USING REMOTE SENSING AND EXPERT KNOWLEDGE TO MAP LANDSCAPE-LEVEL LAND DEGRADATION IN THE ARID GRASSLANDS OF BUSHMANLAND – SOUTH AFRICA

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Abstract

In this study I investigated the use of MODIS NDVI, known as a proxy for vegetation productivity, to quantify land degradation based on spatial and temporal scales. Dryland areas normally have high inter annual rainfall variation. As rainfall is a key factor in determining vegetation growth, changes due to anthropogenic pressures are difficult to quantify. A correlation between cumulative rainfall and averaged MODIS NDVI scenes was performed to determine the best rainfall interval that explains the NDVI variation. The 6 months time interval was found to have the highest correlation to NDVI (0.86), which best explains the NDVI variation within vegetation units. ANOVA test were carried out to establish the phenological variable which best detects change in the vegetation cover. The $NDVI_{min}$, $NDVI_{max}$ and $NDVI_{\Sigma}$ variables were found to best explain phenological profile for all three vegetation units. Taking into account rainfall, vegetation units and phenology, two approaches were developed which used NDVI to quantify land degradation. The spatial scale approach, based on the dry phase only, used the benchmark method to establish thresholds for any changes in veld condition. The temporal scale approach used the residual method based on seven year averaged NDVI. Regression analysis was carried out based on the residual values for each sample point. Overall, despite a lack of appropriate ground-truthing data, the two derived methods have implication to spatially and temporally quantify land degradation in arid and semi-arid environment.. The methodology shows promise for monitoring, & mapping grazing carrying capacity. Further refinement of the methodology is necessary, including ground-truthing for validation purposes.

Keywords*:* Dryland degradation, over grazing, semi arid rangelands, MODIS, NDVI, phenometrics

Abbreviations: MODIS = Moderate Resolution Imaging Spectroradiometer; NDVI = Normal Difference Vegetation Index.

Introduction

Land degradation describes the biological loss or decline of productivity of an area (Beukes & Cowling 2003, Chikhaoui *et al.* 2005, UNCCD 1995). It is believed to be one of the most severe and widespread environmental problems in South Africa and globally (Hoffman *et al*. 1999, Wessels *et al*. 2004). Degradation has a complex impact on the environment through a range of direct and indirect processes which affect a wide array of ecosystem functions and services (Mambo & Archer 2007, Wessels *et al.* 2004). It is estimated that 70% of drylands in Africa, Asia and America and about 54% in Australia has been affected by degradation (Pickup *et al.* 1998).

Land degradation can be attributed to both human and climate factors and includes a range of responses such as soil erosion, ecosystems changes, landslides and deforestation (Chikhaoui *et al.* 2005, Meadows & Hoffman 2002). In South Africa, the increase in human population and domestic livestock overgrazing have been identified as the main anthropogenic causes of land degradation (Dean *et al.* 1995, Dube & Pickup 2001, Milton *et al.* 1994). The rate of natural habitat loss has escalated due to the increase in land use pressures and global impacts (Wilson 1988). In addition, climate change factors such as a reduction in total rainfall or even a slight shift in the seasonal rainfall distribution may augment land degradation by reducing vegetation cover (Mambo & Archer 2007, Wessels *et al.* 2007). This poses a major threat to the continued survival of many species worldwide (Beukes & Cowling 2003) and could result in a significant loss of biodiversity. This continual loss has prompted responses to reduce the current rate of habitat degradation and biodiversity loss (Rouget *et al.* 2003).

The nature and extent of land degradation has been difficult to quantify and the lack of appropriate data is widely regarded as a major obstacle to progress in the monitoring and mitigation of this phenomena especially in semi-arid areas (Mambo & Archer 2007, Tromp & Epema 1999, Wessels *et al.* 2004). Previous efforts to quantify land degradation have been criticised, and of late have been said to be imprecise (Wessels *et al.* 2004). This is due to the interwoven impacts of rainfall variations and human-induced land degradation (Wessels *et al.* 2007). Consequently, understanding and quantifying the rate and spatial dimensions of land degradation and the estimation of the future impact of this phenomenon is an essential prerequisite in formulating mitigation measures for activities such as land use planning, policy formulation and also for making more informed conservation strategies (Rouget *et al.* 2003, Simons & Allsop 2007). There is an urgent need to develop an objective, rapid, repeatable, spatially explicit measure of land degradation and how it might change over time (Pickup 1996, Wessels *et al.* 2004).

Because of the large area covered and the repeated temporal sampling that satellite observations provide (Tromp & Epema 1999, Zhang *et al.* 2003), satellite remote sensing techniques have long been recommended for their potential to detect and monitor dryland degradation (Geerken & Ilaiwi 2004, Holm *et al.* 2003, Prince 1991). Remote sensing approaches also provide information on vegetation cover and how this changes over a range of temporal and spatial scales (Bradley *et al* 2007, Hoare & Frost 2004, Zhang *et al.* 2003). Several studies have interpreted phenological traits which are linked to photosynthetic activity such as the onset of greenness and length of growing season as indicators for detecting susceptibility of vegetation cover to environmental and anthropogenic changes (Chidumayo 2001, Fox *et al.* 2005, Lupo *et al.* 2007, Reed *et al.* 1994). It has been argued that in arid and semi-arid areas, which are subjected to short term droughts, vegetation cover might not be an efficient indicator for long term degradation (Tucker *et al.* 1991). In contrast, other studies have shown that vegetation cover, as well as the phenological response of vegetation, are good indicators of vegetation dynamics and degradation even in arid and semi-arid regions (Fox *et al.* 2005, Geerken & Ilaiwi 2004, Holm *et al.* 2003).

One of the remote sensing-based techniques which has been exploited is satellite-derived spectral vegetation indices as it relates to plant cover and change in temporal variance (Holm *et al.* 2003, Huete *et al.* 2002). The most common vegetation index used to measure vegetation phenology is the Normalized Difference Vegetation Index (NDVI) (Bradley *et al.* 2006, Holm *et al.* 2003, Nicholson *et al.* 1990, Reed *et al.* 1994). The NDVI is a measure of greenness, which provides a means of efficiently and objectively measuring the intensity of vegetation activity over a large area (Reed *et al.* 1994). It has been considered one of the most efficient spectral indices in arid or semi-arid areas where the influence of climate (e.g. rainfall) on the phenological response of the vegetation is particularly strong (Fox *et al.* 2005, Geerken & Ilaiwi 2004, Holm *et al.* 2003). Previous studies have shown that NDVI data can be used to successfully map land degradation in arid areas (Thompson *et al*. 2005, Wessels *et al*. 2007).

Although a number of different remote sensing methods have been adopted to monitor vegetation change, the results have been often confounded by land use differences (Wessels *et al.* 2007). In most arid and semi-arid areas, where vegetation cover is dominated by sparse dwarf shrubs vegetation production is strongly related to intra- and inter-annual rainfall variability (O'Connor & Roux 1995, Pickup 1996, Wessels *et al.* 2007). It is a great challenge in South Africa's semi-arid regions to distinguish between long term changes evident in the landscape as a result of anthropogenic pressures from those which have occurred in response to the effects of the episodic droughts (Dube & Pickup 2001). An interpretation of the impact of anthropogenic pressures are further confounded by the spatial variability such as topography, land use and soil types and the variation in the soil response to spectral signals (Wessels *et al.* 2007). As a result, developing objective rapid and repeatable measuring methods in order to monitor land degradation worldwide has been a challenge in arid and semi arid regions. Without the ability to monitor and quantify patterns and rates of degradation, it is difficult to develop policy or other national-level interventions aimed at managing, mitigating or reversing landscape-level trends in degradation.

With this overall goal in mind this study addresses the following questions relating to vegetation dynamics and patterns of land degradation in the arid Bushmanland area of north-western South Africa:

1. How does the NDVI profile in the region vary in different vegetation types over a seven year period in response to periods of high rainfall versus periods of extended drought?
2. Is there a significant difference in the NDVI profile over a seven year period of regions classified *a priori* by an expert as being degraded compared to those classified as being in a non-degraded or 'good' condition?
3. Which areas within a vegetation type show an ongoing decline in productivity over the seven year period relative to the mean NDVI value?
4. Can these differences be used to map degradation over the entire study area?

Methods

Study Site

The study area is located in the Bushmanland region of north-western South Africa. This is one of the most arid parts of South Africa (Desmet & Cowling 1999, Desmet 2007). Bounded in the north by the Orange River and in the west by Namaqualand, Bushmanland forms the ecotone between the winter rainfall succulent Karoo and summer rainfall Nama Karoo biomes of southern Africa (Figure 1).

This study looks at the three major vegetation units in Bushmanland: Bushmanland Arid Grassland, Bushmanland Sandy Grassland and Bushmanland Inselberg Shrubland (Mucina & Rutherford 2006). The Bushmanland Arid Grassland extends about one degree of latitude around Aggeneys in the west to Prieska in the east. The Bushmanland Sandy Grassland is distributed in the northern Bushmanland and a few isolated patches are found in the south of Copperton on the east edge of the Bushmanland Basin (Mucina & Rutherford 2006). The Inselberg Shrubland is mainly distributed in the north of Bushmanland (see Figure 1). The altitude of Bushmanland varies mostly from 600 to 1200 m. The geology of the Arid and Sandy Grassland areas is characterised by Quaternary sediments predominately shallow aeolean sand overlying calcrete or semi-mobile Kalahari-type dunes. In contrast the soils of the Inselberg Shrubland consist of colluvial rocky soils derived from igneous intrusive or sedimentary quartzitic rocks (Mucina & Rutherford 2006). The soil in the Arid Grassland is characterised mostly by red-yellowy soils (<300mm deep), and the sandy grassland surface is characterised by red sand (> 300 mm deep), forming dunes in places (Mucina & Rutherford 2006).

It is predominantly an area of summer to autumn rainfall (Fox *et al*. 2005, Kelso & Vogel 2007). The rainfall ranges from 70 mm to 200 mm, with a mean of 88 mm and a coefficient variation of 65%. Rain falls in late summer to early autumn (Cowling *et al* 1998, Kelso & Vogel 2007). Mean temperature is 19.4 ºC and daily temperatures extreme ranges from -0.6ºC to 40.6ºC. The incident of frost ranges from around 10 frost days per year in the northwest to about 35 days in the east. The Arid Grassland have three major components, perennial grasses, ephemerals and shrubs, the relative abundance of which vary temporally and spatially with weather and land use (Milton & Dean 2000). The most abundant desert grasses are the C4 summer – rainfall ‘white grasses’ (*Stipagrostis* species – *S. ciliata*, *S. obtusa* and *S. brevifolia*). In the Sandy Grassland drought resistant shrubs are also found (Mucina & Rutherford 2006, Milton & Dean 2000). Shrubland with both succulent as well as non-succulent plants with sparse grassy undergrowth dominate the Inselberg Shrubland (Mucina & Rutherford 2006). Land use is almost exclusively small stock farming with sheep and goats with both private commercial and communal management systems in operation

(Desmet 2007). Overgrazing is evident in many of the areas especially in historic commonage areas.

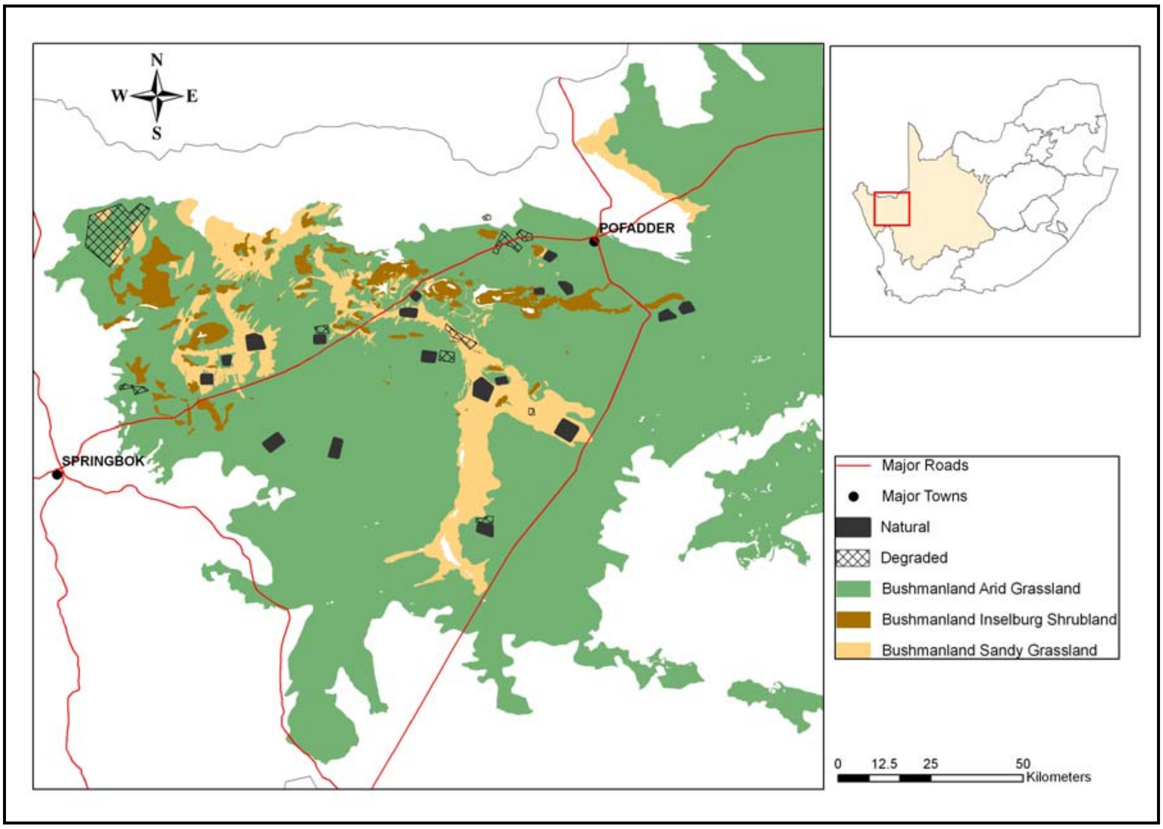

Figure 1. The location of the Bushmanland study area showing the three vegetation units used in this study. The location of areas identified by an expert as being examples of natural and degraded within Bushmanaland Arid Grassland are also shown.

Data preparation

Using NVDI data

NDVI is calculated as a ratio (equation 1), between the maximum absorption of radiation in the red (R) spectral band versus the maximum reflection of radiation in the near infrared (NIR) spectral bank (Lillesand & Kiefer 2000).

NDVI = (NIR - R) / (NIR + R) **(Equation 1)**

It has been found to be a successful vegetation measure allowing meaningful comparisons of seasonal and inter-annual changes in vegetation growth and activity (Huete *et al.* 2002). The index compensates for the changing illumination conditions, surface slope, aspect and several other factors which influence the quality of satellite images (Lillesand & Kiefer 2000). Many studies have used the index as a surrogate for primary productivity, with the time series describing the phenological cycles of vegetation cover (Archer 2004, Geerken & Ilaiwi 2004, Huete *et al.* 2002). Thus, the strength of the NDVI has been found to be in its rationing concept, which reduces many forms of multiplicative noise (illumination differences, cloud shadows, atmospheric attenuation, and certain topographic variations) usually present in multiple bands (Huete *et al.* 2002). In addition, because of its sensitivity to background scattering and soil darkening, which is an influence that becomes increasingly important in sparsely vegetated areas; the NDVI index was found to be suitable for this study. Indices like the Soil Adjusted Vegetation Index (SAVI) introduced by Huete (1988) or the Modified SAVI (MSAVI) (Qi *et al.* 1994) have been shown to take better account of the influence of soil but could not be used in this study. The NDVI index has been found to have a linear relationship with the above ground net primary productivity (NPP) at rainfall of less than 500 mm. Thus, NDVI is by far the most often used spectral index to describe and quantify NPP or green biomass from remotely sensed data (Geerken & Ilaiwai 2004).

MODIS NDVI data

The NDVI data used in this study were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS). The MODIS NDVI 16 day compositing period data was the only available data. It also allowed for capturing of subtle changes in the vegetation phenology in this semi-arid system (Lupo *et al.* 2007). In addition, it would also enable the comparison to the Thompson *et al.* 2005 method and other similar studies, as well as facilitate the identification of spatially-defined, time-dependent spectral variance as a result of local difference in the vegetation production in relation to degradation within Bushmanland.

The MODIS NDVI data, of 16-day repeatable cycles of 250 m spatial resolution from January 2000 to December 2007 were used as the source of remote sensing data. This data was acquired from the Agricultural Research Council (ARC, Pretoria, South Africa). This data is distributed by the Land Processes Distributed Active Archive Center (LP DAAC), located at the U.S. Geological Survey's EROS Data Center (accessed at http://LPDAAC.usgs.gov). The data was downloaded, processed and archived by the ARC, Institute for Soil Climate and Water, as part of the Coarse Resolution Imagery Database project that is funded by the Department of Science and Technology and the Department of

Agriculture. The MODIS NDVI product used in this study has been made modified to reduce the external influences (atmosphere, view and sun angles, clouds) and inherent, non-vegetation influences (canopy background, litter), making it a more effective and 'precise' measure of spatial and temporal vegetation changes.

Vegetation phenological metrics

In this study, a set of phenological variables were identified and calculated based on the 7 year time series NDVI 16 day data (adapted from Jonsson & Eklundh 2004, Reed *et al.* 1994). The seasonal data were extracted for each of the three vegetation units for each sample point (see paragraph below) for the entire 7 years. The first variables defined were the minimum NDVI ($NDVI_{min}$) and the maximum NDVI ($NDVI_{max}$), being the lowest and the highest level of photosynthetic activity throughout the 7-year period (Figure 2). After establishing the two variables, the amplitude NDVI ($NDVI_{amp}$), being the range in NDVI was computed by subtracting the $NDVI_{min}$ from the $NDVI_{max}$. The fourth was the cumulative sum of NDVI ($NDVI_{\Sigma}$) representing the net primary production (NPP), which is the accumulation of energy in plant biomass.

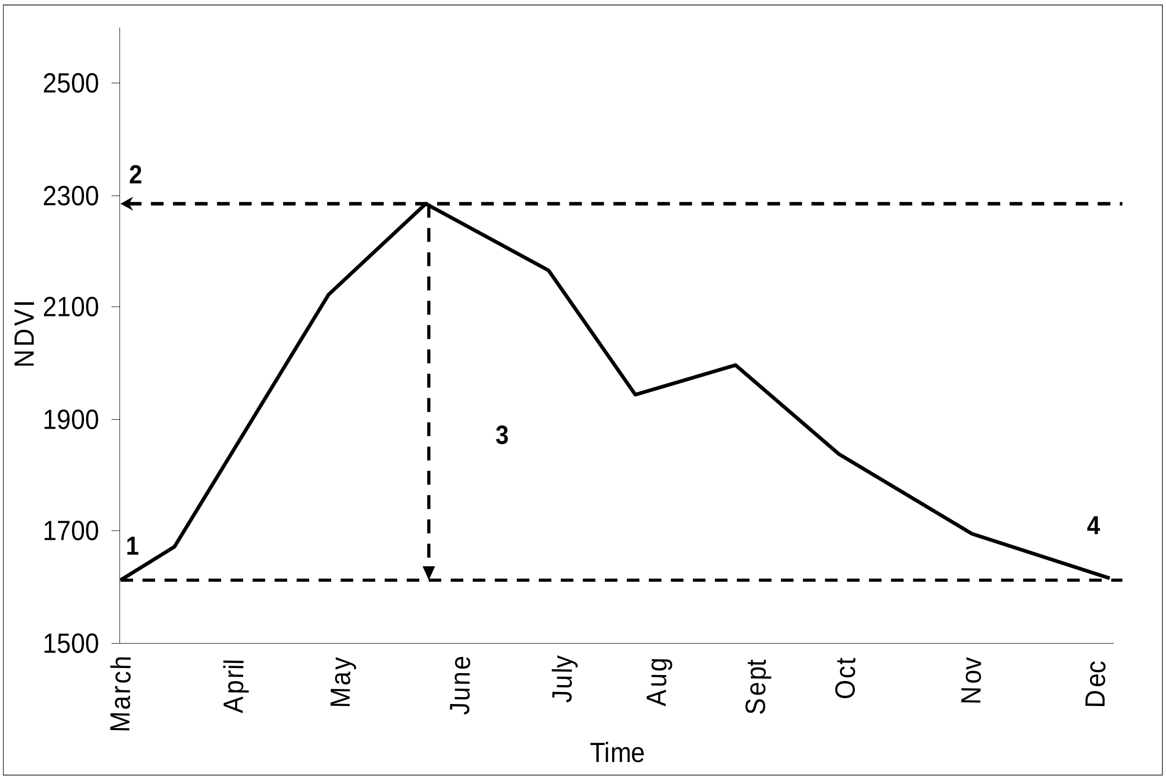

Figure 2. Hypothetical phenological profile of a growing season, showing the four phenometric variables used in this study (adopted from Jonsson & Eklundh 2004, Reed *et al.* 1994), (1) $NDVI_{min}$, (2) $NDVI_{max}$, (3) $NDVI_{amp}$, (4) $NDVI_{\Sigma}$.

Sampling of raw NDVI data for analysis

A random sample point theme was generated in order to analyse the variation of the NDVI profile over a seven year period . NDVI values at each sample point were extracted for each of the three vegetation units within Bushmanland. The sample point theme created contained 11,150 random points stratified within the three Bushmanland vegetation types being studied.(9 515 points for the Bushmanland Arid Grassland, 1 174 for the Bushmanland Sandy Grassland and 461 for the Bushmanland Inselberg Shrubland. A minimum distance of 300m between two random points was kept. This was done to ensure that no more than one point sampled any 250 m grid NDVI cell. Each point was classified according to vegetation type and National Land Cover 2000 (NLC) classification. The points classified as transformed based on the NLC (i.e. cultivated or urban areas) were excluded from the analysis to ensure that known areas of non-natural vegetation land cover did not influence the interpretation of natural patterns. The vegetation map used was a composite created by merging the SANBI 2006 SA Vegetation Types (Mucina & Rutherford 2006) with a finer-scale vegetation map of Bushmanland (Desmet *et al.* 2005).

Climatic data

Continuous daily rainfall data could only be obtained was obtained for Pofadder for the period from 1999 to 2007 from the South African Weather Bureau. The analysis was carried out based on the daily rainfall for Pofadder due to its consistency in comparison to the rest of the weather stations in the study area which all had missing data. From the daily rainfall record a number of cumulative rainfall totals (e.g. one month, six month, etc.) were computed for the Pofadder rainfall station. The rationale for using the climate data was to investigate the climatic variables that could potentially determine the NDVI profile pattern in this semi arid system.

Expert identified natural and degraded sites

Several natural and degraded "training" sites for Bushmanland Arid Grassland types were mapped based on an expert interpretation of the relationship between observed on ground vegetation state and observed patterns on Landsat7 satellite imagery (P.Desmet, unpublished data). These were used as training sites to compare phenometric variables between natural and degraded areas.

Vegetation degradation model

The vegetation degradation model is a conceptual model, which is an important component of the analysis as this gives us an *a priori* understanding of what to expect when comparing phenometrics between natural and degraded areas. Understanding of the vegetation response to overgrazing is a fundamental component to accurately map land degradation in arid environment. Degraded vegetation states exhibit different phenological responses and these differences can be detected by comparing phenometric variables from natural and degraded areas. The extent of degradation was assessed in the Bushmanland Arid Grassland only, as it was the only vegetation type where suitable benchmark sites were known.

The consequence of livestock overgrazing in the Bushmanland Arid Grassland, leads to a decrease in the basal cover and size of grass tussocks, which results in the reduction of the number of tussocks per unit area. In the context of the Bushmanland Arid Grassland, there is no noticeable change in species composition as observed in some other Karoo systems where non-palatable species replace palatable species and overall plant cover does not change significantly (Kraaij & Milton 2006, Wiegand *et al.* 1995), or where there is a shift from a perennial shrubland to an annual dominated herbland with a decrease in species richness (Kraaij & Milton 2006, Todd & Hoffman, 1999). Where overgrazing is on-going this leads to the eventual near total loss of perennial grasses and increase in bare soil cover. This represents the most extreme form of livestock-induced degradation ultimately leading to a wind-eroded soil surface. Due to interannual variation in rainfall, in seasons or years of good rainfall, degraded arid grasslands can support episodic “flushes” of annual herbs and grasses but this is not characteristic of this system. Unfortunately there are no published quantitative accounts of vegetation-level degradation for Bushmanland Arid Grassland.

Therefore, the phenological response curve in the Bushmanland Arid Grassland should not show a distinct phase or amplitude shift as predicted by Thompson *et al.* (2005) for the Little Karoo. The degradation in the arid grassland context simply leads to a decrease in basal cover, resulting in an observable decrease in the total annual NDVI and not a shift in species composition as observed elsewhere in the Karoo (Todd & Hoffman, 1999, Wiegand *et al.* 1995).

Data Analysis

Establishing NDVI profile variation within vegetation units

To determine if there were any trends in the NDVI values over the study period (2000-2007) among the vegetation units, the 16-day average NDVI for all sample points in the Bushmanland was plotted per vegetation unit together with the 16 day rainfall amounts for Pofadder for the same time period. Vegetation response phases were also defined based on the pattern the average NDVI time series displayed corresponding to 16 day calculated rainfall.

Correlation between original NDVI and rainfall

In order to test the strength of the relationship between rainfall and NDVI, Spearman's correlation coefficients were computed between average NDVI value per MODIS scene and cumulative rainfall of two weeks, one month, two months, three months, six months and twelve months over the 7-year period. This analysis was repeated for all three vegetation units.

Testing for difference in phenological profiles between vegetation units

Differences in phenometric variables (min, max, amplitude and sum) between the three vegetation units were calculated using one-way ANOVA and a post-hoc Scheffe multiple range test. The first analysis included all the NDVI data from 2000-2007. Subsequent analyses included an investigation into the phenometric variables for the wet phase 1 (Mar 2000-Dec 2001), dry phase (Jan 2001-May 2005) and wet phase 2 (June 2005-Jan 2007).

Testing for differences in cumulative sum of NDVI of natural and degraded areas

A Student's T-test was performed in order to compare the phenometric variables ($NDVI_{min}$, $NDVI_{max}$, $NDVI_{amp}$ and $NDVI_{\Sigma}$) between the known natural and degraded areas in Bushmanland Arid Grassland for the full data set from 2000 – 2007. I used the average value from 2000 – 2007 for all phenometric variables.

Quantification of natural and degraded areas

Two methods were explored to analyse the spatial and temporal scale of degradation within the Bushmanland Arid Grassland vegetation unit for which suitable information was available. The benchmark method emphasised the spatial scale effect of degradation with a decline of productivity based on the averaged NDVI signal in the dry phase. Thresholds were identified based on *a priori* identification of degraded and natural sites by aspects (P.Desmet, unpublished data). Two thresholds were derived in order to classify the condition of the veld. This was done by computing an NDVI mean value for the defined degraded and natural sample points within the Bushmanland Arid Grassland during the dry phase. All sample points with an NDVI value below the mean value of degraded sites were classified as severely degraded veld. Those with an NDVI value above the mean value for the natural areas were classified as natural veld and those in between the two thresholds were classified as moderately degraded.

The second residual analysis method was adopted from Evans & Geerken (2004) and Wessels *et al.* (2007) to identify the temporal patterns of change using the residual calculation adopted for temporal change analysis. Over the seven year period the difference between original NDVI values at a given date and the NDVI average were calculated for each sample point. Regression analysis was carried out based on the residual values for each sample point, where a negative or positive slope would be indicative of changes in veld conditions. All sample points with a slope 1 standard deviation below the mean, were theoretically classified as areas with a "declining" veld condition. All sample points with a slope 1 standard deviation above the mean were classified as sites with an "improving" veld condition and the rest of the points were classified as "constant" veld condition relative to the mean.

Both these methods were based on the concept that land degradation causes a reduction in vegetation production. Thus the purpose of both methods was to identify the change spatially and temporally and map the change in order to quantify the level of degradation in the Bushmanland Arid Grassland. Combining the results of the two methods made an essential contribution to mapping the spatial and temporal scale of degradation in the Bushmanland Arid Grassland.

Results

Establishing NDVI profile variation within vegetation units

The result of the time series NDVI temporal response showed a geographically consistent pattern of increasing and decreasing NDVI within Bushmanland in response to high rainfall and prolonged drought periods (Figure 3). The trend in the NDVI profile was apparent when moving across the seven year time period for each vegetation unit. Changes in the NDVI values in the wet phases show that changes in vegetation physiology could be detected due to the photosynthetic activity responding to rainfall. In both wet phases, bimodal peaks in the NDVI signal were observed. The wet phase 1 reflected the highest peak of NDVI signal for both wet phases, showing a great response to high rainfall, whereas the wet phase 2 experienced more prolonged rainfall. The NDVI signal response was overall higher for all three vegetation units.

The dry phase, which lasted longer than the wet phases (Nov 2001 – March 2005), had negative impact on photosynthetic activity which is shown by the low NDVI signal responds for all three vegetation units (Figure 3). The NDVI profile for all three vegetation units follows the same trend decreasing as the rainfall decreases for a period of 4 years (Figure 3). All the vegetation units show the persistence of drought with a dramatic decrease in NDVI values beginning in (2001), reaching the lowest in 2003 and increasing gradually to 2005 (Figure 3).This pattern shows NDVI fluctuations between maximum values associated with the flush of green cover that follows rainfall. In general, this pattern for all three vegetation units shows that growth in drylands corresponds well with rainfall patterns (Figure 3). Inter – annual variation in rainfall seems to be large and is reflected in the variability in the NDVI profile in the dry phase. All the vegetation units show a pronounced NDVI profile variation following the rainfall pattern (Figure 3).

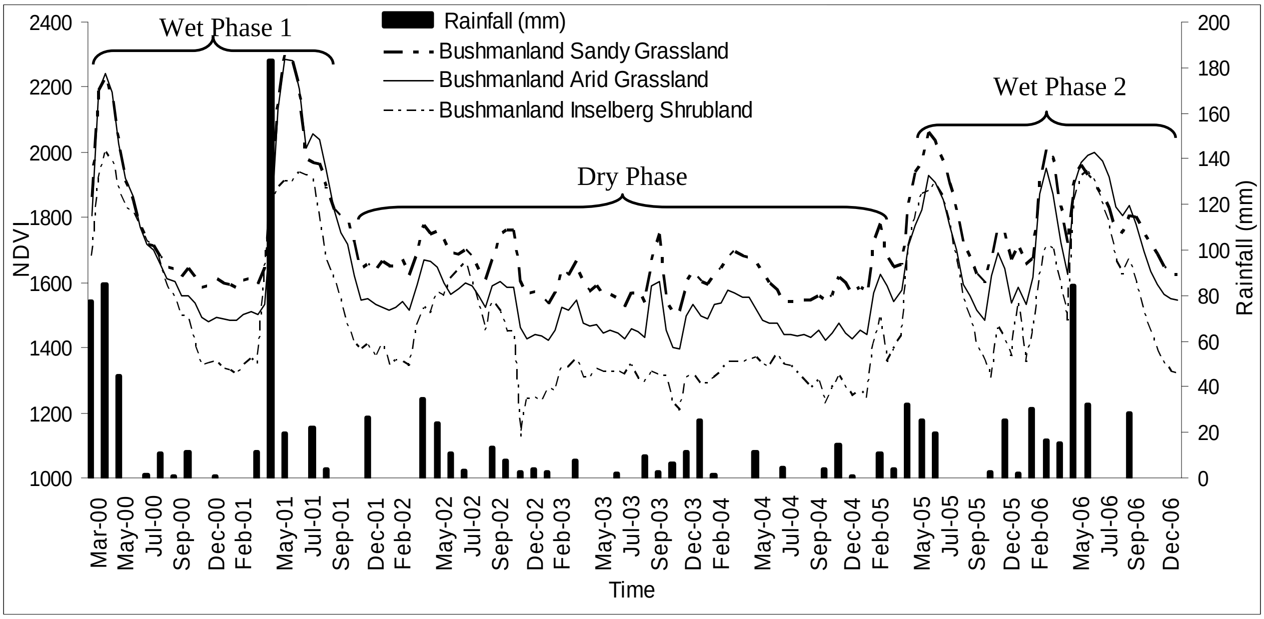

Figure 3. MODIS NDVI values measured every 16 days in the three vegetation units over the period 2000 – 2007 coupled with rainfall data on secondary y-axis.

Correlation between NDVI and rainfall

The correlation coefficients between NDVI of each of the three vegetation units and cumulative rainfall in various time intervals are shown in Table 1. Correlations were generally found between NDVI and cumulative rainfall from one month till three months across all vegetation units. In addition, the highest correlation value between NDVI and rainfall was found at 6-months (Table 1), and this was consistent through all vegetation units. This implies that six months cumulative rainfall is the optimum cumulative time to amplify the NDVI signal.

Even though the coefficient is high at six months for all vegetation units, Bushmanland Arid Grassland seemed to have a slightly higher coefficient (0.86).

Table 1. Correlation coefficients between NDVI and rainfall at 6 different intervals for the three vegetation units in Bushmanland. Maximum correlation is indicated in boldface.

Vegetation units	2 weeks	1 month	2 Months	3 months	6 months	12 months
Bushmanland Sandy Grassland	0.29	0.42	0.61	0.73	**0.82**	0.47
Bushmanland Arid Grassland	0.29	0.40	0.58	0.71	**0.86**	0.55
Bushmanland Inselberg Shrubland	0.30	0.39	0.58	0.71	**0.84**	0.58

Testing for difference in phenological profiles between vegetation units

The ANOVA results for the different phenometric variables are presented in Table 2. All the phenometric variables were compared for all three vegetation units. There was high significance ($p < 0.01$) between the phenometric variables for all three vegetation units (Table 2), although the $NDVI_{max}$ and $NDVI_{amp}$ had consistently low *F*_values. That would mean the two variables were less significant in explaining the vegetation dynamics in this systems in comparison to $NDVI_{min}$ and $NDVI_{\Sigma}$.

The post - hoc multiple Scheffe analysis was used to determine the distinguishable difference between the four phenometric variables for all three vegetation units. In all the phases, all the phenometric variables differed significantly between the vegetation units (Table 2). Although, there was no significant difference in $NDVI_{amp}$ between Bushmanland Arid Grassland and Bushmanland Inselberg in wet phase 1 and wet phase 2 (Table 2). In contrast the NDVI $_{amp}$ between Bushmanland Sandy Grassland and Bushmanland Arid Grassland were significantly different from each other in both wet phase 1 and wet phase 2. In the dry phase there was no significant difference between Bushmanland Sandy Grassland and Bushmanland Arid Grassland NDVI $_{amp}$ (Table 2). Overall NDVI $_{amp}$ seems to display the lowest significance between the vegetation units, and NDVI $_{min}$, NDVI $_{max}$ and NDVI $_{\Sigma}$ were found to be significantly different between all three vegetation units. This means for wet and dry phases these variables in all the vegetation units will behave different from one another thus displaying a different phenological profile.

Table 2. Difference in average phenometric values for each vegetation unit base**d** on ANOVA test. All the phenometric variables differed significantly ($p < 0.001$, df = 2). Standard deviations are presented in brackets.

Vegetation units	Bushmanland Sandy Grassland	Bushmanland Arid Grassland	Bushmanland Inselberg Shrubland	F- statistics
Full record				
NDVI $_{min}$	1431 (±174)[a]	1330 (±183)[b]	1120 (±186)[c]	484
NDVI $_{max}$	2494 (±317)[a]	2546 (±406)[b]	2388 (±399)[c]	41
NDVI $_{amp}$	1064 (±342)[a]	1216 (±412)[b]	1268 (±417)[c]	80
NDVI $_{\Sigma}$	271671 (±23311)[a]	258392 (±27905)[b]	237555 (±27580)[c]	268
Wet phase 1				
NDVI $_{min}$	1516 (±149)[a]	1431 (±170)[b]	1250 (±175)[c]	415
NDVI $_{max}$	2451 (±320)[a]	2482 (±388)[b]	2344 (±400)[c]	31
NDVI $_{amp}$	936 (±332)[a]	1051 (±383)[b]	1094 (±375)[b]	53
NDVI $_{\Sigma}$	71063 (±5117)[a]	69570 (±6973)[b]	64981 (±7968)[c]	131
Dry phase				
NDVI $_{min}$	1439 (±173)[a]	1338 (±181)[b]	1125 (±187)[c]	505
NDVI $_{max}$	1993 (±220)[a]	1899 (±290)[b]	1822 (±307)[c]	78
NDVI $_{amp}$	554 (±183)[a]	561 (±226)[a]	697 (±292)[c]	82
NDVI $_{\Sigma}$	128491 (±12940)[a]	119314 (±14700)[b]	107813 (±13758)[c]	374
Wet phase 2				
NDVI $_{min}$	1551 (±171)[a]	1430 (±179) [b]	1267 (±172)[c]	462
NDVI $_{max}$	2265 (±267)[a]	2308 (±402)[b]	2170 (±312)[c]	32
NDVI $_{amp}$	714 (±261)[a]	878 (±365)[b]	904 (±290)[b]	116
NDVI $_{\Sigma}$	72116 (±6694)[a]	69509 (±8434)[b]	64761 (±7531)[c]	135

[a, b, c] denote differences between vegetation units following a post-hoc multiple comparison Scheffe test.

Testing for differences in cumulative sum of NDVI of natural and degraded areas

The phenometric profile of the Bushmanland Arid Grassland revealed the system to be responsive to variability in rainfall as well as anthropogenic disturbances. In the dry phase there is downward trend for both the natural and degraded areas (Figure 4), and the impact of the prolonged drought is more sever in the degraded areas where the NDVI signal dropping off significantly (Figure 4). The recovery of the vegetation greenness after the prolonged drought in the natural areas was higher than that of the degraded areas shown with the higher peaks in the wet phase2 after the dry phase. These significant trends indicate a system which is highly responsive to rainfall. The last analysis was carried out on the phenometric variables for the natural and degraded areas in Bushmanland Arid Grassland. The results of the Student's *t -test* showed a highly significance differences ($p<0.0001$) amongst all four phenometric variables for the natural and degraded areas in Bushmanland Arid Grassland, due to lower photosynthetic activity in degraded areas.

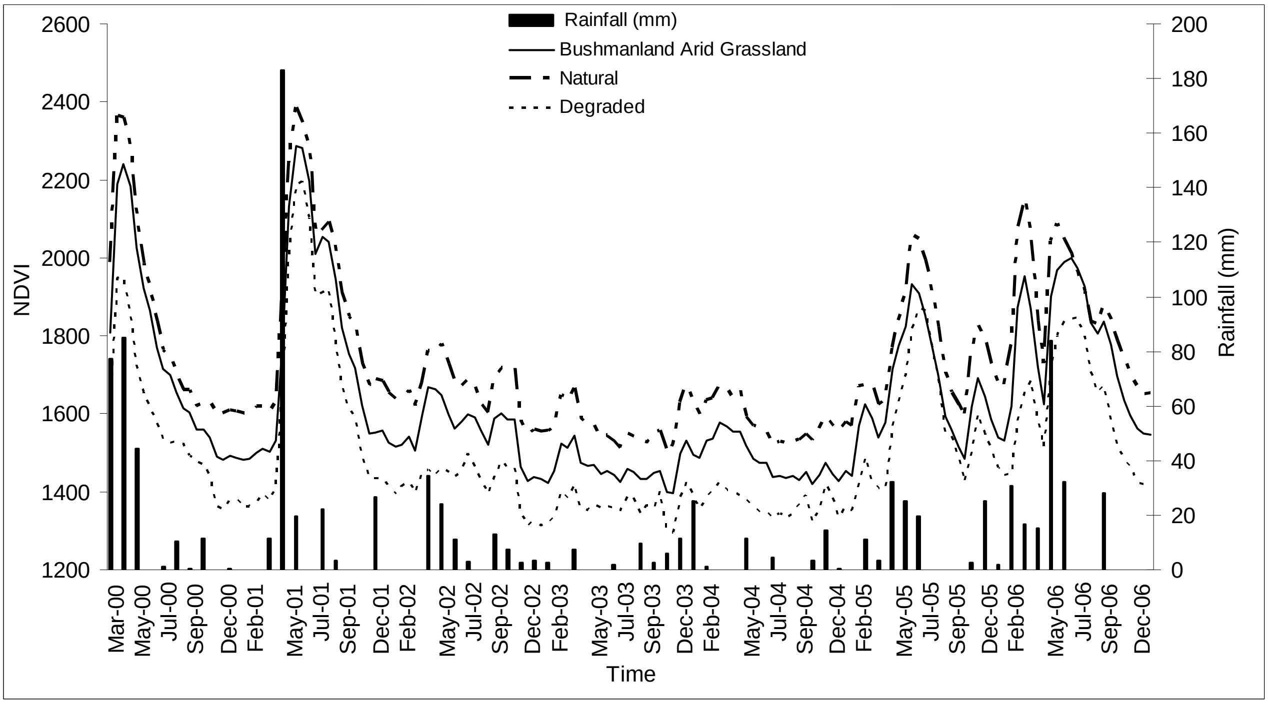

Figure 4. NDVI temporal profile between natural/ high production areas and degraded /low production areas for the Bushmanland Arid Grassland

Quantification of natural/ high production areas and degraded /low production areas

In general the spatial pattern of the degraded /low production areas corresponds well with expert identified as *a priori* degraded sites. The first method is indicative of the current state of degradation /low production at a given time period, best shown in the dry phase (Figure 5). In the dry phase, the natural areas showed a higher NDVI signal as compared to the degraded areas (Figure 4). This being indicative of the ability of natural areas to being highly responsive, even to slight amount of rainfall. The degraded / low production areas tend to have very low response ability due to the fact that there is very little basal cover which reduces biomass productivity and optimization ability. The residual method revealed the temporal trends of degradation over seven years. These results indicated the ongoing trend of the veld condition (Figure 6). A greater percentage (67%) of the area seems to have remained constant through out the seven years (Table 3). A total of 22% of severely degraded areas are improving, which could be associated with a slow shift towards recovery (Table 3). On the other hand, 22% of natural areas are declining, which could be seen as worsening sign that natural areas are being lost (Table 3). The veld condition changing either from better to worse or from worse to better can be attributed to many factors, such as change in management strategies.

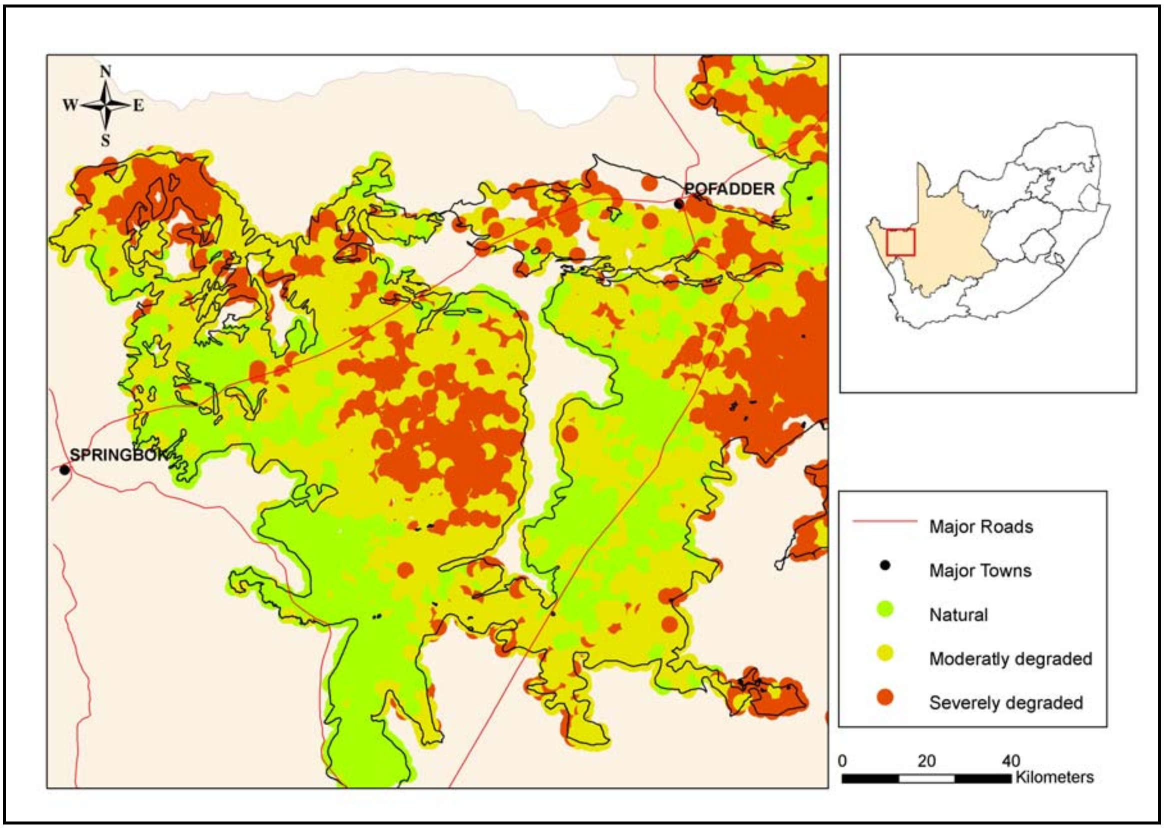

Figure 5. Spatial distribution of the quantified range of the veld conditions (natural, moderately degraded and severely degraded), based on the benchmark method in the Bushmanland Arid Grassland.

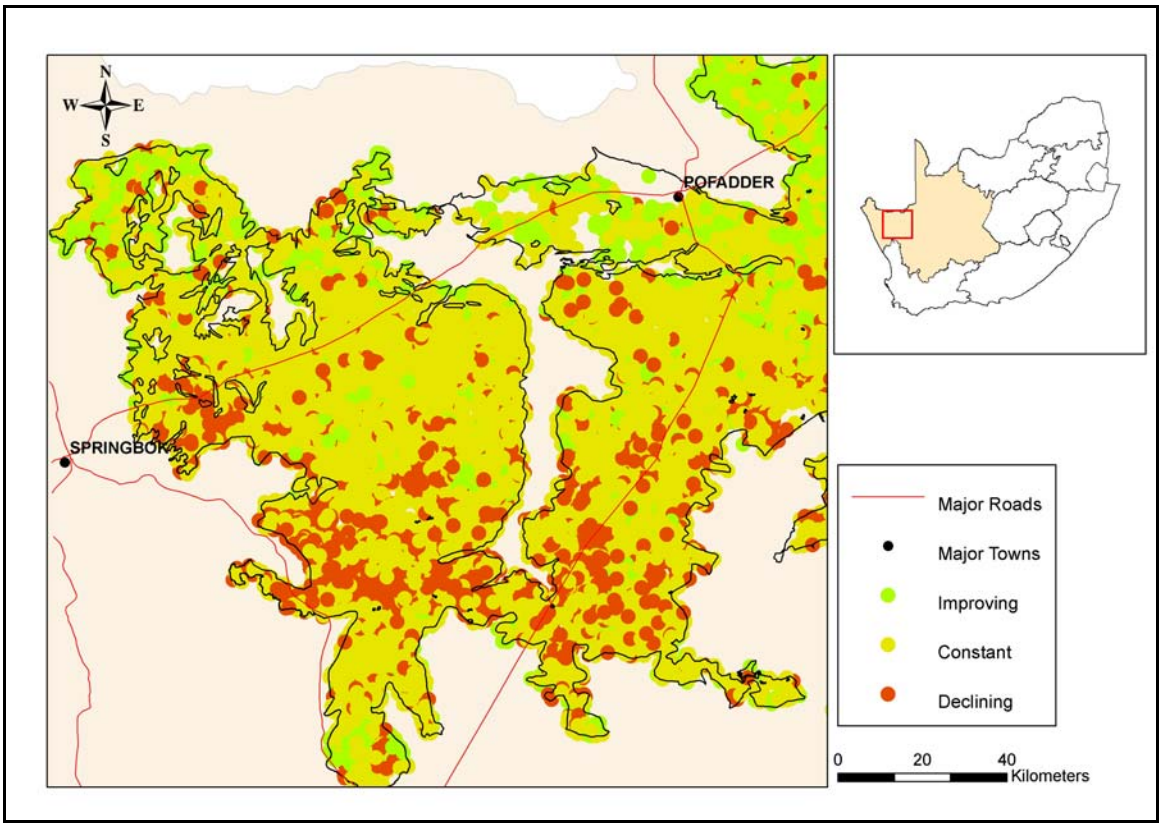

Figure. 6. Spatial distribution of the quantified range of the veld conditions (improving, constant and declining), based on the residual method in the Bushmanland Arid Grassland.

Table 3. Spatial and temporal land degradation of the sample points are indicated for each category in the Bushmanland Arid Grassland

		Temporal		
Spatial	**Constant**	**Declining**	**Improving**	**Total**
Sev. degraded	64	14	22	2533
Mod. degraded	67	15	19	4500
Natural	62	22	16	2482
Total	6157	1572	1786	9515

Discussion

In this study, I used NDVI data to quantitatively deduce changes in vegetation response in the Bushmanland semiarid environment. My results demonstrate that NDVI signal responds very strongly to temporal rainfall patterns. Thus vegetation dynamics during the seven year provided a picture of the temporal pattern of the Bushmanland vegetation to inter annual variation and trends specifically in relation to rainfall. These results confirms previous studies by Ayamba & Tucker (2005), Evans & Geerken (2004), Olsson *et al.* (2005) and others that NDVI signal responds positively to variation in rainfall. Furthermore, most of the NDVI variation is explained by the cumulative rainfall of up to 6 months as shown by the highest correlation coefficient (0.86, see Table 1). Several studies have found good correlations between the NDVI and rainfall, using different cumulative time intervals of rainfall (Evans & Geerken, 2004, Herrmann *et al*. 2005, Nicholson *et al*. 1990; Yang *et al*. 2005). It is however difficult to generalise from these studies as the rainfall interval varies considerably from one system to another. In Bushmanland, NDVI data can be used to detect medium-term changes in vegetation but cannot accurately track recent changes in rainfall.

Although the overall Bushmanland NDVI temporal profile pattern of all three vegetation units remained similar in relation to rainfall, it was also apparent that the maximum photosynthetic activity varied between the three vegetation units The variation in the NDVI profile of the three vegetation units may indicate a change in the dominant vegetation cover across Bushmanland. Consequently, several studies support our findings that NDVI signals should be stratified according to vegetation type in order to quantify anthropogenic-induced changes with the aid of NDVI signal. (Fox *et al.* 2005, Olsson *et al.* 2005, Thompson *et al.* 2005). A detailed vegetation map showing vegetation types or vegetation units as well as detailed soil map of the area is essential in land degradation studies (Mambo & Archer 2007).

The results indicate that land degradation can be quantified using NDVI if rainfall, vegetation types and inter – annual and long term phenology of the system are holistically taken into account. The two proposed models in this study can be used to quantify the spatial and temporal patterns of land degradation. The spatial scale model, quantified the veld condition within the dry phase (Jan 2001-May 2005). This enabled us to assess the veld condition within dry conditions and assess the NDVI signal of natural and degraded veld based on the defined thresholds. The second model looked at temporal scale of land degradation for a seven year period from 2000 – 2007. Results suggest that most of Bushmanland are moderately degraded and that this has been the case for the last 7 years (see Table 3). Several land degradation studies have explored the residual and threshold methods in quantifying this phenomenon (Evans & Geerken 2004, Wessels *et al.* 2007). Our two approaches are repeatable and relatively inexpensive. However, understanding the phenology of the system is a key requirement of such models. Phenology is likely to differ from one vegetation type to another, thus the importance of taking vegetation types into account (Thompson *et al.* 2005).

The challenge in using absolute thresholds is that they require a large well distributed sample size to derive an accurate threshold. In addition, accurate fine scale vegetation mapping is of great importance. This might be difficult in areas where botanical knowledge is lacking. Even the scale of the SA vegetation map (Mucina & Rutherford, 2006) might be too coarse for such analysis, with the result that natural spatial landscape variability may mask the impacts of human land degradation.

Conclusion

While land degradation may be defined in terms of loss or reduction of biological productivity, these consequences are difficult to quantify since degradation varies in different environment. A well-accepted definition of land degradation is needed to formulate adequate methods for quantifying and monitoring changes in vegetation. My analysis shows that the general spatial distribution of NDVI in the Bushmanland corresponds directly to rainfall, and to vegetation type. This stresses the need to collect daily rainfall in order to test the various cumulative rainfall. The results support the need of high quality fine scale vegetation map, climatic data and *a priori* knowledge of the phenological changes in arid vegetation. This is required for a proper interpretation of remote sensing data in arid environments. Detailed ground-truthing exercise is necessary to validate degradation models.

Further research is needed on the potential uses of remote sensing data. As this study indicates, remote-sensing data can be successfully used to quantify and map land degradation, even in arid environments where previous attempts have shown limited success. Such approach has also management implications as it could be applied to map grazing carrying capacity more accurately. Lastly, the use of MODIS NDVI data, which has a high correlation with a variety of vegetation parameters, and have extensive area coverage, is well suited for monitoring vegetation changes spatially and temporally.

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