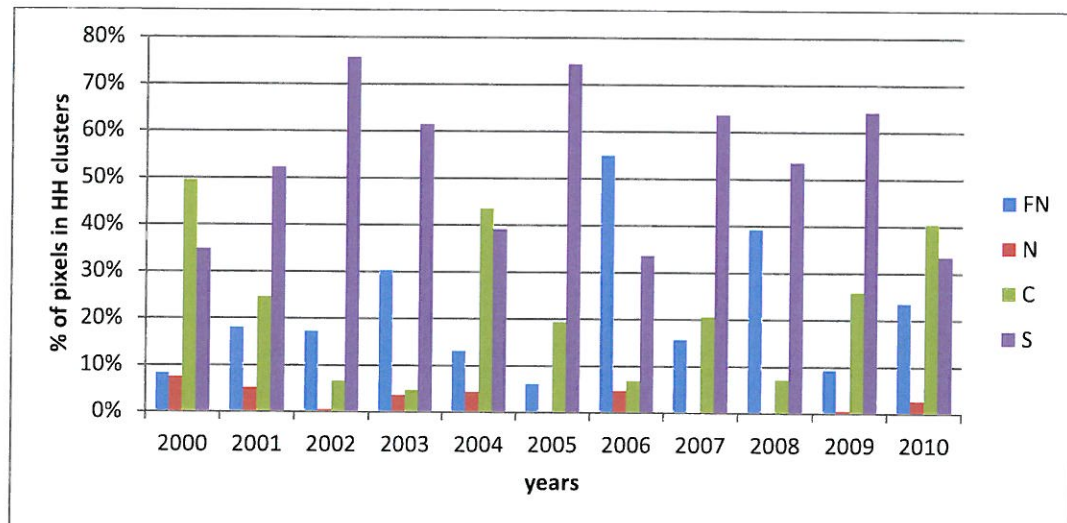


Figure 6: The % of pixels in the greenest (HH) clusters that fell on the different geographic regions (FN, N, C and S) from 2000-2010.

The pixels from HH clusters fell mainly on granite in the far north and south almost every year. The north and central varied as pixels fell on either geology (Table 3). This shows that vegetation greenness in the various geographic was not mainly driven by geology as one would expect more pixels to fall on basalt geology than granite.

Table 3: The % of pixels in the greenest (HH) clusters of KNP by geology and geography from 2000 to 2010.

Year	FN		N		C		S	
	Ba	Gr	Ba	Gr	Ba	Gr	Ba	Gr
2000	3%	5%	7%	1%	45%	5%	13%	22%
2001	6%	12%	5%	0%	17%	8%	16%	36%
2002	2%	15%	0%	0%	2%	5%	13%	63%
2003	6%	24%	1%	2%	2%	2%	12%	49%
2004	8%	5%	4%	0%	39%	5%	17%	22%
2005	4%	2%	0%	0%	5%	14%	10%	65%
2006	41%	14%	5%	0%	4%	3%	9%	25%
2007	6%	9%	0%	0%	10%	10%	10%	53%
2008	19%	21%	0%	0%	3%	4%	5%	48%
2009	2%	8%	0%	0%	11%	15%	11%	53%
2010	10%	13%	2%	1%	12%	29%	5%	28%

5.2.1.2 Comparisons in greenness of pixels making the HH clusters, per geographic and geological region

The differences in greenness between basalt and granite were significant in 7 years from the p values, with exceptions of 2002, 2005, 2007 and 2008 (Table 4).

This shows greenness of vegetation in the two geologies, is not the same for most years as was expected.

Table 4: T-test results for the differences in greenness between basalt and granite geology from the greenest (HH) clusters for EVI_{max} (2000 – 2010).

Year	Ba (n)	Gr (n)	Ba EVI mean	Gr EVI mean	Equality of Variances (p)	Pooled (p) value	Satterthwaite(p) value
2000	1124	544	5146	5279	<.0001	<.0001	<.0001*
2001	792	416	4771	4966	<.0001	<.0001	<.0001*
2002	392	1888	4688	4734	0.0043	0.0475	0.0328
2003	432	1476	4279	4365	<.0001	<.0001	<.0001*
2004	1400	680	5877	5761	0.0918	<.0001*	<.0001
2005	468	2020	5229	5250	0.1559	0.2633	0.2787
2006	920	680	6417	6237	<.0001	<.0001	<.0001*
2007	568	1548	5123	5145	<.0001	0.1992	0.1348
2008	690	1508	5515	5517	0.0007	0.8857	0.8808
2009	596	1888	5701	5608	<.0001	<.0001	<.0001*
2010	540	1655	5188	5275	0.0042	<.0001	<.0001*

To determine which *p* value to use (Pooled*p* value or Satterthwaite*p* value), first we test for equality of variances between the different regions. If variances are equal we use the Pooled *p* value, if variances are unequal we use the Satterthwaite*p* value to test for differences in mean .Areas shaded in grey indicate the *p* value used to compare the differences in the EVI value, and *indicates *p* values that showed significant difference (0.05 level) in mean EVI values between the two regions for that year.

In the years that showed significant difference in greenness between the two regions, the mean EVI (greenness) was higher on granite than basalt with exceptions for 2004, 2006 and 2009 (Figure 8), although the margin of difference was not so high. Hence vegetation on granite is greener than that on basalt which differs from what was hypothesised.

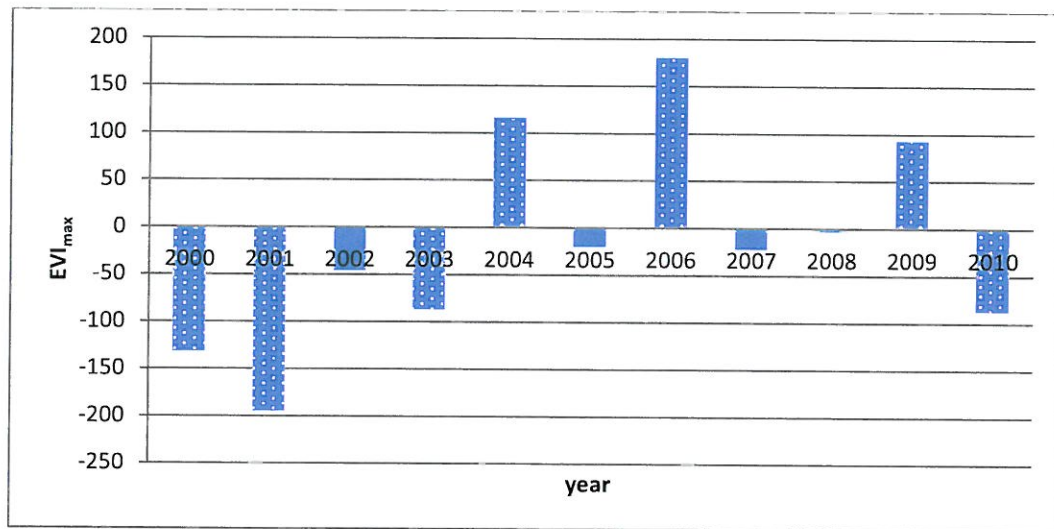


Figure 7: Differences of the mean greenness between basalt and granite geology from the greenest (HH) clusters for EVI_{max} (2000 – 2010). Polka dotted bars indicate years with significant difference in greenness between the regions being compared.

The greenness in vegetation amongst the regions differed significantly throughout the 11 years (Table 5) as indicated by the p values each year as was expected.

Table 5: ANOVA results for the differences in the greenness amongst the geographic regions from the greenest (HH) clusters for EVI_{max}(2000-2010).

Year	Mean EVI FN	Mean EVI N	Mean EVI C	Mean EVI S	(p) value
2000	5248	5089	5232	5315	<.0001*
2001	4741	4654	4778	4939	<.0001*
2002	4738	4801	4733	4682	0.0371*
2003	4192	4071	4164	4254	<.0001*
2004	5889	5734	5834	5776	<.0001*
2005	5346	5171	5270	5239	0.0024*
2006	6557	6709	6159	6237	<.0001*
2007	5252	5021	5061	5076	<.0001*
2008	5567	5530	5406	5515	<.0001*
2009	5856	5490	5669	5667	<.0001*
2010	5338	5200	5211	5185	<.0001*

*indicates *p* values that showed significant difference (0.05 level) in mean EVI_{max} values amongst the four regions for that year.

Where significant differences in mean greenness lay amongst the regions varied by year, with the differences being small most of the years. The differences in greenness between the south-far north, far north-central and north-far north, were the greatest (Figure 9) in most years. The south and far north were significantly different from each other every year of the study except 2000. However in all those years, 2001 and 2003 are the only years the south was greener than the far north, which is different from what was hypothesized. The south and north were significantly different from each other from 2000 to 2003 and 2006, with the south being significantly greener in 2000, 2001 and 2003 than the north. The north was significantly different from central region of KNP in 5 years, with the north only being greener in 2002 and 2006 of the 5 years, similar to our hypothesis of the central regions being greener than the north. The far north was significantly different from

the central region from 2006 to 2010, with the far north being greener in all those years, which did not match our hypothesis. The results depict what was expected in the study were the south and central regions are greener than the north. However, interesting was how the greenness of the far north appears greener than the central and south of Kruger as one would expect the greenness in the vegetation to follow the rainfall gradient with greenness increasing from the north to the south. This suggests other factors other than rainfall affecting the greenness of vegetation in the far north.

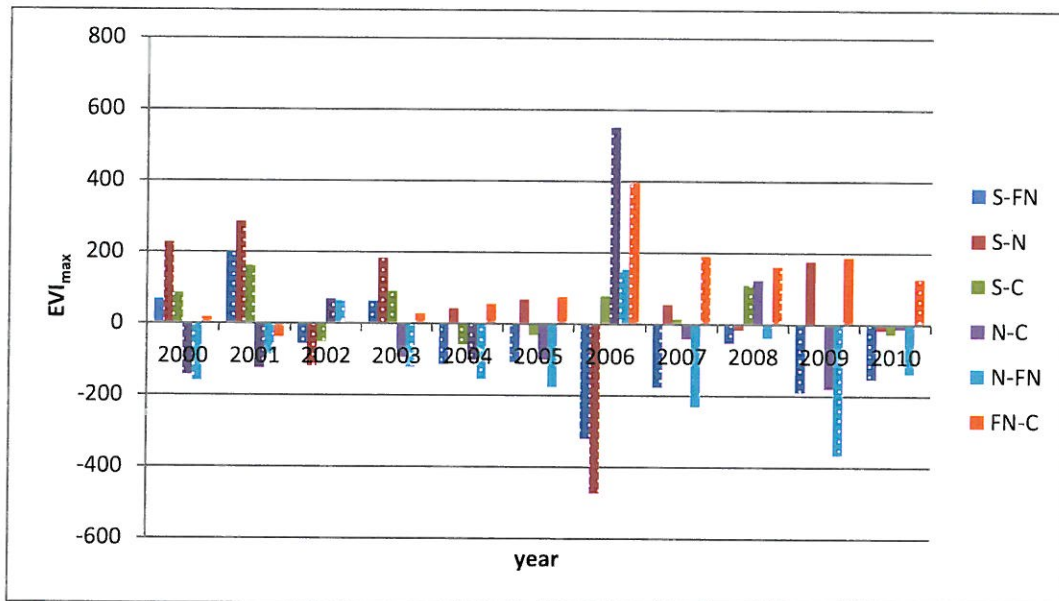


Figure 8: Tukey multiple comparison tests results for the differences in the mean greenness amongst the geographic regions from the greenest (HH) clusters for $EVI_{max}(2000-2010)$. Polka dotted bars indicate years with significant difference in greenness between the regions being compared.

5.2.2 ΣEVI

5.2.2.1 Location and number (area) of pixels making up the clusters

The greenest clusters were located in the south and tips of the far north on average over the 11 years (Figure 10). The pixels making up the HH clusters were located mainly in the south and the far north (mainly its tips) almost every year except for 2000, 2001 and 2010, where the pixels were scattered throughout KNP (Figure 11*a* to *k*). These pixels fell more on granite geology than basalt geology throughout the study. The results suggest $\sum EVI$ was highest in the south and far north tips on granite geology

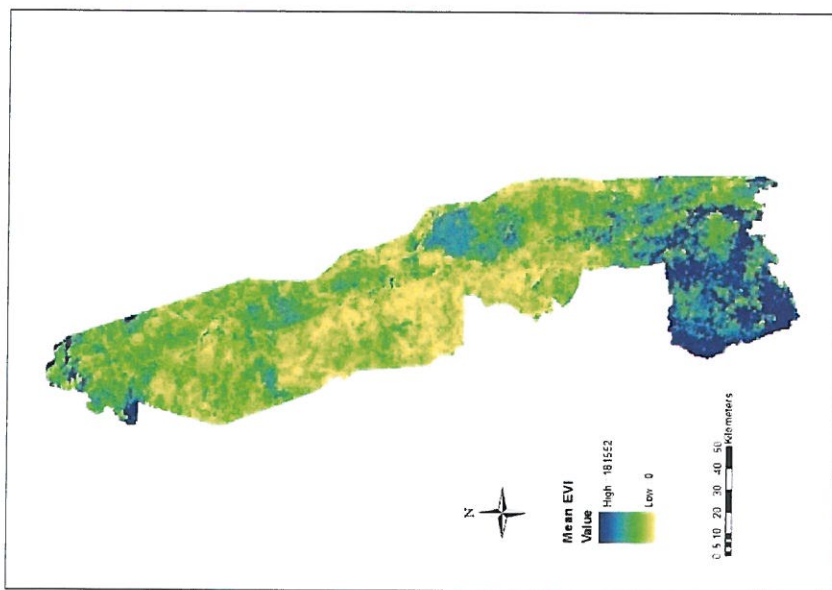


Figure 10: Mean spatial distribution of Σ EVI metric for the period 2000-2010 in KNP

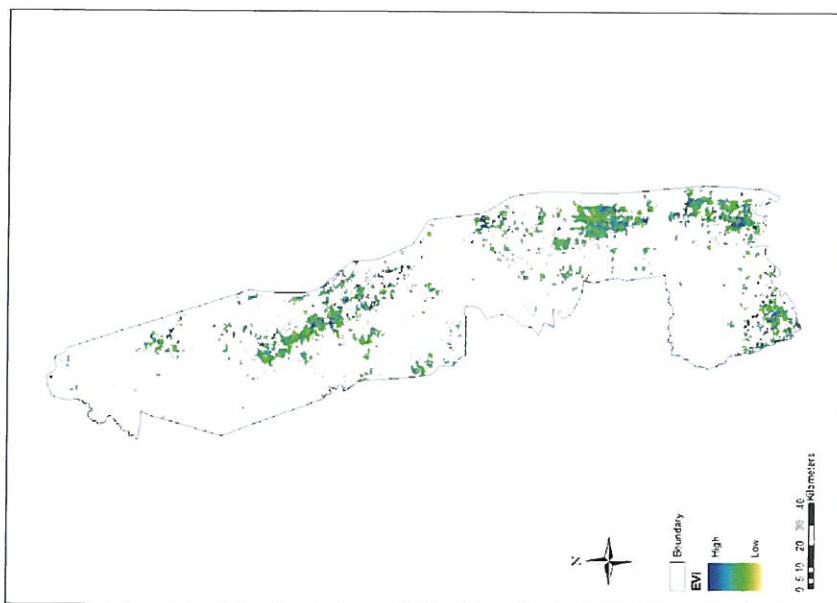


Figure 11(a): Annual spatial distribution of Σ EVI pixels belonging to the greenest (HH) clusters in KNP (2000).

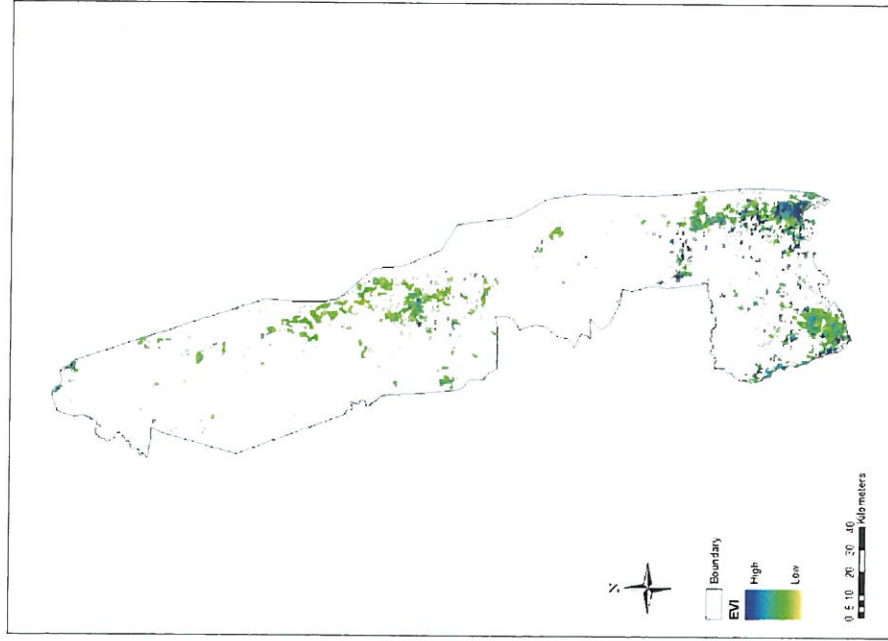


Figure 11(b): Annual spatial distribution of Σ EVI pixels belonging to the greenest (HH) clusters in KNP (2001).

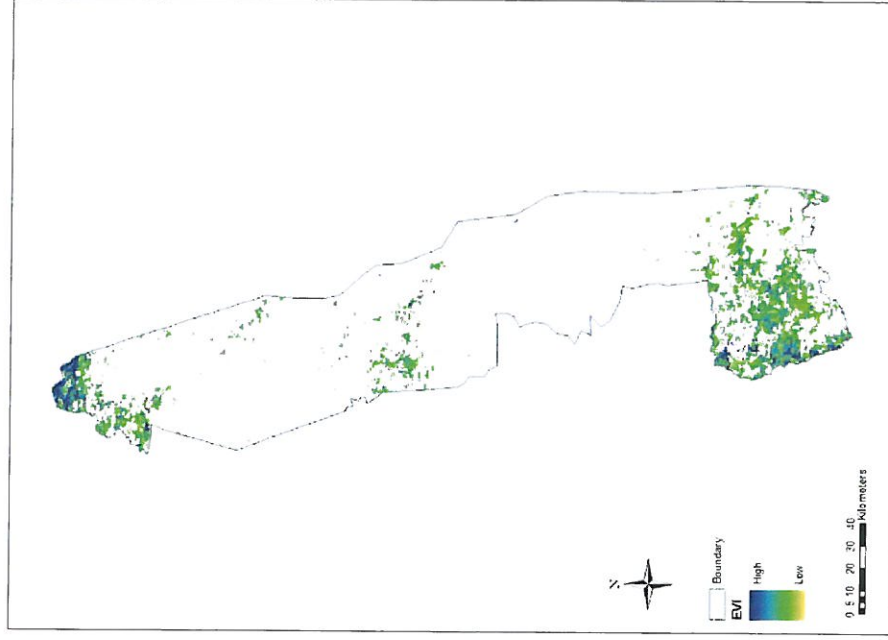


Figure 11(c): Annual spatial distribution of Σ EVI pixels belonging to the greenest (HH) clusters in KNP (2002).

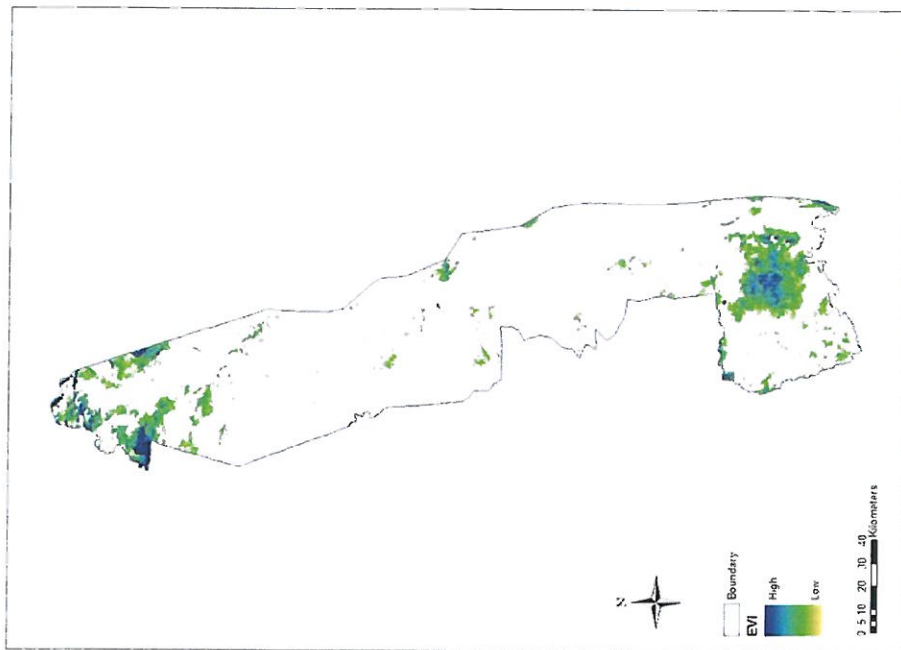


Figure 11(d): Annual spatial distribution of Σ EVI pixels belonging to the greenest (HH) clusters in KNP (2003).

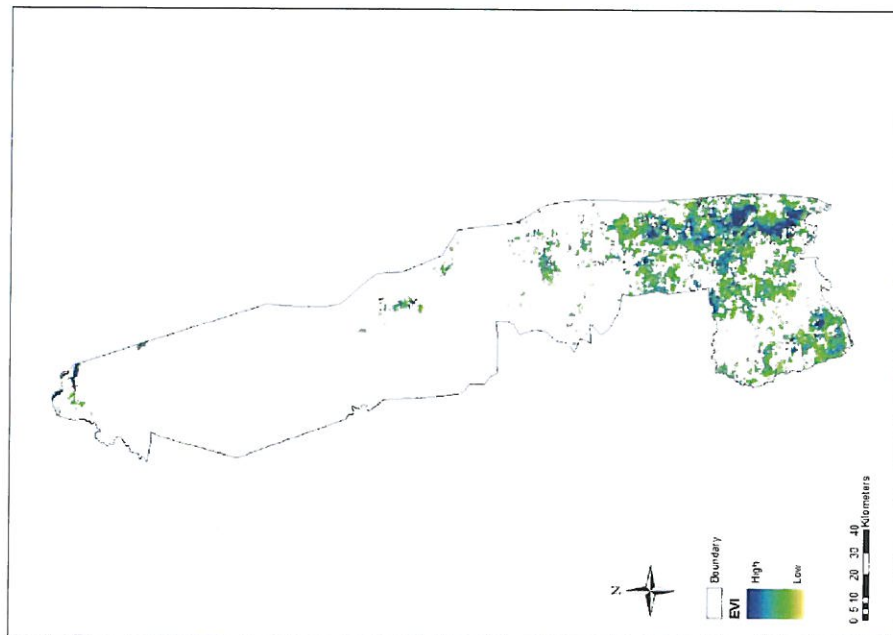


Figure 11(e): Annual spatial distribution of Σ EVI pixels belonging to the greenest (HH) clusters in KNP (2004).

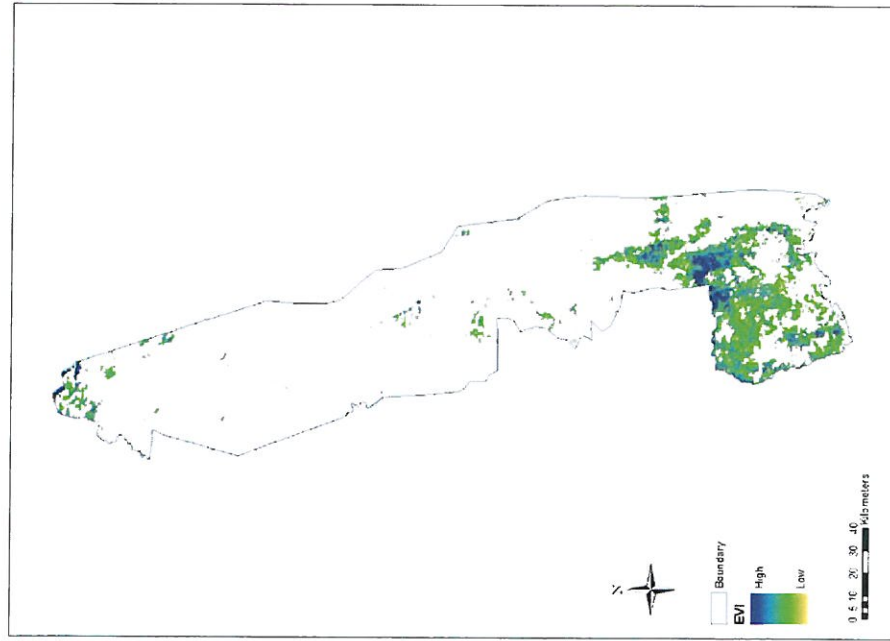


Figure 11(e): Annual spatial distribution of Σ EVI pixels belonging to the greenest (HH) clusters in KNP (2005).

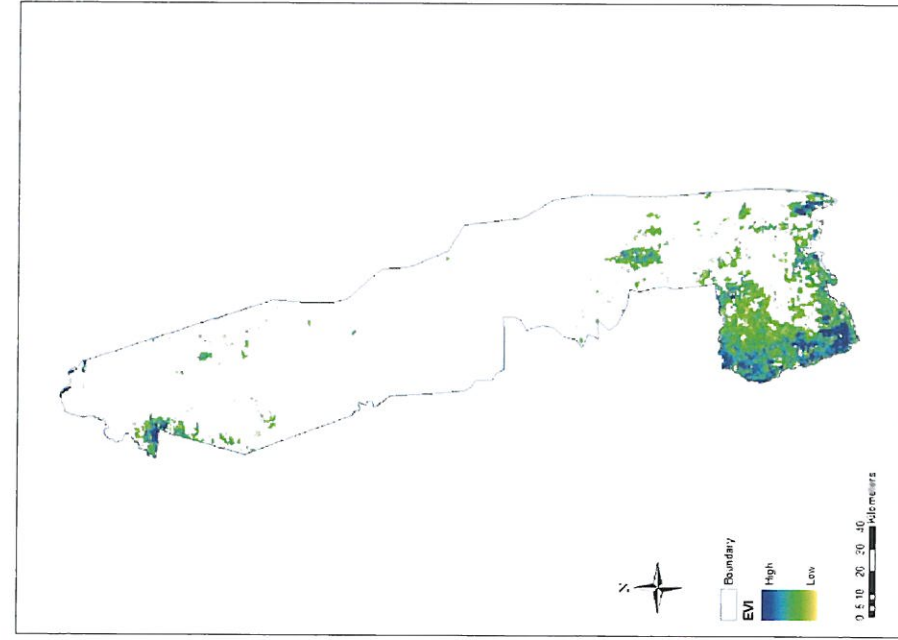


Figure 11(g): Annual spatial distribution of Σ EVI pixels belonging to the greenest (HH) clusters in KNP (2006).

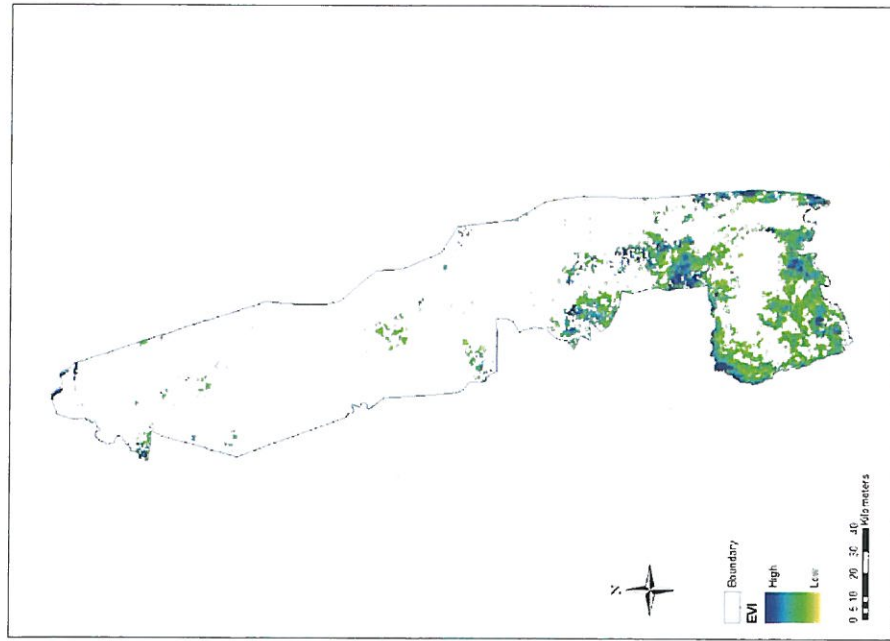


Figure 11(h): Annual spatial distribution of Σ EVI pixels belonging to the greenest (HH) clusters in KNP (2007).

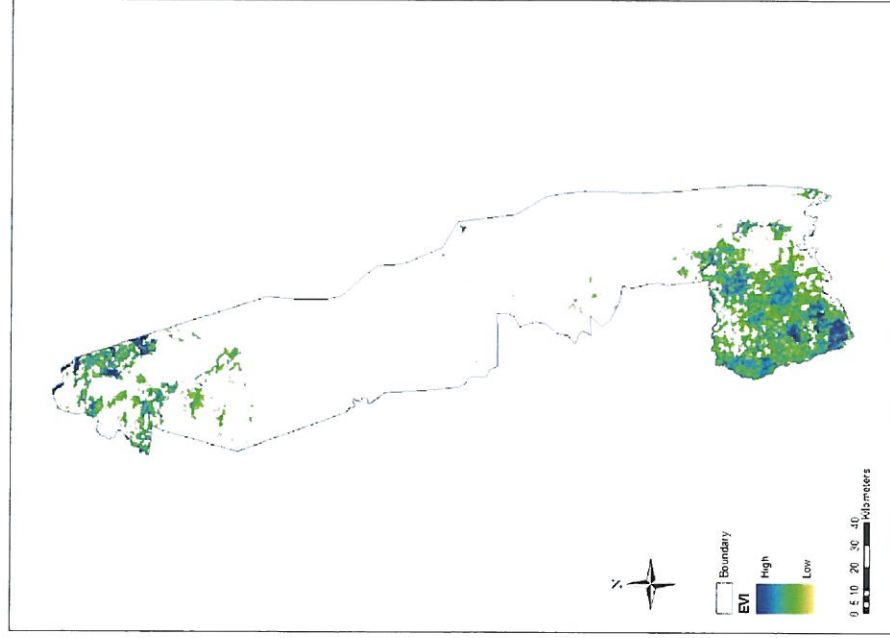


Figure 11(i): Annual spatial distribution of Σ EVI pixels belonging to the greenest (HH) clusters in KNP (2008).

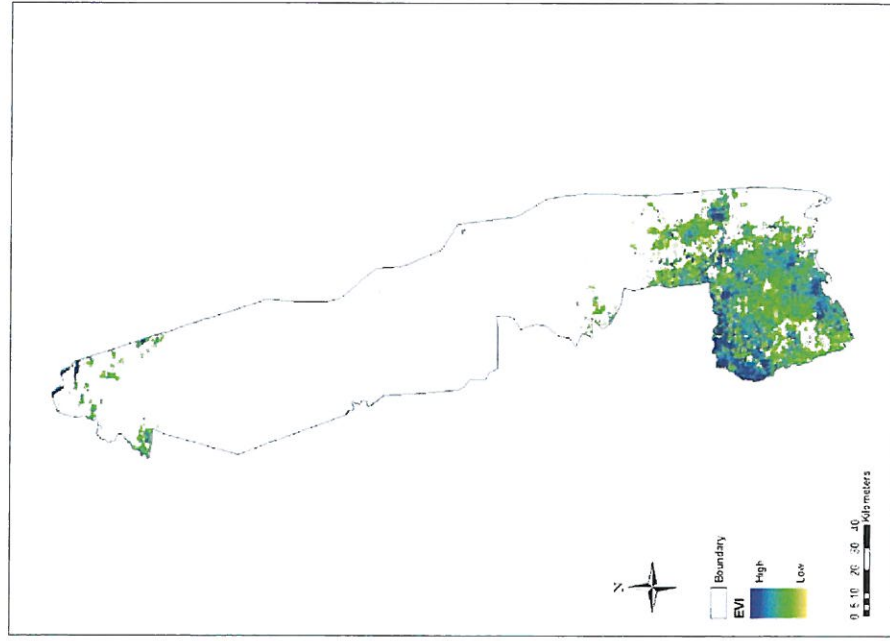


Figure 11(j): Annual spatial distribution of Σ EVI pixels belonging to the greenest (HH) clusters in KNP (2009).

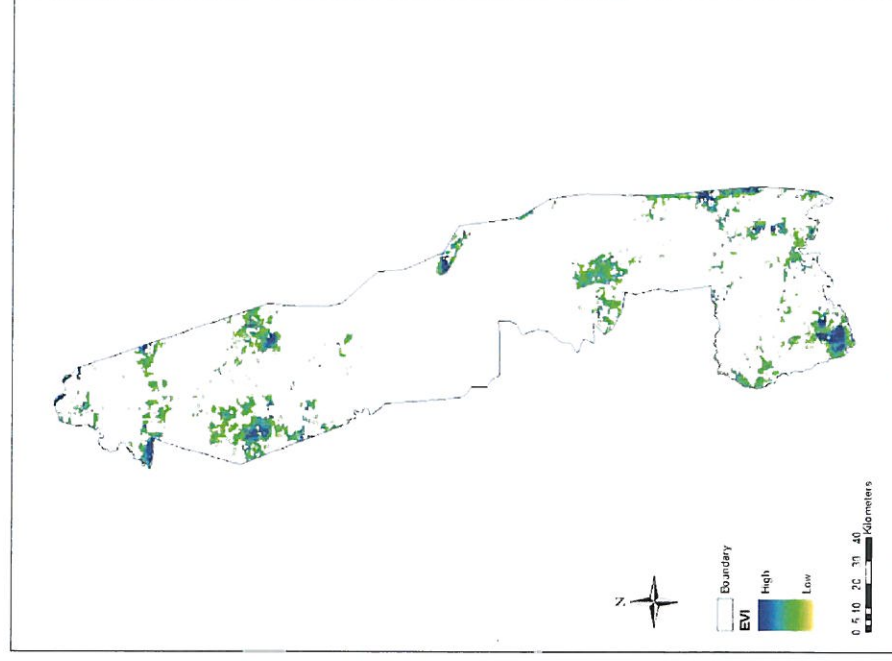


Figure 11(k): Annual spatial distribution of Σ EVI pixels belonging to the greenest (HH) clusters in KNP (2010).

As already seen from the maps (Figure 10 and 11a to k), the pixels from HH clusters fell more on granite than basalt geology throughout the 11 years with exceptions for 2000 and 2001 (Figure 12) and on average 78% fell on granite with 22% on basalt geology of KNP which was not expected. Therefore $\sum$ EVI on granite geology was higher than that on basalt geology.

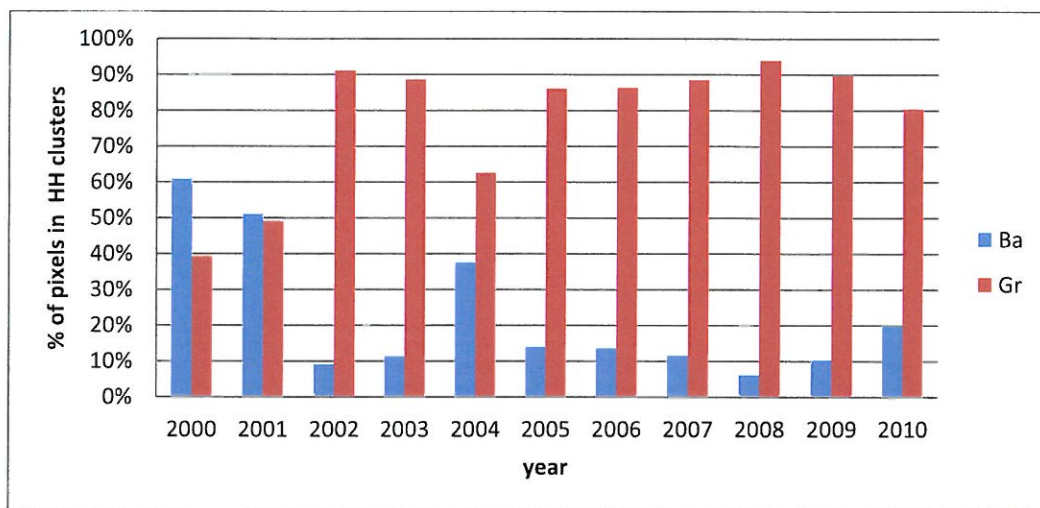


Figure 9: The % of $\sum$ EVI pixels belonging to the greenest (HH) clusters that fell on either basalt or granite geology between 2000 to 2010 in KNP.

Throughout the 11 years, the number of pixels of HH clusters varied in terms of the geographic boundary they fell in. Most pixels fell in the south except 2000 where more pixels fell in the central and 2010 where the far north had the highest number of pixels (Figure 13). On average 59% of the pixels fell in the south, 17% in the far north, 16% in the central and 8% in the north. The results match the hypothesis of more pixels falling in south than northern region. However the central and far north were not too different from each other, with the far north having more

pixels than was expected.

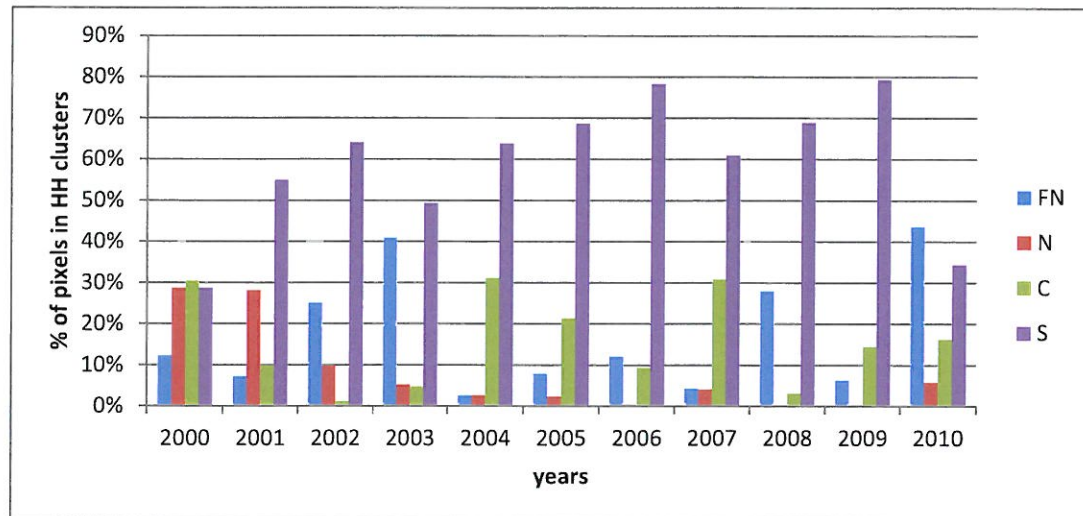


Figure 10: The % of pixels in the greenest (HH) clusters that fell on the different geographic regions (FN, N, C and S) from 2000-2010 in KNP.

The pixels from HH clusters fell mainly on granite in the far north and south of KNP in the 11 years. The north and central varied as pixels fell on either geologies of KNP (Table 6). This could suggest that rainfall more than geological substrate seems to determine the spatial distribution of $\sum EVI$.

Table 6: The % of pixels in the greenest (HH) clusters in KNP by geology and geography from 2000 to 2010.

	FN		N		C		S	
	Ba	Gr	Ba	Gr	Ba	Gr	Ba	Gr
2000	7%	5%	17%	12%	24%	6%	13%	16%
2001	4%	3%	20%	8%	5%	5%	22%	33%
2002	3%	22%	2%	8%	0%	1%	4%	60%
2003	4%	37%	1%	5%	1%	4%	6%	44%
2004	0%	2%	2%	1%	19%	12%	16%	48%
2005	1%	7%	1%	1%	7%	14%	5%	64%
2006	2%	10%	0%	0%	5%	5%	7%	71%
2007	0%	4%	1%	3%	7%	24%	4%	57%
2008	4%	24%	0%	0%	0%	3%	2%	67%
2009	0%	6%	0%	0%	4%	10%	6%	74%
2010	11%	32%	1%	5%	3%	14%	5%	30%

5.2.2.2 Comparison in greenness of pixels making the HH clusters per geographic and geological region.

Differences in greenness between granite and basalt geology differed significantly, except 2000 and 2008 (Table 7). This suggests that the vegetation greenness (Σ EVI), in the two geologies is different.

Table 7: T test results for the differences in greenness between basalt and granite geology from the greenest (HH) clusters for $\sum\text{EVI}(2000 - 2010)$.

Year	Ba (n)	Gr (n)	Ba EVI mean	Gr EVI mean	Equality of Variances (p) value	Pooled (p) value	Satterthwaite (p) value
2000	1084	700	71443	71296	0.0296	0.6865	0.6817
2001	792	1036	4709	4903	<.0001	<.0001	<.0001*
2002	172	1740	92035	96290	<.0001	0.0002	<.0001*
2003	204	1688	114122	118912	<.0001	<.0001	<.0001*
2004	896	1488	157740	155047	<.0001	<.0001	<.0001*
2005	300	1805	120283	125178	<.0001	<.0001	<.0001*
2006	276	1728	156547	158600	0.0036	0.0008	0.0002*
2007	264	2004	125106	126483	0.0973	0.0372*	0.0273
2008	148	2280	126905	124999	0.2258	0.0569	0.0431
2009	292	2548	132473	137034	<.0001	<.0001	<.0001*
2010	340	1392	109179	113068	<.0001	<.0001	<.0001*

To determine which p value to use (Pooled p value or Satterthwaite p value), first we test for equality of variances between the different regions. If variances are equal we use the Pooled p value, if variances are unequal we use the Satterthwaite p value to test for differences in mean. Areas shaded in grey indicate the p value used to compare the differences in the EVI value, and *indicates p values that showed significant difference (0.05 level) in mean EVI values between the two regions for that year.

In all years, except in 2004 and 2008, $\sum\text{EVI}$ was higher on granite than basalt geology. Mean greenness of pixels on granite were higher than pixels on basalt with exception of 2004 when values on granite were lower than on basalt and 2008 when the difference was not significant (Figure 14). This result is very different from the corresponding results in $\text{EVI}_{\max}$ where the direction of the difference was not as consistent through time.

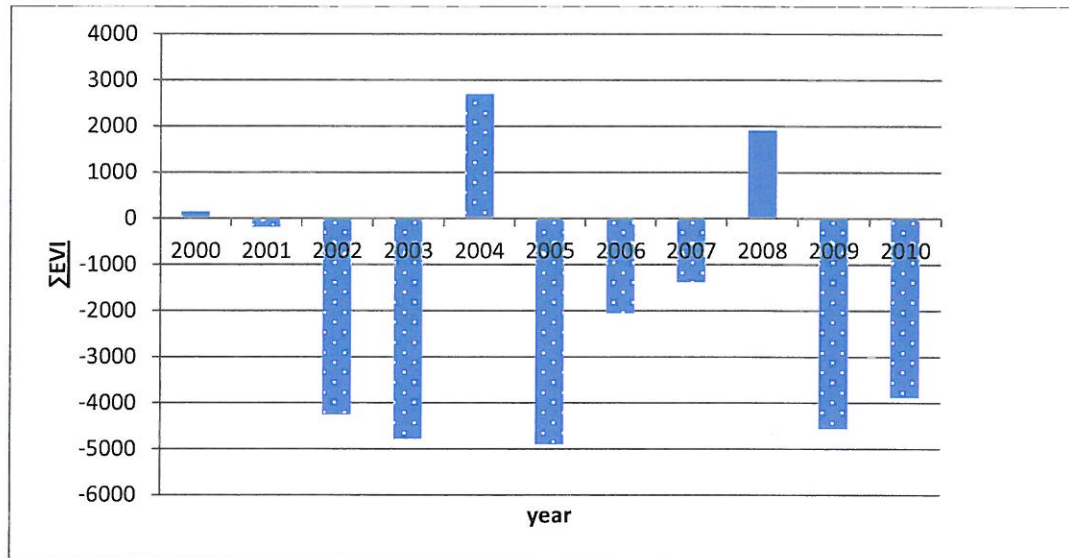


Figure 11: Differences of the mean greenness between basalt and granite geology from the greenest (HH) clusters for $\Sigma\text{EVI}(2000 - 2010)$. Polka dotted bars indicate years with significant difference in greenness between basalt and granite.

Total vegetation greenness was different in each region since the greenness of pixels making up the HH for ΣEVI differed significantly among the regions in every year of the study (Table 8). However the degree of difference varied from year to year amongst the regions (Figure 15).

Table 8: ANOVA results for the differences in the greenness amongst the geographic regions from the greenest (HH) clusters for $\sum \text{EVI}(2000-2010)$.

	Mean EVI FN	Mean EVI N	Mean EVI C	Mean EVI S	(p) value
2000	70792	70310	71233	71996	0.0002*
2001	4741	4694	4728	4912	<.0001*
2002	101633	89480	86275	90732	<.0001*
2003	119400	112989	111910	115789	<.0001*
2004	168670	152375	154415	156037	<.0001*
2005	135848	117641	124291	122735	<.0001*
2006	161524	150908	152301	158231	<.0001*
2007	138115	122713	127254	125795	<.0001*
2008	121081	120607	119827	124506	<.0001*
2009	137504	135075	131587	133898	<.0001*
2010	111950	113358	112177	115003	<.0001*

*indicates p values that showed significant difference (0.05 level) in mean $\text{EVI}_{\max}$ values amongst the four regions for that year.

The differences between the south and far north, far north and central and the north and far north, were the highest (Figure 15). The south and far north were significantly different from each other every year of the study except 2000, with the south significantly greener than the far north only in 2001, 2008 and 2010 which is different from what was hypothesized as we expected the south to have greener years than the far north. The south and north were significantly different from each other in 2000, 2001 and 2003 to 2007, with the south being significantly greener in all the years as would be expected. The north was significantly different from central region in 2005 and 2007 with the north being greener, different from our hypothesis of the central regions being greener than the north. The far north was significantly different from the central region in 2002, 2004 to 2007 and 2009, with the far north being greener in all those years, which did not match our hypothesis. The results match the

hypotheses were the south and central regions are greener than the north. However, it is interesting was how the greenness of the far north appears greener than the central and south of Kruger as one would expect the greenness in the vegetation to follow the rainfall gradient with greenness increasing from the north to the south. This suggests that annually, the far north is the greenest region of KNP and the north the driest region of KNP.

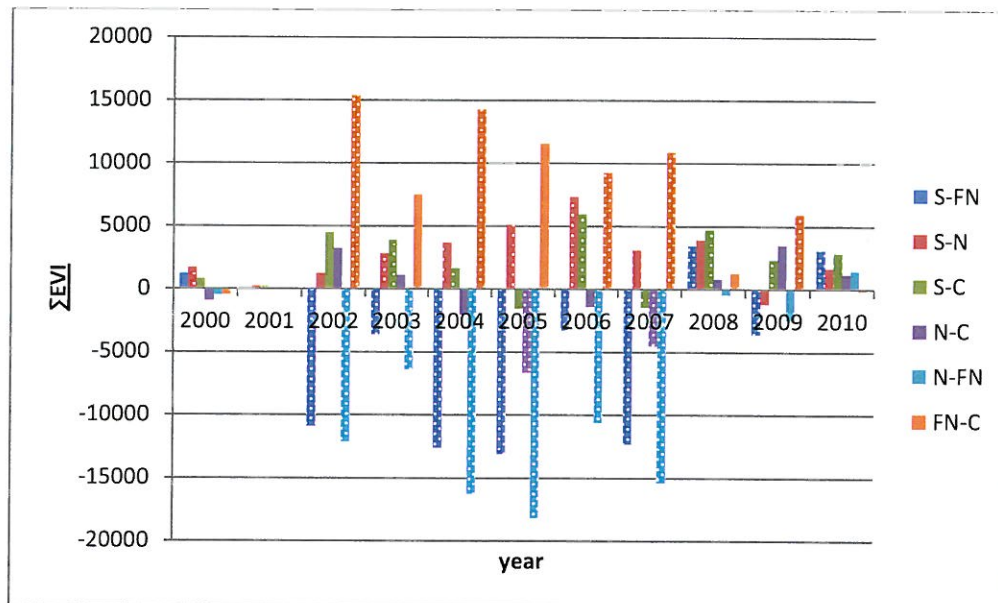


Figure 12: Tukey multiple comparison tests results for the differences in the mean greenness amongst the geographic regions from the greenest (HH) clusters for $\Sigma\text{EVI}(2000-2010)$. Polka dotted bars indicate years with significant difference in greenness between the regions being compared.

5.3 Objective two: To assess temporal changes in vegetation greenness by analyzing the temporal changes in the EVI metrics ($\text{EVI}_{\max}$ and ΣEVI).

For the results of objective two, findings for EVI_{max} were presented first, followed by those of the $\sum EVI$ metric. Under each metric first to be presented was the extent of KNP covered by the pixels making up the HH clusters year after year. Next was the mean-variance plot of the EVI values to show vegetation shifts of KNP over the 11 years. This was followed by the frequency of reoccurrence of pixels in the maps of KNP created in the study period. Finally was the spatial overlap of map of the frequency reoccurrence pixels over the 11 years.

5.3.1 EVI_{max}

The extent of KNP covered by pixels of HH clusters varied throughout the study period as was expected. The years 2005 and 2009 covered the biggest area of 18% with 2000 and 2006 covering the smallest area of 12% of KNP (Figure16). This suggests that KNP's greenest years were 2005 and 2009 with 2000 and 2006 being the driest years. The extent of KNP covered by pixels making up the HH clusters varied in the 11 years but increased from 2000 to 2010 as was expected.

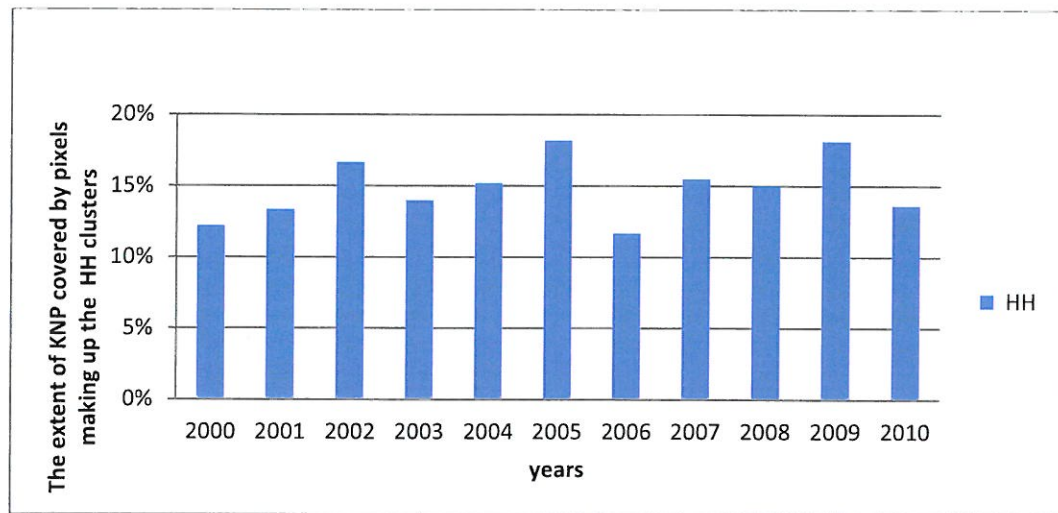


Figure 13: The extent of KNP covered by pixels of the greenest (HH) clusters (2000-2010).

When mean and variance of EVI_{max} for the same period were plotted against each other (mean–variance analysis after Washington-Allen *et al.* 2009) over the 11 years, it showed a decrease in the mean from 2000 to 2003. From 2003 to 2010, the mean continued to go back and forth, increasing and decreasing. From 2000 to 2002, the variance increased. It decreased in 2003 and increased up to 2006. From then it went back and forth up to 2010 (Figure 17). The vegetation greenness in terms of its mean and variance is erratic but appears to be highly variable over the 11 years. The results suggest that the landscape of KNP is highly variable; changing from being heterogeneous to homogenous and increasing and then decreasing in vegetation greenness. However the landscape appears to move towards increasing vegetation greenness and being more heterogeneous, hence KNP is getting greener and highly heterogeneous.

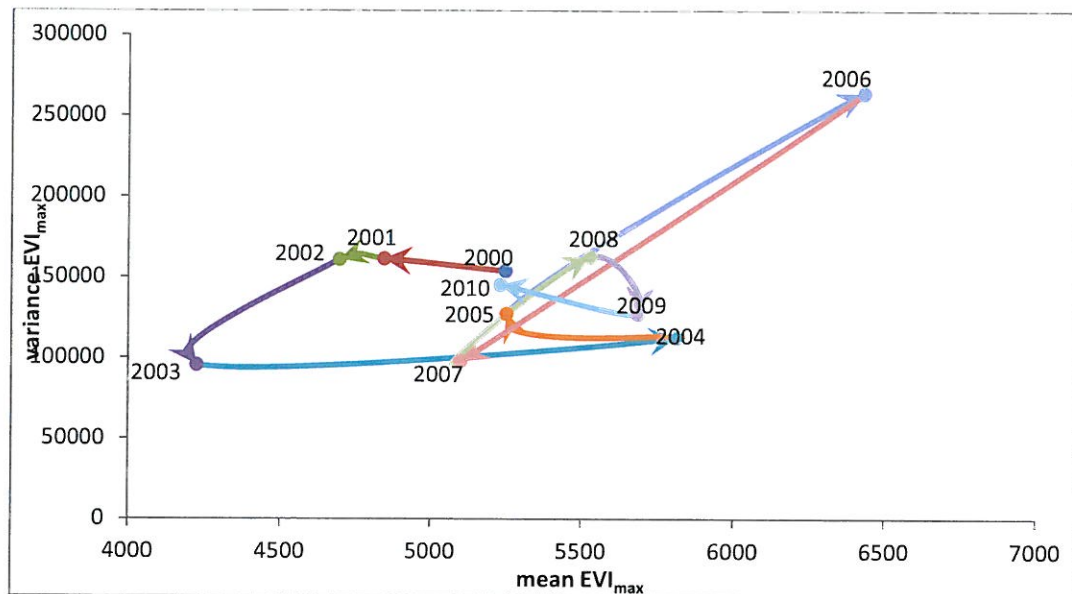


Figure 14: Mean- variance analysis for the period 2000-2010 showing vegetation states in KNP's landscape for EVI_{max} (After Washington-Allen *et al.* 2009).

Frequency of pixels reoccurring in HH clusters year after year was low, with only 7 % occurring at least 6 times or more throughout the 11 years (Figure 18), also suggesting a highly variable landscape in terms of location of pixels with EVI_{max}. The spatial overlap of pixels is low and spatial distribution of the pixels in KNP is variable every year. Spatial overlap of pixels making up the HH clusters was more common in the south, central and parts of the far north of KNP but again, with a low frequency (Figure 19). Therefore, the south, central and tips of the far north were the most consistent in terms of vegetation greenness (maximum/absolute vegetation greenness) than the north in the study period, although spatial overlap was low. The low spatial overlap of EVI_{max} pixels suggests that KNP is a highly heterogeneous, with a variable landscape in terms of vegetation greenness as was expected.

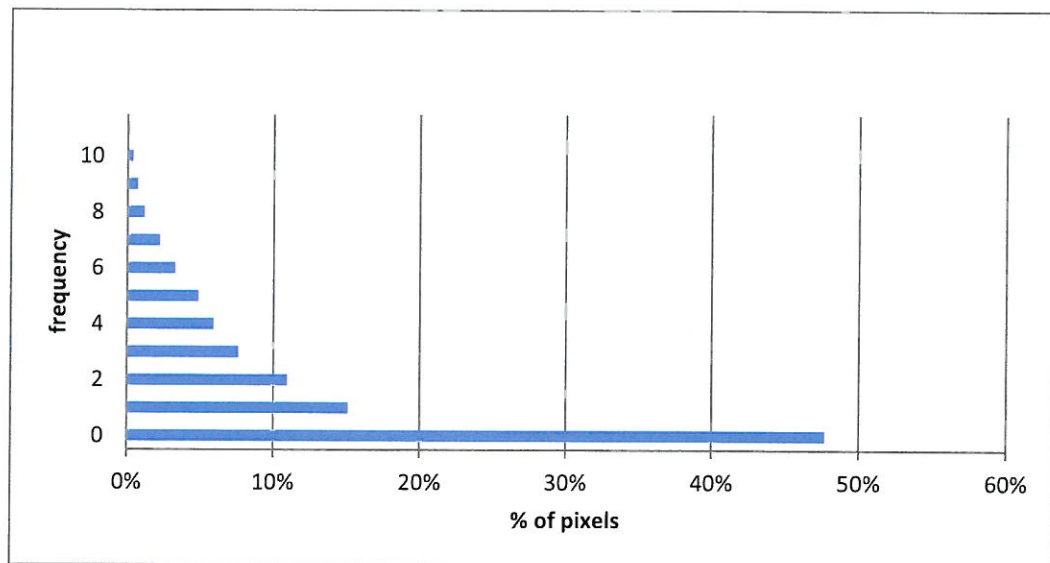


Figure 15: Frequency of pixel reoccurrence in space of the greenest (HH) clusters over 11 years.

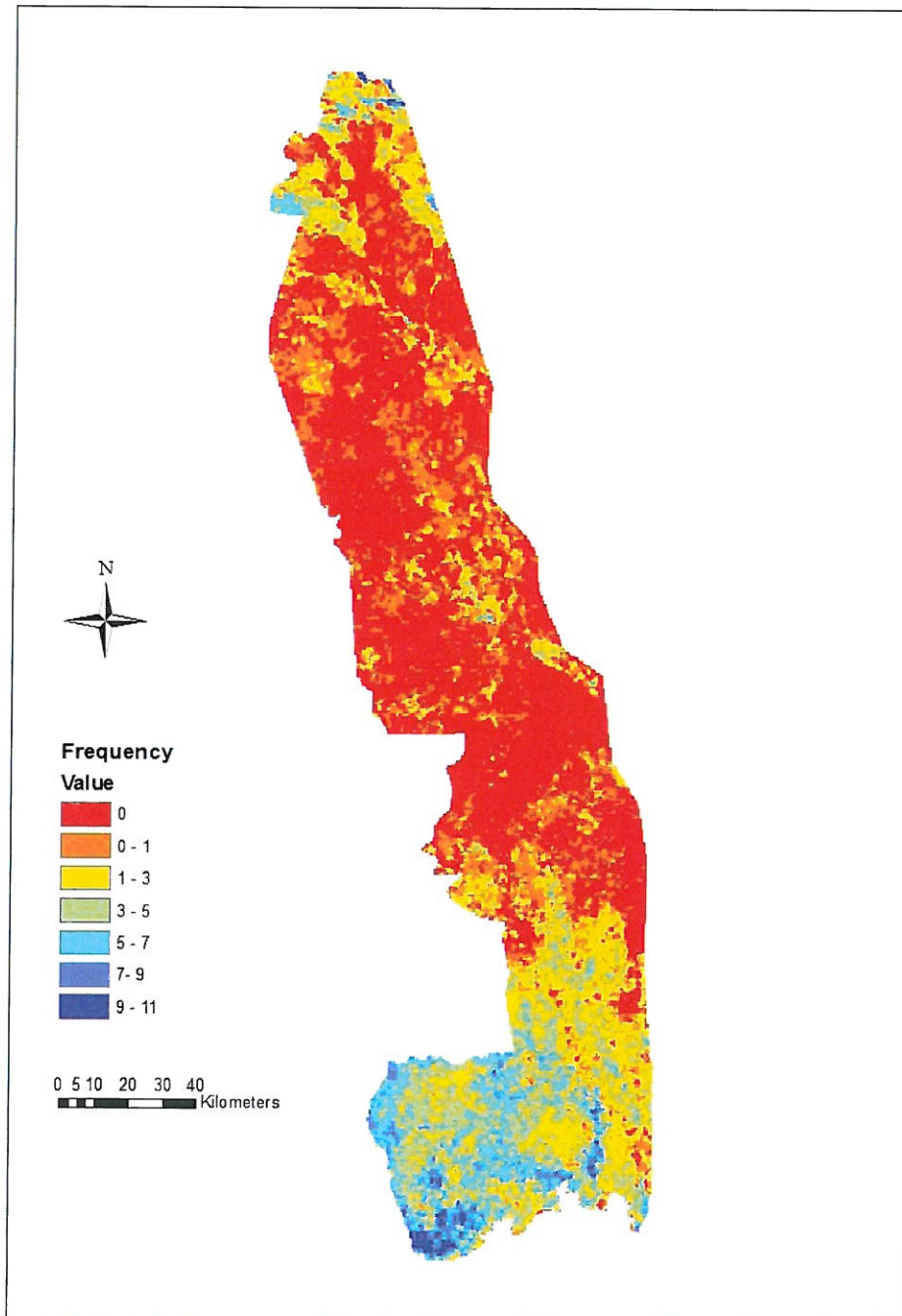


Figure 16: Frequency of spatial overlap of pixels in the greenest (HH) clusters between 2000 and 2011 in KNP.

5.3.2 Σ EVI

The extent of KNP covered by pixels of HH clusters also varied and was between 11% and 21 % in the 11 years of study. The year 2001 covered the smallest area, with 2009 covering a larger area (Figure20), suggesting 2009 was the year with the most green vegetation throughout the year with 2001 less green vegetation. From 2000 to 2010 the extent of KNP covered by pixels making up the HH clusters increased, suggesting KNP is getting greener over the study period as hypothesised.

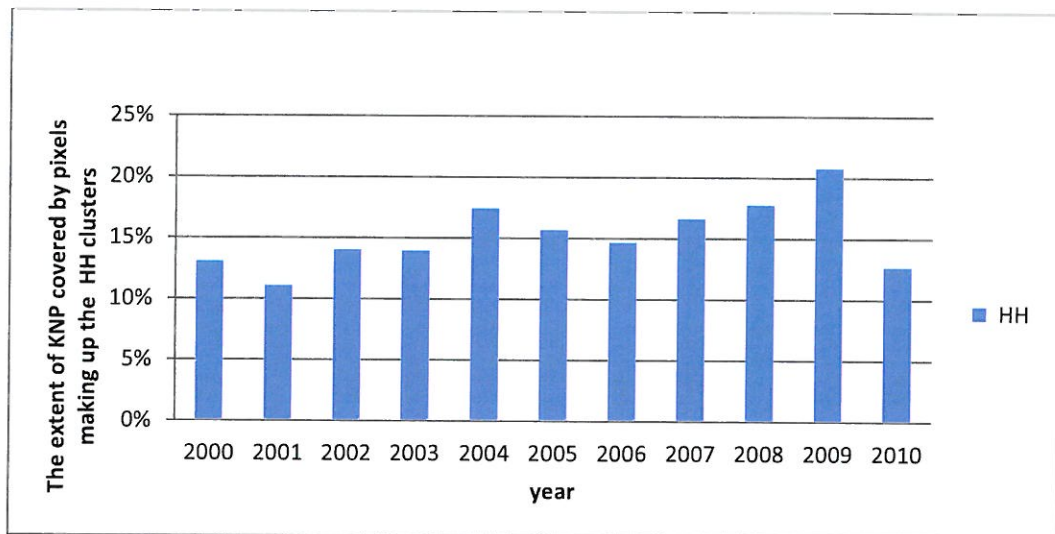


Figure 17: Trend of % area covered by HH clusters as a % of KNP (2000-2010)

From mean–variance analysis of the Σ EVI, the mean decreased significantly from 2000 to 2001, only to increase again in 2002 and continued to increase until 2004. The mean decreased in 2005 and went back and forth, increasing and decreasing until 2007. It continued to decrease in 2008, increasing in 2009, then

decreasing in 2010. The $\sum\text{EVI}$ variance decreased from 2000 to 2001, only to increase significantly in 2002 by. It decreased in 2004 and continued to increase and decrease year after year up to 2010(Figure 21). The vegetation greenness is also erratic and highly variable similar to EVI_{max} with an increase in the mean and high variability. This suggests that the landscape of KNP is also highly variable in its mean greenness and heterogeneity of $\sum\text{EVI}$. Over the study period KNP's landscape appears to be increasing in vegetation greenness and becoming more heterogeneous as was hypothesised.

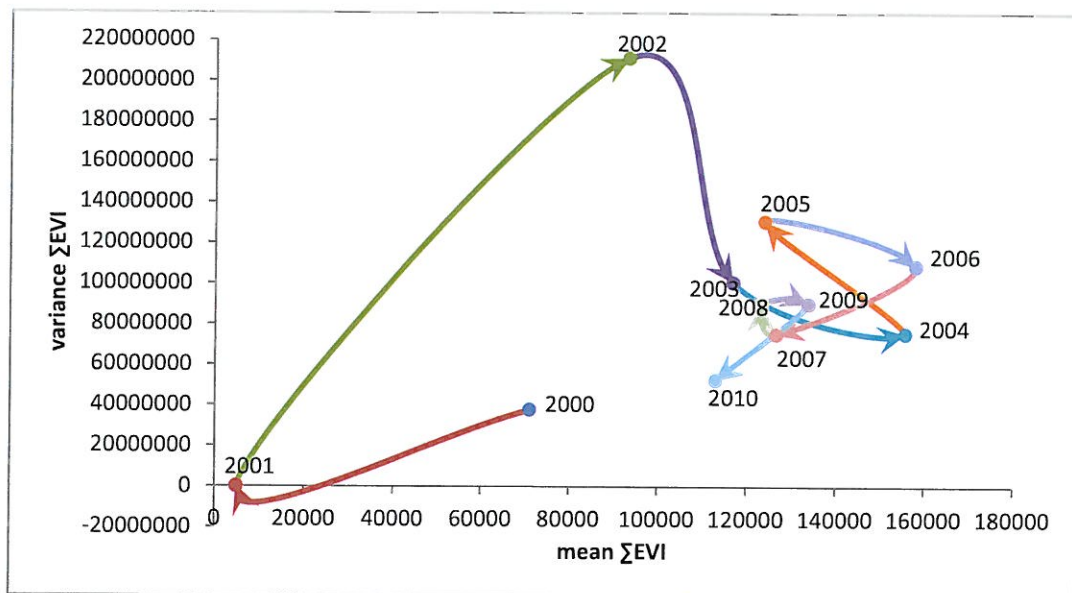


Figure 18: Mean- variance analysis of for the period 2000-2010 showing vegetation states in KNP's landscape for $\sum\text{EVI}$ (After Washington-Allen *et al.* 2009).

Frequency of pixels reoccurring in the HH clusters was low with only 8 % of the pixels occurring at least 6 times or more throughout the 11 years (Figure 22) suggesting a highly variable landscape in terms of $\sum\text{EVI}$. This means the spatial distribution of $\sum\text{EVI}$ of KNP is highly variable. Spatial overlap of HH clusters across years was more frequent in the south and tips of the far north of KNP (Figure 23), but was very low. This suggests that although spatial overlap of pixels was low, the south and far north the predictability of locations with high $\sum\text{EVI}$ is slightly higher than the rest of Kruger. KNP's low spatial overlap of $\sum\text{EVI}$ pixels suggests it is a highly heterogeneous landscape that is highly variable landscape in terms $\sum\text{EVI}$ as was expected.

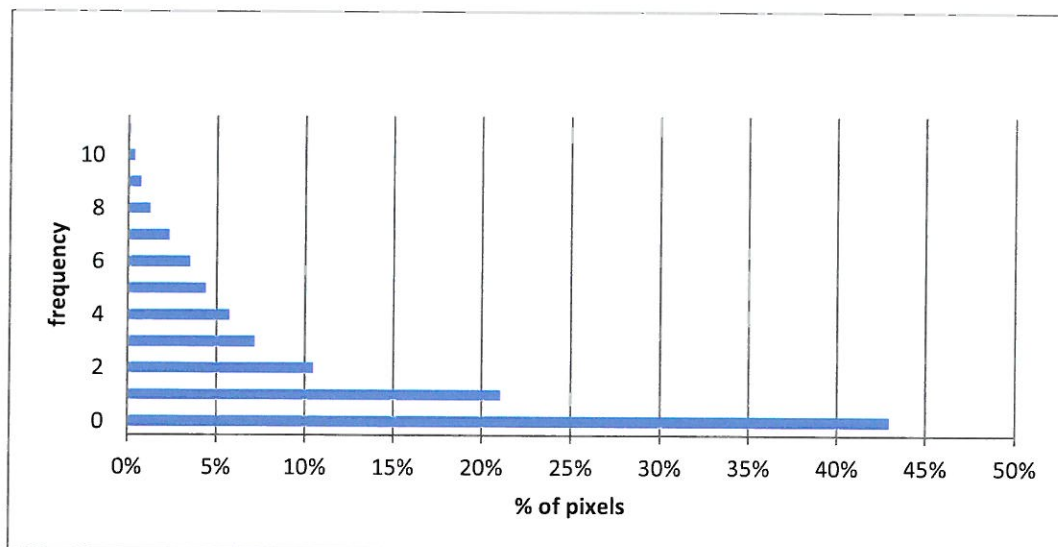


Figure 19: Frequency of pixel reoccurrence in space of HH clusters over 11 years

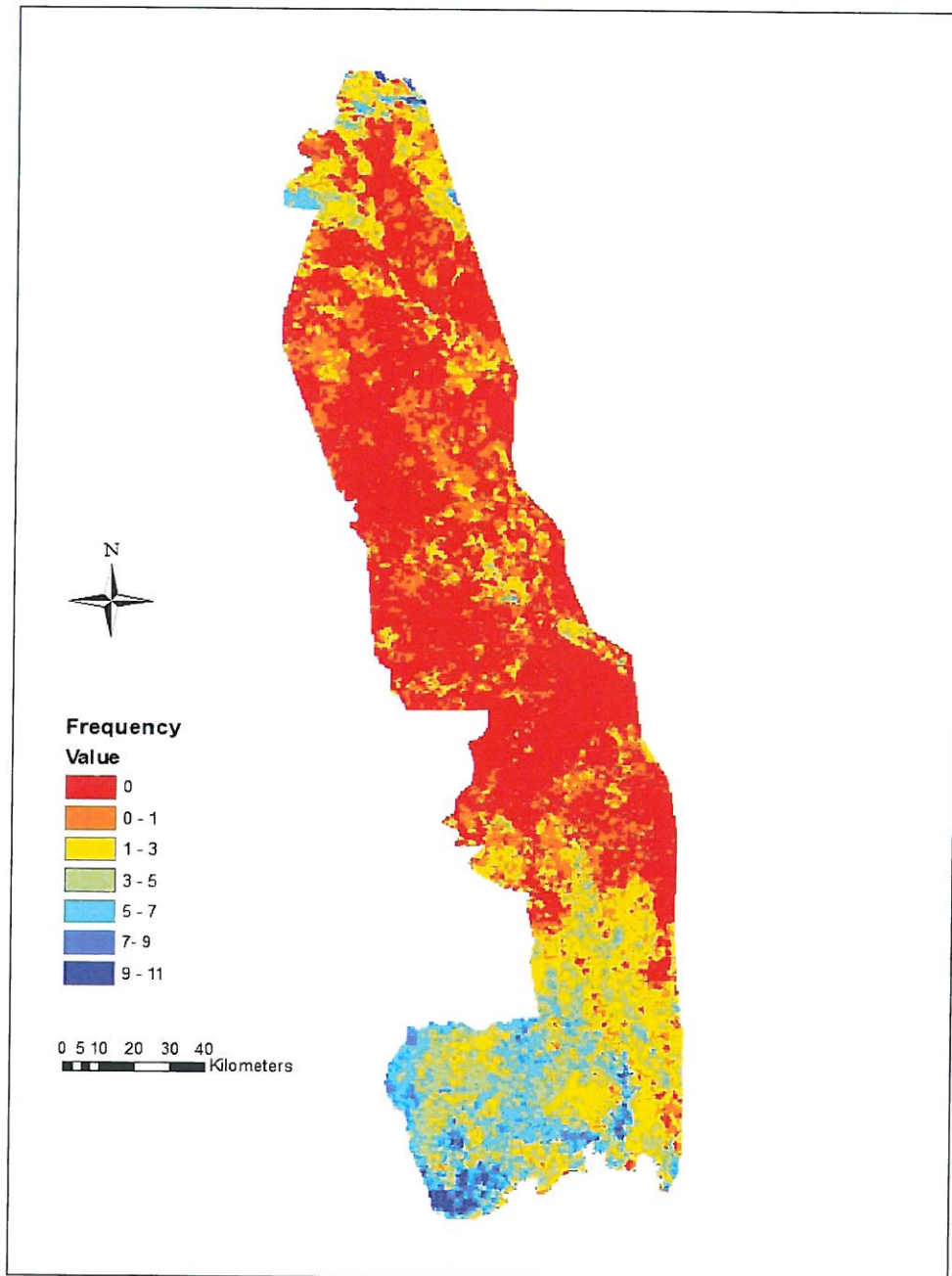


Figure 20: Frequency of spatial overlap of pixels in greenest (HH) clusters of Σ EVI between 2000 and 2011 in KNP.

6 Discussion

The spatial distribution of the EVI metrics was variable throughout the study period. Geological and geographical position had an impact on the greenness and number of pixels making up the clusters for both EVI metrics. Both EVI_{max} and $\sum EVI$ clusters had greener and more pixels on the granite than basalt geology, which was the opposite of what was hypothesized. Basalt derived soils were expected to have high values for the EVI_{max} and $\sum EVI$ due to the fertile clayey soils, compared to the granite derived soils which are infertile, porous and easily leached. Hence the vegetation on basalt geology was expected to have higher absolute and total vegetation greenness compared to vegetation on granite geology. However the results of this study suggest vegetation in the granite derived soils had higher absolute greenness and total vegetation greenness on granite than that on basalt geology. Winnie *et al.* (2008) and Munyati and Ratshibvumo (2009) used NDVI derived from 30 m resolution Landsat ETM to assess granite-basalt differences, with Munyati and Ratshibvumo (2009) also using MODIS 250 m resolution images. They both found that basalt was greener than granite, but they did not use NDVI metrics just NDVI values at one point in time. The use of single snapshots which are rainfall dependent given that they are captured in the wet season, gives different greenness patterns compared to the use of EVI metrics representing the whole year. Also the effects of other drivers like herbivory and fire that impact on vegetation greenness are difficult to take into account when looking at snapshots as they affect vegetation greenness throughout the year.

When looking at geographical differences, clusters of high values occupied a larger area in the south and central regions than the north, a result that is consistent with the initial hypothesis. Surprisingly in the far north the clusters occupied a larger area than in the north, more similar to the area occupied in the central region. The far north clusters were also the ones with the highest EVI_{max} and $\sum EVI$ values, followed by the south and central region with the north being the driest. The results were expected to follow the increasing rainfall gradient from north to south experienced by the Kruger National Park: larger areas of high EVI_{max} and $\sum EVI$ in the south and smaller areas of high value clusters for the same matrix in the north. In accordance to the rainfall gradient pattern, Parrini and Erasmus (2009) found that wet season rainfall up to the month before $NDVI_{max}$ and total wet season rainfall to be the best predictor for $NDVI_{max}$ and $\sum NDVI$ respectively. The anomaly in the far north suggests certain factors besides rainfall affecting the vegetation greenness observed in that region. These factors are discussed in more detail later in this discussion.

Clusters location and size was variable each year, with areas of high values pixels showing an increase in size from 2000 to 2010, suggesting an increase in areas with high EVI_{max} and $\sum EVI$ over time as was hypothesized. However the variance of both metric was high and variable each year, suggesting a high variability in the actual EVI_{max} and $\sum EVI$ values making up the high greenness clusters. This, together with the low spatial overlap of areas classified as high value clusters between years (shown by the low frequency of pixels reoccurring in a cluster each year) confirms

the hypothesis that Kruger is heterogeneous in vegetation greenness over time as would be expected of a savanna ecosystem. Parrini and Erasmus (2009) looked at spatio-temporal clusters of NDVI metrics from 1985 to 1999 and found a very low overlap between clusters in subsequent years, similar to the results presented here.

This study did not test for relationship between vegetation greenness and other drivers and elements (fire, herbivory, soil moisture, temperature) that affect vegetation growth as the large-scale nature of the experiments needed to unpack the relative effects of these drivers were outside the scope of the report. However, using known relationships between vegetation greenness and these drivers and the satellite-derived greenness metrics, we can at best infer some of the likely causes of observed patterns, and, at worst, provide context for the observed patterns. The fact that the area and location covered by the clusters was variable in time, and the results concerning basalt and granite, seems to imply that the spatial arrangement of the EVI metrics is not mainly substrate determined. If substrate was the most important factor in determining greenness patterns, then these patterns should be repeated between years. Clearly they are not, so other factors affect vegetation greenness patterns.

Temporal variations in vegetation greenness are closely linked to precipitation. A strong relationship between vegetation indices and inter-annual climate variability has been supported through studies of spatio-temporal vegetation index data in relation to climatic patterns (Goward and Prince 1995; Nicholson *et al.* 1990; Richard and Pocard 1998; Wang *et al.* 2001). For the KNP, Parrini and

Erasmus (2009) found a relationship between rainfall and vegetation greenness to exist during the period 1985-1999 with absolute vegetation greenness best explained by wet season rainfall up to the month before the maximum NDVI and the total vegetation greenness of the season to be mainly influenced by the rainfall in the wet season and mean minimum temperature. Fluctuations and variability in weather variables like precipitation give rise to variable patterns in vegetation greenness (Nicholson *et al.* 1990; Goward and Prince, 1995), which is possibly what is reflected in the high cluster spatial variability and greenness variations observed in this study.

KNP has variable inter-annual rainfall patterns partly associated with the El Niño-Southern Oscillation (ENSO), which has been found to affect vegetation production in savanna ecosystems (Wessels and Dwyer, 2011). The ENSO results in a 4-7 year sequence of dry and wet years, with drought years resulting in a reduction of rainfall by 25% (Venter *et al.* 2003), producing variable patterns in vegetation greenness during and post an ENSO period. Although the mechanisms behind ENSO are not well understood, its impacts on vegetation greenness patterns are apparent. The rainfall patterns of the ENSO cycles in KNP determined by Ogutu Owen-Smith (2003) matched Parrini and Erasmus (2009) vegetation greenness patterns in the dry season from 1988, and the effects of the 1991-1992 droughts where annual rainfall over KNP was less than the long term mean, resulting in lower vegetation greenness in that same period. Hence, the high variability in EVI metrics observed in KNP is likely associated with the KNP rainfall patterns which are also highly variable. In addition, rainfall in KNP occurs as discrete localized events, often as thunderstorms

(Venter, *et al.* 2003). The mechanisms that create these events could possibly stay the same year in and out, but rainfall will not necessary occur in the same spot over the years. This coupled with fire and herbivory effects should explain the variability in high value clusters locations each year, with rainfall as a strong determinant of the greenness patterns observed.

Vegetation properties like absolute and total vegetation greenness are greatly influenced by disturbances like fire and herbivory (Bond 2008). The basalt plains are more open savannas with higher grass production than the granite regions (Scholes 1993) and for that reason vegetation indices were expected to be higher on basalt than granite. However, the basalt plains because of their higher grass biomass, are also more prone to intense fires and higher herbivory than the granite (Venter *et al.* 2003; van Wilgen *et al.* 2003). Both heavy grazing and high herbivory leads to reduction in herbaceous biomass (Bond and Keeley 2005; Bond and van Wilgen 1996), which can be picked up by vegetation indices and hence could explain the lower EVI_{max} and $\sum EVI$ observed in the basaltic region when compared to the granite. Tree cover was another important predictor in some of the models by Parrini and Erasmus (2009) to explain observed patterns of $NDVI_{max}$ and $\sum NDVI$. Woody canopy cover is higher on granite than basaltic geologies of KNP (Eckhardt *et al.* 2000 Bucini *et al.* 2009), which would possibly also agree with higher EVI_{max} and $\sum EVI$ in the granite substrate compared to the basalt observed in the current study. Trees and grass green up at different times with trees flushing earlier before the rainy season than grass after rainfall. Trees produce leaves earlier and keep them for longer than grasses and hence

stay greener for longer periods (Higgins *et al.* 2011). However the timing of increase in vegetation greenness picked up from vegetation indices is similar for both late flushing trees and grasses, making it difficult to separate greenness of trees and grasses (Higgins *et al.* 2011).

The northern regions of Kruger have high woody canopy cover (Bucini *et al.* 2009) Hence vegetation structure could have an impact on vegetation greenness as the spatial distribution of the greenest regions together with the basalt-granite geology comparisons, match the spatial distribution of woody cover vegetation in KNP observed by (Eckhardt *et al.* 2003; Bucini *et al.* 2009).

7 Conclusion and Recommendations

Various drivers are at play in savannas ecosystems that determine vegetation greenness patterns as plant growth results from a combination of many factors. The spatio-temporal analysis of vegetation greenness patterns using EVI metrics observed in KNP appear to show that Kruger is a heterogeneous and variable ecosystem.

Although there are patterns related to substrate, the overriding driver appears to be rainfall, mediated by substrate, fire and herbivory. The vegetation greenness patterns follow the rainfall gradient of KNP and match the variable rainfall patterns associated with KNP. Vegetation structure appears to be an important contributor to the greenness patterns of the current study as it appears to match the spatial distribution of woody vegetation cover of KNP.

The EVI appears to be a strong measure of heterogeneity, however consolidating this study and other studies over a longer period of time, improves on the measure of patterns of vegetation heterogeneity of KNP. Maintenance of the heterogeneity of KNP is important as it facilitates habitat and ecosystem diversity. The maps produced from the current study can be used by park managers and ecologists to assess current vegetation greenness patterns, which would help monitor and maintain the heterogeneous nature of KNP. Heterogeneity is a strong aspect of KNP's Thresholds of Potential Concern (TCP), which are group of operational goals that provide a framework from which KNP's spatiotemporal heterogeneity has to be managed. Vegetation both herbaceous and woody are components of heterogeneity

under these TCP's, hence the current and similar studies become important to park managers as they give information to help meet set management goals of KNP, maintaining its biodiversity.

In longer time frames, if rainfall is patchy and drives greenness variability, then animals that rely on greenness will have to change their movement patterns in response to climate change conditions. Since intensity and frequency of intense rainfall events is predicted to change under climate change conditions, then access to green vegetation for herbivores will change. This is likely to be a key mechanism of climate change impacts on large herbivores (Ogutu & Owen-Smith 2003) and hence studies addressing the current relationship between current greenness patterns and herbivores movement patterns should be encouraged. Variation in vegetation structure contributes in an as yet unknown way to the patterns of vegetation greenness. Vegetation structure, which impacts on vegetation greenness, also affects the browsing-grazing value for animals and therefore a better understanding of how tree-grass rations contribute to vegetation indices is important when trying to predict animal movement changes due to greenness pattern changes. Given how trees and grass green up at different times with trees flushing earlier before the rainy season and grass after rainfall, methods that differentiate greenness of trees and grasses become important and need to be applied. Separation of trees and grasses allow us to monitor changes in trees and grasses separately allowing the accurate measure of how much vegetation are available for herbivores and where it is located. This in turn affects survival of animals and their movement patterns.

Given that rainfall appears to be a key driver in vegetation greenness, park management can only manipulate other drivers that affect vegetation greenness to maintain vegetation heterogeneity of KNP. Herbivory can be manipulated through placement of water points in KNP, which spreads population densities to areas with low grazing pressure. Fire also can be used to maintain KNP's heterogeneity through planned burning, which is a current practice in some parts of KNP.

8 References

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