Trends in vegetation productivity and seasonality for Namaqualand, South Africa between 1986 and 2011: an approach combining remote sensing and repeat photography

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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that it has not been previously in its entirety or in part submitted at any university for a degree.

Claire Davis 30 July 2013

Signed by candidate

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Abstract

This thesis presents an assessment of vegetation change and its drivers across a subset of Namaqualand, South Africa. Namaqualand forms part of the Succulent Karoo biome, which is characterised by exceptionally high species biodiversity but which has undergone severe transformation since the arrival of pastoral colonists. Vegetation productivity in Namaqualand is of great importance since there is a high dependence on natural resources, livestock and agriculture for both subsistence and income. However, there is considerable debate on the relative contribution of land-use change and climate change to vegetation change and land degradation in Namaqualand. Early studies based on bioclimatic envelop models suggest that an increase in temperature and more arid conditions could result in the vegetation cover of the Succulent Karoo being significantly reduced. On the other hand, more recent studies show that less extreme changes in rainfall could result in the vegetation of the biome remaining fairly stable with possible increases in the spatial extent by 2050. Furthermore, field observations and repeat photography, suggest that the change in vegetation in the region over the course of the 20th century generally portrays an increase in cover largely as a result of changes in land-use.

By combining repeat photography and satellite data from NOAA-AVHRR and TERRA-MODIS sensors as well as baseline climatology data from the CRU TS 3.2 data set this study aimed to:

- Determine the critical pathways of inter-annual and intra-seasonal vegetation change in the Namaqualand
- Investigate the role of land-use and climate variability as key drivers of vegetation change in Namaqualand.

This study presents a unique approach in the sense that it employs multi-source and multi-temporal data to assess vegetation change over time. A key component of this research was to determine whether historical repeat photography could be successfully used in combination with the remotely sensed vegetation indices possibly serving as a means of validation.

The first component of the research investigated the trends in local climate for Namaqualand. This provided a basis for the interpretation of the trend in vegetation derived

from remotely sensed information as well as the repeat photographs. There is good evidence, based on the analysis of the CRU TS 3.2 data set (1901-2009), to suggest that temperatures in the region have been increasing over the last century and that the rate of warming has been increasing. There was no clear evidence, however, for a significant change in mean annual rainfall and the rainfall time series remains dominated by oscillating wet and dry periods.

The second component of the study qualitatively assessed the repeat photographs in order to determine the extent of vegetation change within the different land tenure systems (commercial or communal) and land-use practises (livestock grazing or cultivation) in the region. The repeat photographs demonstrated that perennial species have been able to recolonize previously cultivated fields. This improvement is, however, limited in the communal areas where sites have been subjected to heavy grazing pressure over a long period of time. The repeat photographs also provided evidence of an increase of *Acacia karroo* along rivers and small tributaries.

The third component of the research investigated the extent, nature and rate of recent changes in vegetation productivity and phenology using remotely sensed vegetation indices. Both the normalised vegetation index (NDVI) and the enhanced vegetation index (EVI) derived from the AVHRR and MODIS satellite sensors were used as proxies of vegetation in this research. The remote sensing data was analysed using a combination of spatial and non-spatial trend analysis techniques including the Earth Trends Modeler in Idrisi Taiga, Rain-use efficiency (RUE), trend in the standardised residuals (RESTREND), TIMESAT software as well as linear and piece-wise regressions. Phenological and productivity metrics derived from the AVHRR NDVI and MODIS NDVI and EVI time series data included the start, end and length of the growing season, time of peak NDVI, maximum NDVI, cumulative NDVI of the growing season, and minimum NDVI. The results indicate that the vegetation in Namaqualand is considerably variable over space and time and responds to changes in rainfall and altitudinal gradients. Increases in vegetation productivity were noted over the escarpment and Kamiesberg regions of Namaqualand whereas decreases were observed over Bushmanland. There were no distinct changes in the start, end or peak of the growing season but a significant decreasing trend decrease in the seasonal amplitude supported the finding from the repeat photographs that there has been a shift in dominance from annual to perennial plants in the study area. In terms of the sensor datasets used in this study, there is a clear trade-off between the longer time series of the older AVHRR sensor with a lower resolution and higher noise and the MODIS sensor with the shorter time series but higher resolution and less noise.

This study was able to demonstrate that climate variability and changing land-use patterns have a considerable influence on vegetation change in the region and are important filters through which to interpret vegetation change in Namaqualand. Overall, a trend towards improved vegetation cover and composition is evident in the study area. The findings of this study have created a baseline or reference conditions for Namaqualand against which future change can be assessed. This study offers new insights into the spatial and temporal trends in vegetation productivity and seasonality for Namaqualand that could not have been accomplished without the combined use of both long-term satellite time series data and repeat photography. The repeat photographs were able to add value the analysis of NDVI and EVI by providing information on species composition changes as well as changes in land-use practises. The photograph pairs, however, only represent two, sometimes 3 snapshots in time and are thus not representative of the average cover experienced at a particular site. Furthermore, the start and end dates of the repeat photographs do not match those of the satellite time series. Despite these limitations, repeat photographs could be a promising alternative ancillary data source that could be used in satellite based vegetation monitoring studies in semi-arid regions.

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Chapter 1: Introduction and Background

1.1. Problem statement

Namaqualand, a winter-rainfall desert region of north-western South Africa (Cowling et al. 1999), forms part of the Succulent Karoo biome which is globally recognised as one of only two biodiversity hotpots located within a desert environment (Myers et al. 2000). Namaqualand covers a total area of about 50 000 km^2 and contains about 3 500 species of which nearly 40% are endemic to the region (Desmet 2007). The region has however, undergone severe transformations since the arrival of pastoral colonists. Today, the Succulent Karoo is governed by a complex range of economic activities including conservation and tourism, commercial livestock production and smallholder livestock systems (Hoffman & Rohde 2007). A dual land tenure system of private and communal ownership has primarily characterised the way in which the land has been utilised (Hoffman et al. 2007). The communal areas account for more than 25% of the region and are used extensively for livestock production and support 45% of its population (Hoffman et al. 1999). Overgrazing by both communal and commercial livestock has negatively influenced approximately two-thirds of the vegetation of the Succulent Karoo (Driver & Maze 2002) and there is strong evidence to show that the vegetation and species composition in these areas has been significantly altered (Hahn et al. 2005; Todd & Hoffman 2009; Anderson & Hoffman 2011). Additional challenges facing the region include small and large-scale prospecting and exploitation of mineral deposits as well as irrigated agriculture (Milton et al. 1997). Namaqualand is often considered to be environmentally and economically marginal, particularly since there is a high dependence of people on natural resources, livestock, and agriculture (Benjaminsen et al. 2006; Cousins et al. 2007). External stresses such as climate change, shifts in agricultural production and land use (including land reform) may further negatively impact the productivity of Namaqualand (Nel & Hill 2008).

The latest climate change projections for the winter rainfall region of South Africa indicate that both temperature and evapotranspiration are likely to increase into the 21st century (Van Jaarsveld & Chown 2001; Pachauri & Reisinger 2007; Archer & Tadross 2009; Tadross et al. 2011). Rainfall is expected to decrease in the future (Tadross et al. 2011; Christensen et al. 2007) as a result of a poleward retreat of rain-bearing mid latitude cyclones (MacKellar et al. 2007). Studies based on bioclimatic envelop models (Rutherford et al. 1999; Midgley & Thuiller 2007) indicate that the Succulent Karoo and Namaqualand in particular will be significantly impacted by the changes in climate. These models suggest that the biome may suffer a reduction in spatial extent by the year 2050 (Figure 1.1) as well as consequent reductions in the abundance and diversity of endemic species (Midgley & Thuiller 2007; Hannah et al. 2002). Furthermore, these models predict that as much as 40% of the biome will fall outside the current climate envelope with the Succulent Karoo vegetation being replaced by an unknown arid vegetation type (Rutherford et al. 1999). Revised biome change predictions based on more recent climate data and analysis methods (Driver et al.

2012) however, demonstrate that the Succulent Karoo biome will remain stable over time with the desert biome expanding into areas previously occupied by the Nama-karoo biome (Figure 1.2). Exactly how these climate-driven changes are likely to manifest themselves in the context of the complex range of land-use activities in the region remains unclear. Furthermore, the basis of these bioclimatic model outputs is currently being questioned (Pearson & Dawson 2003; Huntley et al. 2010; Araújo & Peterson 2012) and little effort has been made to assess their key assumptions by relating them to quantitatively-measured vegetation data.

Within the BMBF-funded BIOTA AFRICA project, nine BIOTA Biodiversity Observatories were installed in the western Succulent Karoo along a south-north transect. Analyses of vegetation data acquired at these observatories over the last decade indicated that vegetation dynamics respond to climate signals (in particular the inter-annual variability in rainfall) but that vegetation has experienced an unexpected positive trend in terms of both cover and species richness (Schmiedel et al. 2012). Evidence from field data in Namaqualand based on a series of matched photographs beginning in the late 1800s (Hoffman & Rohde 2010) suggests that vegetation in both commercial (Hoffman & Rohde 2007) and communal areas (Rohde & Hoffman 2008) generally portrays an increase in cover and possibly in plant diversity. These studies propose that the majority of the changes can be interpreted in terms of the changes in land-use in the area over time.

Understanding the rate and extent of historical vegetation change in Namaqualand in response to local drivers, such as livestock grazing and climatic variability, is required as it provides the necessary benchmarks against which future changes can be assessed. An accurate determination of the extent of vegetation change in Namaqualand over time remains a challenge. Not only does the region cover a large, bio-climatically diverse area but the lack of long-term observations and scientific data makes reliable reconstruction difficult. There has been very little work in the region that has used satellite imagery to study changes in vegetation patterns. Remote sensing data and techniques are becoming increasing important for monitoring vegetation in arid and semi-arid regions and have the potential to detect changes in vegetation at a variety of spatial and temporal scales (Justice et al. 1985; Hobbs 1990; Zhao et al. 2012). Remotely sensed vegetation indices, such as the Normalised Difference Vegetation Index (NDVI), are used as a proxy for vegetation productivity and have been used extensively to study vegetation–climate interactions (for example Herrmann et al. 2005; Martiny et al. 2006; Brown et al. 2010; Philippon et al. 2011; Anyamba & Tucker 2012), for detecting long-term vegetation trends (for example Anyamba & Tucker 2005; Eklundh & Olsson 2003; Wessels et al. 2007; Fensholt et al. 2012), and to assess vegetation phenology (for example Wessels et al. 2010; de Jong et al. 2011b; Eklundh et al. 2012; Vrieling et al. 2013).

Remotely sensed vegetation indices in combination with historical repeat photography are utilised in this study in order to effectively determine the critical pathways of vegetation change in Namaqualand. This study presents a unique approach to the problem stated above by combining remotely sensed information with repeat photographs at a comparative spatial scale. Currently there are only two such studies in peer-reviewed publications (McClaran et al. 2010; de Mûelenaere et al. 2012). It is hoped such an approach may provide a means, or at least recommendations, to which on-going monitoring can be successfully implemented in Namaqualand to detect critical changes in vegetation productivity and phenology. In addition, the results from this study will provide a benchmark against which future vegetation change can be assessed. Such information is essential for effective planning and land management in the region as well as the improvement of strategic adaptation responses to climate change.

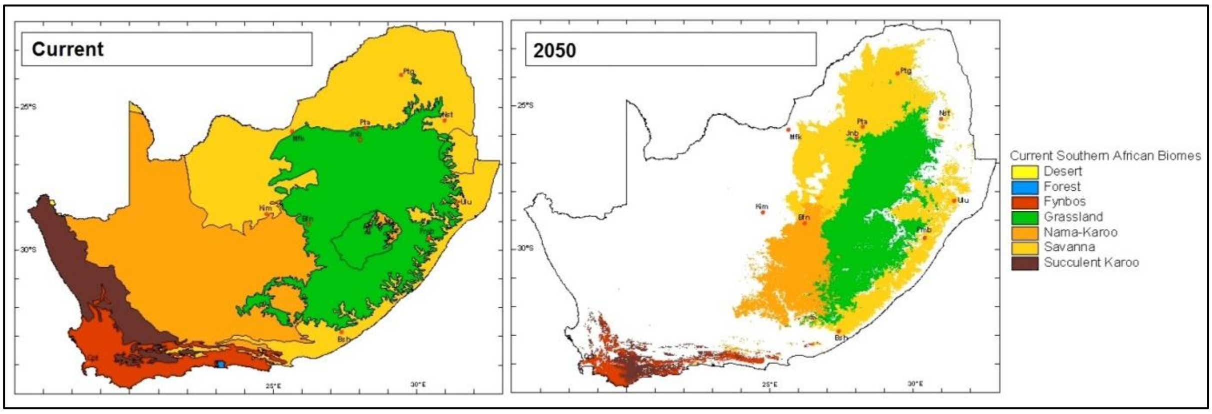


Figure 1.1: The current and predicted future (2050) distributions of the major South Africa biomes (Fynbos, Succulent Karoo, Nama-karoo, Savanna and Grassland) as a result of climate change as described by Rutherford et al. (1999). The future scenario is based on the HadCM3 model and A2 emissions scenario and an atmospheric carbon dioxide concentration of 550ppm (excluding sulphates).

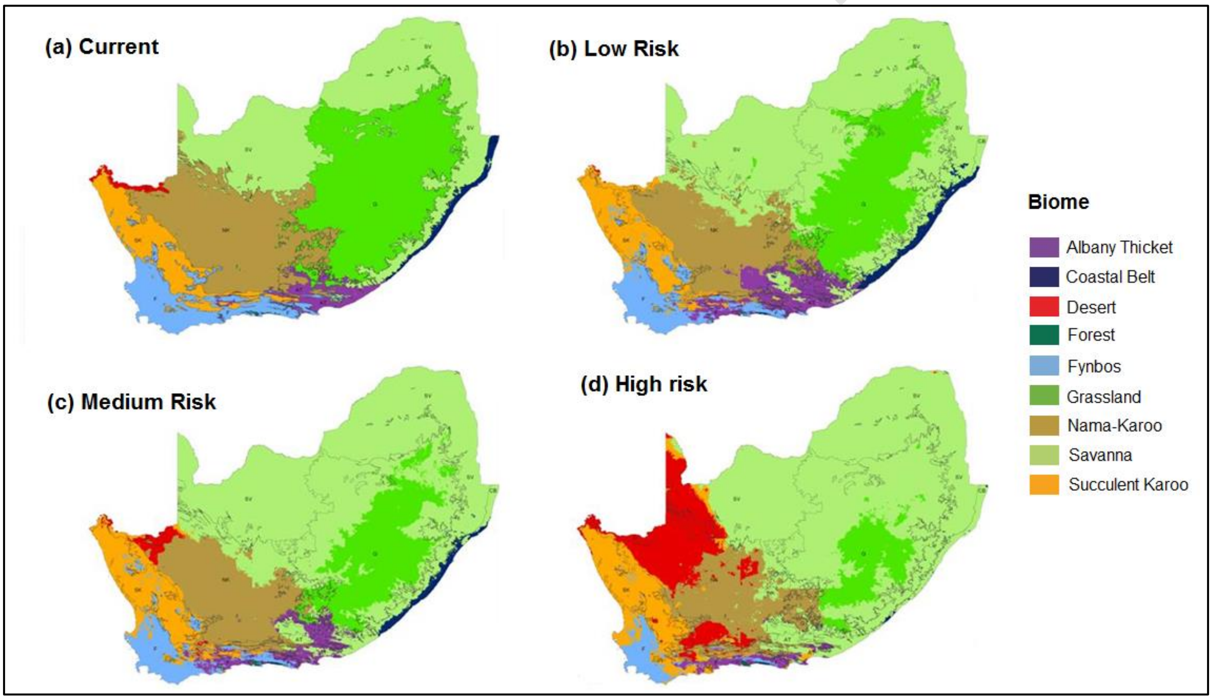


Figure 1.2: Predictions of biome climate envelopes under difference climate scenarios by 2050 as described by Driver et al. (2012). The future scenario is based on 15 downscaled global circulatiuon models and the A2 emissions scenario.

1.2. Background and context

1.2.1. Land degradation

Land degradation is defined by the Land Degradation Assessment in Drylands (LADA) as – "a reduction in the capacity of land to perform ecosystem functions and services that support society and development" (FAO 2010; Van Aardt et al. 2011; Bennett et al. 2012). Degradation is accompanied by a decrease in palatable grasses, succulents and herbaceous species, an increase in less palatable dwarf shrubs and annual grasses and a reduction in total grass and woody biomass (Tanser & Palmer 1999). Land degradation has been recognised as a key challenge to agricultural production and development in South African rangelands (Hoffman & Ashwell 2001).

In the first national review of land degradation in South Africa, Hoffman and Ashwell (2001) suggest, like Reynolds et al. (2007) that degradation is influenced by historical, biophysical and social factors. They used a qualitative assessment of degradation and suggested that, in general, it was the communal areas of South Africa that were perceived as being most degraded and that degradation was related to rural population density and poverty as well as the biophysical environment (Hoffman & Todd 2000). Communal rangelands are concentrated in the former homeland areas of South Africa, which were established under the Natives Land Acts of 1913 and 1936. Communal areas are generally characterised by high population and livestock numbers and much debate has focused on the vulnerability of these areas to land degradation (Hoffman & Ashwell 2001; Hoffman & Todd 2000).

Several recent attempts have been made at providing a more quantitative estimate of land degradation in South Africa (Bennett et al. 2012; Tanser & Palmer 1999; Wessels et al. 2004; Bai & Dent 2007; Wessels et al. 2007; Thompson et al. 2009). All of these studies have used remotely sensed satellite data and have relied on assessing changes in the Normalized Difference Vegetation Index (NDVI) over time (refer to section 1.2.4 for detailed information on remote sensing and NDVI).

Wessels et al. (2004; 2011) used AVHRR-derived normalized difference vegetation index (NDVI) data to compare degraded rangelands associated with communal areas to intact rangelands in north-eastern South Africa. They found that even though degraded areas had lower vegetation production than non-degraded areas they were able to support large numbers of livestock suggesting that are functionally stable. Bennet et al. (2012) found a similar pattern in the communal areas of the former Ciskei region of the Eastern Cape. The communal areas showed some evidence of vegetation degradation relative to the adjacent commercial farm but range productivity had not declined in the short term. This appears to reflect a similar situation to the communal areas of Namaqualand, which although often perceived as highly degraded, do not contain lower local species richness than adjacent commercial rangeland (Todd & Hoffman 2009; Todd & Hoffman 1999). The shift to annuals in the communal areas, however, reduces biomass transfer from year to year (Richardson et al. 2005), with the consequence that exceptionally dry years result in large-scale mortality of up to 80% of livestock on the communal rangeland (Richardson et al. 2007).

For the Limpopo province, Wessels et al. (2007) found that productivity per unit rainfall was significantly reduced in degraded areas and that negative trends in vegetation productivity were associated with communal areas of the province. For some well-known degraded areas in the province they were unable to detect negative trends since much of the degradation had taken place before the start of the satellite record. Thompson et al. (2009) indicated that previous degradation assessments of the Little Karoo (for example Fairbanks et al. 2000) 'massively underestimated' the extent of severe degradation in the region. Bai and Dent's (2007) analysis covered the entire land area of South Africa and assessed changes in the spatial pattern of NDVI for the period 1981-2003. They found that NDVI was strongly related to rainfall and that a distinct pattern of declining productivity in the north-east of the country and increasing productivity in the west was evident. Degradation was weakly related to rural population density. While land degradation was confirmed as a serious issue in the communal areas of South Africa (particularly in KwaZulu-Natal, and the former Gazankulu and Transkei regions), large areas managed under commercial land tenure were also affected (Bai and Dent 2007). An increase in Net Primary Productivity was recorded in a third of the country over the period 1981-2003. Of this, 84% was comprised of rangelands and the signal was dominated by the semi-arid rangelands of the Nama-karoo biome in the western part of the country (Bai and Dent 2007).

Land degradation is expected to accelerate under scenarios of climate changes specifically in the former homelands or communal areas of South Africa (Meadows & Hoffman 2003). For example, a higher frequency of drier spells or a lower critical rainfall season can affect vegetation cover with implications for both erosion processes and livestock production. In an area under pressure from overgrazing or inappropriate water use, climate change can act as an additional pressure or stressor that can amplify land degradation (Archer & Tadross 2009). In addition, if small-scale farmers are re-settled on farms without support and extension advice the danger exists that high, uncontrolled stocking rates will impact negatively on the long-term productivity of the new land reform farms (Wessels et al. 2004). The link between rainfall, land-use and degradation is thus important (Archer & Tadross 2009).

1.2.2. The influence of climate and land-use on land degradation

The vegetation composition and productivity of arid and semi-arid regions is strongly affected by both fluctuations and directional changes in climate and disturbances regimes, such as livestock grazing (Archer 2004; Hoffman & Vogel 2008). In the Succulent Karoo, the combination of the magnitude, timing and frequency of rainfall events drives and maintains the diversity of vegetation (Reineking et al. 2006). The moderate temperature regime and the predictable rainfall are often cited as an important determinant of the high biodiversity in the region (Cowling et al. 1999). Given that the Succulent Karoo occupies a wide range of aridity, it seems unlikely that a reduction in the amount or effectiveness of rainfall alone will be the driving factor of land degradation (Hoffman et al. 2009).

There are two main agricultural production systems in the Namaqualand which correspond to the communal and commercial tenure systems (Hoffman et al. 1999). Communal and commercial areas differ in their farming objectives, economic conditions, demographic patterns and land-use practises (Hoffman & Ashwell 2001). Commercial livestock production on privately owned land has a clear income-generating objective and a high proportion of livestock are sold every year for meat and wool. Livestock numbers are usually in line with the recommendations set by the Department of Agriculture and seldom fluctuate dramatically. Livestock are rotated between camps ensuring that a high proportion of the rangeland is rested. Commercial farms account for about 50% of the land area in Namaqualand and the number of commercial farmers in 2001 was estimated to be between 400 and 700 (Desmet 2007).

High stocking densities and overgrazing by livestock, in conjunction with communal land tenure, is widely cited as a key driver of land degradation in the Succulent Karoo (Hahn et al. 2005; Hoffman & Ashwell 2001). Communal areas have a long history in Namaqualand and were initially set aside by the colonial government in the first decades of the 19th century to protect indigenous pastoralists from being dispossessed of their land by settler farmers. From the middle of the 20th century, however, the communal areas were reserved for exclusive occupation by coloured people during the apartheid regime. The majority of Namaqualand's population (approximately 80 000) reside in the communal areas. Income from livestock and dryland crop farming activities often supplement wage labour and state welfare (Benjaminsen et al. 2006; Desmet 2007). Livestock production is characterised by several herds individually herded in response to a wide range of social and environmental influences. The lack of sufficiently large grazing areas means that herders are seldom able to rest large portions of the land. The area sometimes supports more than twice the number of livestock as recommended by the National Department of Agriculture (Hahn et al. 2005) but also falls below this number in years of poor rainfall (Hoffman et al. 1999; Hoffman and Ashwell 2001).

Livestock impacts on rangelands include herbivory, trampling, nutrient redistribution within a landscape and an increase in unpalatable plant species. Furthermore, overgrazed areas showed a reduction in the vegetation cover, which exposes the soil surface to wind and water erosion, increases surface water flows and reduces the infiltration of water (Le Maitre et al. 2007). These impacts interact with climate to affect the physical, chemical, and biological properties of ecosystems in a number of ways. In Namaqualand heavy grazing and drought conditions often leads to the replacement of perennial succulent and non-succulent palatable shrubs and grasses by annuals, geophytes, and unpalatable perennial shrubs (Todd & Hoffman 1999; 2009; Rutherford & Powrie 2010). The change in species composition is usually attributed to selective grazing which can reduce the reproductive output of the preferred palatable perennial species (Todd & Hoffman 2009; Milton & Hoffman 1994). It has thus been hypothesised that degraded land in the Succulent Karoo would be dominated by annual plants which demonstrate spring growth pulses in NDVI whereas intact vegetation is dominated by a diverse array of perennial plants which produce a NDVI curve showing stable year-round growth (2009).

1.2.3. Recent trends in climate and land-use in Namaqualand

There are numerous regional studies of recent trends in temperature, rainfall and extreme weather events over Africa and southern Africa (Mason & Jury 1997; Mason et al. 1999; Hulme et al. 2001; Fauchereau et al. 2003; Kruger & Shongwe 2004; New et al. 2006; Haensler et al. 2010). Where records are of sufficient length there have been detectable increases in the number of heavy rainfall events (Solomon et al. 2007) and over southern Africa regional studies have shown that the length of the dry season and the average rainfall intensity has increased (New et al. 2006). Furthermore, a study considering changes in extreme rainfall events over South Africa (Mason et al. 1999) found that 70% of the country has experienced a significant increase in the intensity of extreme rainfall events between 1931-1960 and 1961-1990. Regional differences between the north-eastern and central parts of South Africa were also identified. Existing evidence for rainfall trends suggests moderate decreases in annual rainfall over parts of South Africa (for example Kruger 2006). There is also evidence from other studies which shows that inter-annual rainfall variability over southern Africa has increased since the late 1960s and that droughts have become more intense and widespread in the region (Fauchereau et al. 2003).

Only 3 studies have focused on the historical climate of the Namaqualand. Kelso and Vogel (2007) reconstructed the climate of the 1800's in Namaqualand using historical documentary sources. Mackellar et al (2007) analysed trends in observed rainfall for the period 1950–1999 and later Hoffman et al. (2009) investigated whether annual rainfall has declined and whether the incidence of drought has increased since 1900. While annual rainfall has increased significantly in some areas in Namaqualand and decreased in others (MacKellar et al. 2007), 20th century climates have been little different from 19th century climates in terms of the frequency of drought and wet periods (Kelso & Vogel 2007). Various palaeoclimate studies in the winter rainfall zone of South Africa (Chase & Meadows 2007; Benito et al. 2011a; Benito et al. 2011b; Weldeab et al. 2013) have also contributed to the understanding of the long-term changes in climate in the region.

Land-use practises in Namaqualand are dynamic and change in response to a wide range of influences. The number of people living in the rural areas of Namaqualand as well as the predominant land use practices of the region has changed significantly in response to a range of economic, social and political factors (Nel & Hill 2008; Benjaminsen et al. 2006; Cousins et al. 2007). Cultivation of the lowlands, particularly in marginal, low rainfall areas, has been abandoned and most of these areas have reverted to an early successional form of Succulent Karoo biome vegetation (Hoffman and Rohde 2007). Similarly, land use practices have also changed in the communal areas where the predominance of subsistence agriculture has given way to a mixed livelihood approach with livestock production forming only a relatively minor component of household income in recent years (Rohde and Hoffman 2008; Anseeuw & Laurent 2007; Berzborn 2007). In Namaqualand, the area used for the cultivation of wheat, oats, barley and rye crops peaked in 1971 and since then the area under cultivation has declined by nearly two-thirds (Hoffman & Rohde 2007; Rohde et al. 2003). This is largely a result of the large-scale abandonment of wheat farming in marginal, low rainfall areas where it is no longer economically viable (Hoffman & Rohde 2007). Cultivation in the communal areas has also declined significantly since the 1960s (Rohde et al. 2003).

1.2.4. Future trajectories of vegetation change for the Succulent Karoo

Projected impact of climate change

It is widely recognised that there has been a detectable rise in global temperature during the last 100 years (Solomon et al. 2007). In 2010, the global average temperature was 0.53°C above the 1961-1990 average (World Meteorological Organization 2011). The rate of temperature increases has also increased during the latter half of the 20th century, suggesting that increases in average surface temperatures are accelerating (Solomon et al. 2007).

The Succulent Karoo has been predicted to be the biome within South Africa that will be the most severely impacted by climate change (Rutherford et al. 1999; Midgley & Thuiller 2007) Early bioclimatic envelope models predicted that as much as 40% of the biome will fall outside the current climate envelope by 2050 and will be likely to undergo large changes in community composition (Figure 1.1). Based on the HadCM3 model and A2 emissions scenario (Nakicenovic et al. 2000), the Succulent Karoo is projected to be substantially reduced in extent, particularly along its eastern border (Rutherford et al. 1999). Assuming that the vegetation currently to the east of this retracting margin will expand westwards in response, then the grass and woody shrub component of the vegetation of this area is likely to increase. Should such shifts occur, then large areas of the Succulent Karoo biome are likely to resemble the Nama Karoo or Desert biomes in composition and structure.

Revised biome change predictions as part of the 2011 National Biodiversity Assessment (Driver et al. 2012) are based on more recent climate data and analysis methods and demonstrate that the Succulent Karoo biome will remain stable over time (Figure 1.2). This is mainly attributed to the statistically downscaled climate models which project less extreme changes in rainfall for the winter rainfall region of South Africa. The desert biome is predicted to expand into areas previously occupied by the Nama-karoo biome (Driver et al. 2012).

In terms of individual species' responses, Midgley and Thuiller (2007) modelled the response of 20 endemic succulents and although the ranges of the majority of species were predicted to contract, the responses varied considerably. Three species increased in range, by as much as 80%, the remaining 17 species, however, all declined by an average of 56% with several species predicted to experience range contractions in excess of 70%. The possibility of range expansion assumes adequate dispersal ability as well as the ability to survive on different substrates. Since substrate plays such a dominant role in determining the distribution of many species in the region (Desmet 2007), it will have an overriding effect on the ability of plants to respond to climate change. Consequently, the ability of many species to track areas of suitable climate or take advantage of increases in potential range will be highly curtailed, and the predictions of Midgley and Thuiller (2007) may, in fact, represent best-case scenarios. Midgley and Thuiller (2007) further argue that a severe effect of climate change on the succulent flora of the Karoo can be expected because the flora evolved during a period when it was cooler and probably also wetter and atmospheric CO_2 content was lower. Consequently, the higher temperatures and CO_2 content predicted for the future does not reflect any past conditions the area is likely to have experienced in recent times and so is likely to push many species outside their tolerance limits or at least require extensive range shifts.

A unique feature of the Succulent Karoo biome is the high degree of structural diversity (Cowling et al. 1999), which may confer some degree of resilience to climate change impacts because at least some growth forms are likely to tolerate or benefit from the changes. Consequently, future vegetation composition is likely to be derived largely from tolerant species already present in the vegetation, probably with a lesser component consisting of species invading from adjacent areas. In the Succulent Karoo particularly, this still leaves considerable scope for large changes in vegetation structure and dominant growth forms. Broennimann et al. (2006) modelled changes in the distribution of different life forms within southern Africa and found that geophytes and succulents were particularly vulnerable to climate change. Overall, Broennimann et al. (2006) predicted a minimum decline in species richness of 41% for the Succulent Karoo biome and the broader Cape Floristic Region. Since succulents and geophytes comprise a large proportion of the diversity of the Succulent Karoo (over 50% in Namaqualand), the impacts on vegetation diversity may exceed those on structure. Dwarf succulents which comprise a large proportion of the endemic species of the Succulent Karoo appear to be particularly vulnerable to climate change (Midgley & Thuiller 2007; Musil et al. 2009). These species are also often edaphic specialists and have very limited dispersal ability (Schmiedel & Jürgens 1999; Klak et al. 2004; Schmiedel & Mucina 2006), which would restrict their potential to track areas of suitable climate. Annuals were, however, particularly resilient in the face of climate change and were the only growth form where large declines in range were not predicted (Broennimann et al. 2006).

Since climate change is also expected to alter the frequency and intensity of drought events (Fauchereau et al. 2003), understanding vegetation responses to such events is also key to predicting the likely future vegetation composition of the Succulent Karoo. Partly in an attempt to address this research gap Hoffman et al. (2009) reviewed the responses of succulent and woody shrub species to drought. Although the responses where to some extent case- and site-specific, some succulent shrub seedlings were able to tolerate drought conditions for a lot longer than the woody species that had been included in the study. In the seedling phase, woody shrub seedlings do not yet have access to the deeper water resources and so are vulnerable to drought conditions compared to succulent seedlings which are able to tolerate drought conditions for a significant amount of time due to low transpiration rates and a canopy-stored water reserve.

Projected impact of land reform

Uncertainties around land reform add to the challenges of coping with climate change in the Succulent Karoo (Vetter 2009). In South Africa, land reform is aimed at redressing the racial inequalities of the previous land legislation which determined which racial groups were able to own land (Benjaminsen et al. 2006; Cousins et al. 2007). van Jaarsveld et al. (2003) state that the unpredictable nature of land allocation politics may undermine the best conservation intentions in South Africa. Given the economic growth potential of conservation as a form of land use in the Succulent Karoo, promoting community-based conservation could therefore, play an important role in promoting land reform.

In one of the few studies on the potential effect of the land reform programme on the vegetation of the Succulent Karoo, Hoffman et al. (2005) investigated the impact of livestock on the vegetation of Riemvasmaak, a 75 000 ha communal area in the Northern Cape. Using a series of 29 repeat photograph pairs taken in 1995 and then 10 years later in 2005, Hoffman et al. (2005) reported little difference in the tree and shrub component over time. However, grass cover declined significantly, particularly on the sandy pediments of the area. This decline was attributed to the increase in livestock in Riemvasmaak. While the sandy pediments in particular had been affected by the introduction of large numbers of domestic herbivores, the livestock industry had also made a significant contribution to the livelihoods of people re-settled in the area after their forced removal in 1974. The trade-off between enabling small-scale and emerging farmers to earn a living while sustaining the basic goods and services derived from these areas is one of the most important challenges facing people who live, work and are responsible for South Africa's semi-arid and arid regions (Benjaminsen et al. 2006; Cousins et al. 2007). If a decline in primary production in response to climate change is likely then decisions about carrying capacity, mobility, alternative livelihoods and governance will become even more critical.

1.2.5. Monitoring vegetation change using remote sensing

The monitoring of vegetation has been boosted by the advancement of computer based geographic information systems (GIS), satellite, and remote sensing technologies (Reuben et al. 2008). Remotely sensed information from Landsat, SPOT, MODIS and NOAA satellites has emerged as a valuable tool for graphically understanding changes in vegetation and land use at a range of temporal and spatial scales (Reuben et al. 2008; Foody 2002). The detection of vegetation cover changes through the creation of vegetation indices has become an important application of remotely sensed imagery (de Jong et al. 2011a). Vegetation indices have been successfully used to map droughts, land degradation, phenology and land-use change at both large spatial and long temporal scales (Horning et al. 2010). There is extensive international literature on the use of remote sensing and vegetation indices to monitor vegetation change in arid and semi-arid regions globally and in Africa. A tabular synthesis of selected published studies is provided in Table 1.1.

Table 1.1: Synthesis of select remote sensing studies on land degradation in arid and semi-arid regions in Africa arranged according to year of publication

Year	Author	Location	Spatial Scale	Data Used	Method	Time period
1985	Justice et al.	Global	Global	AVHRR NDVI	Global assessment of vegetation phenology	1985
1985	Tucker et al.	Sahel	Sub-continental	AVHRR NDVI	Comparison of NDVI and sampled above-ground biomass data	1980-1984
1996	Mackay & Zietsnian	Karoo, South Africa	Local	Landsat-TM	Soil Adjusted Vegetation Index	1992
1998	Nicholson et al.	Sahel	Sub-continental	AVHRR NDVI	Integrated NDVI and rainfall regressions, rain-use efficiency	1980-1995
1998	Palmer & van Rooyen	Southern Kalahari, South Africa	Local	Landsat-TM	Change vector analysis of three bands (visible, red, near-infrared)	1989 and 1994
1998	Prince et al.	Sahel	Regional	AVHRR NDVI	Rain-use efficiency	1982-1990
1998	Sannier et al.	Etosha National Park, Namibia and Zambia	Regional	AVHRR NDVI	Vegetation Condition Index (VCI)	
1999	Saltz et al.	Israel	Local	Landsat-TM	Transformed Soil Adjusted Vegetation Index (TSAVI)	1995 and 1987
1999	Tanser and Palmer 1999	Great Fish River basin in the Eastern Cape, South Africa	Local	Landsat-TM	Moving Standard Deviation Index and NDVI	February 1994
2000	Azzali & Menenti	Sub-Saharan Africa	Sub-continental	AVHRR NDVI	Temporal Fourier analysis	1981-1991
2001	Diouf & Lambin	Senegal	Local	AVHRR NDVI	Relationship between NDVI and rainfall, rain-use efficiency	1988-1997
2001	Weiss et al.	Saudi Arabia	Regional	AVHRR NDVI	Coefficient of variation of inter-annual NDVI	1982-1994
2003	Eklundh & Olsson	Sahel	Sub-continental	AVHRR NDVI	Trends in NDVI and rainfall	1982-1999
2004	Archer	Eastern Karoo, South Africa	Local	AVHRR NDVI	Detrended NDVI analysis	1985-1997
2004	Evans & Geerken	Syria	National	AVHRR NDVI	Annual maximum NDVI, RESTREND	1981-1996
2004	Li et al.	Senegal	National	AVHRR NDVI	Growing-season integrated NDVI, relationship between NDVI and rainfall	1982-1997
2004	Wessels et al.	Limpopo Province, South Africa	Local	AVHRR NDVI	Cumulative sum NDVI, relationship between NDVI and rainfall	1985-2003
2005	Anyamba & Tucker	Sahel	Sub-continental	AVHRR NDVI	Spatial time series analysis	1982-2003

2005	Fensholt & Sandholt	Senegal	National	MODIS EVI, NDVI and AVHRR NDVI	In situ measurements of vegetation are compared to satellite derived VI's	2001-2002
2005	Fox et al.	Greater Namaqualand	Regional	AVHRR NDVI	Utilised NDVI to determine vegetation patterns and the relationship with climate	1985-2001
2005	Herrmann et al.	Sahel	Sub-continental	AVHRR NDVI	Long-term average and monthly NDVI in relation to rainfall. Calculated RESTREND	1982-2003
2005	Olsson et al.	Sahel	Sub-continental	AVHRR NDVI	Phenology metrics derived from TIMESAT in relation to rainfall	1982-1999
2006	Martiny et al.	Africa	Continental	AVHRR NDVI	Rain-use efficiency	1981-1995
2006	Wessels et al.	Kruger National Park, South Africa	Regional	AVRR NDVI	Analysed the relationship between NDVI summed for the groth season and herbaceous biomsass in field sites	
2006	Seaquist et al.	Sahel	Sub-continental	AVHRR NDVI	Used TIMESAT software to create a light use efficiency model to map NPP	19682-1999
2007	Mambo & Archer	Zimbabwe	Catchment	Landsat TM and ETM	Image differencing	1992 and 2002, 2 images
2007	(Wessels et al. 2007b)	Limpopo province, South Africa	Provincial	AVHRR NDVI	RUE and RESTREND	1985-2003
2007	Heumann et al.	Sahel	Sub-continental	AVHRR NDVI	Used TIMESAT software to estimate phenological parameters	1981-2005
2008	Bai et al.	Global	Continental	AVHRR NDVI	Rain-use efficiency, RESTREND, Energy-use efficiency	1981-2003
2009	Wessels et al.	Skukuza, Kruger National Park	Landscape	MODIS NDVI	Used TIMESAT software to estimate phenological parameters	2000-2006
2010	Wessels et al.	South Africa	National	AVHRR NDVI	Phenological metrics derived from TIMESAT were used to reconstruct the biomes of South Africa	1985-2000
2010	Jönsson et al.	Sweden	National	MODIS NDVI and WDRI	Used TIMESAT software to estimate phenological parameters	2001-2006
2010	Brown et al.	Africa	Continental	AVHRR NDVI	Investigate the relationship between phenology metrics derived from NDVI and key climate indices	1981-2008
2011	Huber & Fensholt	Sahel	Sub-continental	AVHRR NDVI	Teleconnections between NDVI and sea surface temperature	1982-2007

2011	de Jong et.	Global	Global	AVHRR NDVI	Breaks for Additive Season and Trend (BFAST)	
2011	de Jong et.	Global	Global	GIMMS NDVI	Harmonic analyses and non-parametric trend analysis of NDVI	1981-2006
2011	Shisanya et al.	South-east Kenya	Regional	AVHRR NDVI	Relationship between NDVI anomalies and ENSO climate teleconnections	1981-2003
2011	Sjöström et al.	Seven CarboAfrica-associated sites	Local	MODIS EVI	Relationship between vegetation gross primary productivity and MODIS EVI	2000-2008 depending of the site
2012	Fensholt et al.	Global	Global	AVHRR NDVI	Trends in NDVI	1981-2007
2012	Wessels et al.	Kruger National Park, South Africa	Regional	AVHRR NDVI	Simulate land degradation in order to evaluate the methods used to detect vegetation changes	1985-2003
2013	Fensholt et al.	Sahel	Sub-continental	AVHRR NDVI	Trend analysis of RUE	1982-2010
2013	Vrieling et al	Africa	Continental	GIMMS NDVI	Determined vegetation phenology, length of the growing period, across Africa	1981-2011

Vegetation Indices

Green vegetation has a characteristic spectral response pattern where visible blue and red energy is absorbed, visible green light is reflected, and near infrared energy is strongly reflected. The majority of vegetation indices are functions of the absorbed radiation by chlorophyll in the red band and scattering by cellulose in the near-infrared (NIR) band (Eastman 2003; Tucker 1979). These two bands contain more than 90% of the information on a plant canopy. The normalized difference vegetation index (NDVI) is the most commonly applied index (Tucker 1979) since it is simple and easy to calculate with the use of a wide variety of computer software and suitable satellite imagery at a 1-4 km spatial resolution has been acquired at a daily basis since 1978. It is expressed as:

$$\boldsymbol{NDVI} = \frac{(\textbf{Near Infrared} - \textbf{Red})}{(\textbf{Near Infrared} + \textbf{Red})}$$

Vegetation indices produce a single image indicating the amount of green vegetation production and biomass (Archer 2004) where low index values usually indicate less vegetation while high values indicate higher photosynthetic activity. There is a strong positive relationship between vegetation indices and primary production (Tucker & Sellers 1986). The Normalised Difference Vegetation Index (NDVI) is strongly correlated with leaf area index (LAI), aboveground biomass, fraction of absorbed photosynthetically active radiation (FAPAR), photosynthetic capacity, community coverage and phenological change (Justice et al. 1985; Tucker et al. 1985; Prince 1991; Fensholt et al. 2004; Tucker et al. 2005). Consequently, vegetation indices are frequently used as a proxy for vegetation productivity (Fensholt et al. 2012; Huber & Fensholt 2011; Wessels et al. 2012; Mbow et al. 2013).

The foundation for using NDVI in monitoring arid and semi-arid regions is based on the large body of research since the 1980's (Table 1.1), which clearly demonstrate the close relationship between NDVI and rainfall variations on seasonal to inter-annual time scales (Herrmann et al. 2005; Martiny et al. 2006; Brown et al. 2010; Shisanya et al. 2011; Nicholson & Farrar 1994). The Normalised Difference Vegetation Index (NDVI) derived from the Advanced Very High Resolution Radiometer (AVHRR) sensor is the most commonly used tool for detecting long-term vegetation changes at global, continental and regional scales. The Advanced Very High Resolution Radiometer (AVHRR) NDVI time series is one of the most complete NDVI datasets in the world (Wessels et al. 2012). The 25 year 1 km AVHRR NDVI time series and has been successfully used in many studies to monitor long-term trends in vegetation conditions in arid and semi-arid regions (Anyamba & Tucker 2005; Eklundh & Olsson 2003; Vrieling et al. 2013; Wessels et al. 2004; de Jong et al. 2011a; Myneni et al. 1997; Fensholt et al. 2013). AVHRR NDVI has also been used to examine the linkages between climate variations and ecosystem dynamics especially those associated with El Nino Southern Oscillation phenomenon (Philippon et al. 2011; Anyamba & Eastman 1996; Camberlin et al. 2007; Philippon et al. 2007) and has been used to monitor drought in regions with sparse rainfall monitoring networks (Anyamba & Tucker 2012; Fensholt et al.

2013; Kogan 1995; Peters et al. 2002). Time series of NDVI data have also been used to gain information on seasonal vegetation dynamics in order to investigate the impact of climate change on vegetation phenology (Jönsson & Eklundh 2004; Van Den Bergh et al. 2012). The majority of these studies have focused on the extraction of phenological metrics from NDVI time series, such as start of the growing season (Wessels et al. 2010; Jönsson & Eklundh 2004; Zhang et al. 2003; Reed 2006; White et al. 2009).

The Normalised Difference Vegetation Index (NDVI) is, however, affected by a range of factors, biophysical and other, which can complicate the attribution of vegetation change (Archer, 2004). In semi-arid areas NDVI is highly sensitive to seasonal rainfall variability since variability in the rainfall directly affects the vegetation in the region (Li et al. 2004; Richard & Poccard 1998). Wessels et al. (2007) emphasize that this short-term variability in vegetation production makes it difficult to distinguish long-term anthropogenic land degradation from the effects of seasonal rainfall variability. Various approaches, such as rain-use efficiency (RUE), (Prince et al. 2004) and the trend in standardised residuals (RESTREND), (Wessels et al. 2007; Archer 2004) have been developed to overcome this problem (refer to Table 1.1 for examples). In addition, NDVI is affected by seasonal variations in atmospheric water vapour, atmospheric aerosol content and large areas of bare soil in arid and semi- arid areas, which may cause significant variations in NDVI which are not associated with actual vegetation cover (Anyamba & Tucker 2005; Reuben et al. 2008; Huete & Tucker 1991).

The development of alternative vegetation indices such as the Soil-Adjusted Vegetation Index (SAVI) (Huete 1988), the Transformed Soil-Adjusted Vegetation Index (TSAVI) (Baret & Guyot 1991), the Modified Soil-Adjusted Vegetation Index (MSAVI) (Qi et al. 1994), and the Enhanced Vegetation Index (EVI) (Huete et al. 2002) are intended to minimise some of these problems. The Enhanced Vegetation Index (EVI) was developed to be implemented using the data from the Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) sensors (Huete et al. 1994; Huete et al. 2011). EVI differs from NDVI in that in addition to the red and near infrared bands, the blue band is used to overcome limitations identified in the NDVI. EVI is computed as (Huete et al. 2002):

$$\boldsymbol{EVI} = \mathbf{G}\frac{(\mathbf{Near\ Infrared} - \mathbf{Red})}{(\mathbf{Near\ Infrared} + \mathbf{C_1Red} - \mathbf{C_2Blue} + \mathbf{L})}$$

Coefficients for MODIS EVI algorithms are: L=1, C_1=6, C_2=7.5 and G=2.5

The MODIS Enhanced Vegetation Index (EVI) developed by Huete et al. (2002) has been used to circumvent the problems associated with the AVHRR NDVI. This index combines the advantages of the SAVI and reduces the sensitivity to atmospheric and soil effects but remains sensitive to a wide range of variation in canopy density (Zhang et al. 2005). The EVI, however, is more sensitive to topographic conditions than NDVI (Matsushita et al. 2007), which successfully retains the ability to minimise topographic effects while producing a linear measurement scale (Eastman, 2003). Huete et al (2002) thus maintain that the NDVI and EVI complement each other in global vegetation studies and improve upon the detection of vegetation changes and extraction of canopy biophysical parameters.

Various methods have been used to analyse vegetation indices for the purpose of detecting changes in vegetation dynamics. These include (i) statistical approaches such as principal component analysis (PCA) which decompose the NDVI image time series into various spatial and temporal components (Anyamba & Eastman 1996; Hirosawa et al. 1996), (ii) statistical-frequency techniques such as Fourier analysis which can detect temporal variability patterns by breaking NDVI into phase and amplitude components (Olsson & Eklundh 1994; Azzali & Menenti 2000), (iii) time series analysis which comprise methods that attempt to understand underlying forces structuring the data, identifying patterns and trends, detecting changes (Van Den Bergh et al. 2012), (iv) curve fitting to derive phenology metrics (Jönsson & Eklundh 2004), (v) change vector analysis (Lambin & Strahlers 1994; Mambo & Archer 2007), and more recently decomposition of time series into trend, seasonal and noise components (Verbesselt et al. 2010a; Verbesselt et al. 2010b).

Characteristics of NOAA AVHRR and MODIS

The National Oceanic and Atmospheric Administration (NOAA) satellite series was developed for meteorological purposes and has a coarser spatial and spectral resolution than land orientated satellites (Lillesand et al. 2004). The Advanced Very High Resolution Radiometer (AVHRR) sensors have been flown on a series of NOAA satellite platforms, from NOAA-6 to the current NOAA-17. In contrast to Landsat imagery that was originally used widely in vegetation studies, the fine temporal resolution of the AVHRR sensor as well as its low cost makes it more suitable for vegetation studies.

The Moderate-resolution Imaging Spectroradiometer (MODIS) is a scientific payload flying on board the Terra (EOS-AM) satellite launched by NASA in 1999 (Lillesand et al. 2004). The sensor is considered an improvement on the AVHRR sensor in terms of spatial, radiometric and spectral resolution, and instrument characterisation (Gutman & Masek 2012). The MODIS sensor is more advanced than NOAA with regard to its high spatial (250 -1km) and spectral resolution. MODIS data is distributed by the Land Processed Distributed Active Archive Centre (LP DAAC), located at the U.S Geological Survey's EROS Data Centre.

The MODIS data is referred to as the "continuity index" to the existing 20 plus AVHRR NDVI time series, which can be extended by MODIS data to provide a longer data record use in vegetation monitoring studies (Huete et al. 2002). Efforts are underway by NASA's Land Long Term Data Record (LTDR) project (Pedelty et al. 2007) and Swinnen and Veroustraete (2008) to create a multi-sensor long-term data record by reprocessing the older AVHRR and more recent MODIS and SPOT VEGTATION in such a way that their NDVI data are potentially comparable through time.

1.2.6. Use of repeat photography for understanding vegetation change

Repeat photography has been used as a technique to monitor vegetation change in a wide variety of arid and semi-arid environments across the globe and has proved to be a valuable tool for demonstrating the effects of land management policies, climate variability and land-use change over time (Webb et al. 2010). The repeat photography methodology involves the comparison of historical and recent landscape photographs taken from the same camera point (Kull 2005; Nyssen et al. 2010). The process also is called photographic monitoring, photo point monitoring, fixed point photography or comparison photography. Repeat photography studies vary widely in the time frame of analysis from the re-photography of a historic photo after the passage of a century to yearly or monthly photographic monitoring of a specific site (Kull 2005).

The technique was pioneered by two vegetation ecology studies in the western United States. Firstly, the 'Changing Mile' project in southern Arizona and Mexico investigated changing desert vegetation based on historical photographs from the late 1800s and early 1900s which were re-photographed in the 1960s (Hastings & Turner 1965) and again in the 1990s (Turner 2003). Secondly, a study by Skovlin and Thomas (1995; 2001) compared photographs taken before 1925 with photos taken as recently as 1992 to interpret the changes within the ecosystems of the Blue Mountains, Oregon. One of the earliest examples in Africa is the work of Shantz and Turner (1958) who in 1956 re-photographed images taken by Shantz in 1919. This study produced a characteristic analysis of environmental change for the African continent and a baseline for further studies. Other work using repeat photography includes Yosemite National Park (Vale 1987), Madagascar (Kull 2005), Khumbu region of Nepal (Byers 1987), northern Pakistan (Nüsser 2000), Ethiopia (Nyssen et al. 2010; Nyssen et al. 2009), Kenya (Tiffen et al. 1994), Namibia (Rhode 1997; Rohde & Hoffman 2012), the eastern Karoo (Hoffman & Cowling 1990), and Kimberley regions in South Africa (Ward et al. 2012), and Namaqualand – the focus of this study (Hoffman & Rohde 2010; Hoffman & Todd 2010; Hoffman & Rohde 2011).

The advantages and disadvantages of repeat photography are outlined in Table 1.2. Since photography become widespread by the late 1800s, repeat photography studies are able to assess change over a longer time than aerial photography or satellite remote sensing (Kull 2005). The oblique perspective and larger scale of photography enables features to be easily recognised and understood by a wide range of audiences. It also allows for the detailed analysis of species composition. Repeat photography has however, been largely based on qualitative assessments and little progress has been made to quantify the spatial and temporal trends of vegetation change according to the photograph series. In addition, the historic photograph series are often separated by large periods of time and the field of view in ground photographs is usually oblique and covers little total area which limits its usefulness in determining change over a larger area. If pursued in conjunction with fieldwork or satellite-based remote sensing investigations, repeat photography is efficient in time and cost and can be useful in identifying trajectories of environmental change worthy of further investigation. Photographs can also provide information to help classify and validate land cover mapping products derived from satellite imagery (McClaran et al. 2010; de Mûelenaere et al. 2012) and to compare interpreted historical terrestrial photographs with observations from Landsat TM imagery (McClaran et al. 2010).

de Mûelenaere et al. (2012) successfully combined both Landsat TM imagery and historical repeat photographs taken to develop land-use and land cover maps for the Ethiopian highlands. They note that the use of repeat photography with remote sensing techniques is promising and requires further investigation. McClaran et al (2010) utilised Landsat TM imagery covering the same area as the repeat ground photography to estimate the amount of vegetation cover at the site. They state that one way to overcome the limitations of the repeat photographs, such as them having a narrow field of view, while maintaining their benefits, such as species level identification, is to combine them with aerial photography or satellite images. To date, these are the only two published papers that have utilised both methodologies. The study presented in this thesis attempts to address this gap.

<u>Table 1.2:</u> Advantages and limitations of repeat photography (Burton et al. 2011)

Advantages	Limitations
More accurate and longer lasting record of visible detail than observer's memory	May only detect changes large enough to see by eye from the camera position
Simple, quick, portable and inexpensive	Can measure qualitative change in object number and size but limited accuracy for quantification
Little technical skill needed	Comparisons between sites may be limited without additional data
Low impact on sampling area	May not provide any evidence of cause of change in the variable of interest
Potential to store electronically and link to site records	External effects, such as the season or light level, may make detection of changes of interest difficult
Useful supplement to narrative descriptions	Representation of objects may be biased by photographer
May provide information on change indicator in response to management change or major events	Changes in operators and technology/equipment used may affect results
Useful for physical and social phenomena	Changes in some phenomena require extreme precision, such as the consistent measurement of distance from camera to object
Can investigate changes in phenomena individually or as part of a larger whole	The field of view in the image is oblique making areal quantification difficult

1.3. Research objectives and questions

In the problem statement outlined in section 1.1, several gaps relating to the trajectory of vegetation change in the Succulent Karoo as well as the key drivers were introduced. Detecting and characterising vegetation change over time is the natural first step toward identifying the drivers of change and understanding the change mechanism. It is thus hypothesised that an understanding of the pattern and process of vegetation change in the recent past as well as the identification of the most important drivers of this change can help predict the character of future vegetation regimes under a range of climatic scenarios (Figure 1.3). Several future trajectories are possible, for example, an increase in temperature and more arid conditions could result in the vegetation cover of the Succulent Karoo being significant reduced by up to 40% (Rutherford et al. 1999) whereas less extreme changes in rainfall could result in the vegetation of the biome remaining fairly stable with possible increases in the spatial extent by 2050 (Driver et al.2012).

The study has two main emphases (Figure 1.4). Firstly, this study aimed to determine the critical pathways of inter-annual and intra-seasonal vegetation change in the Namaqualand region of the Succulent Karoo biome in South Africa. Secondly, the study aimed to investigate the role of land-use and climate variability as key drivers of vegetation change in Namaqualand. This research adds value to current and recent studies in the region.

By combining repeat photography (Hoffman & Rohde 2010) and satellite data from NOAA-AVHRR and TERRA-MODIS sensors as well as baseline climatology data from the CRU TS 3.2 data set, this study addresses four key research questions:

1. How has vegetation cover changed in Namaqualand over the last 25 years as determined from satellite imagery?
2. Do the patterns of vegetation change replicate the assessment of repeat photographs?
3. Can the trajectory of vegetation change be explained by recent changes in climate, specifically rainfall and temperature?
4. Can the trajectory of vegetation change be explained by changing land-use patterns?

This study is unique in that it utilises both repeat photography and remotely sensed vegetation indices in order to assess changes in vegetation productivity and seasonality in Namaqualand. Consequently, a key component of this research was to determine whether historical repeat photography can be successfully used in combination with the remotely sensed vegetation indices possibly serving as a means of validation.

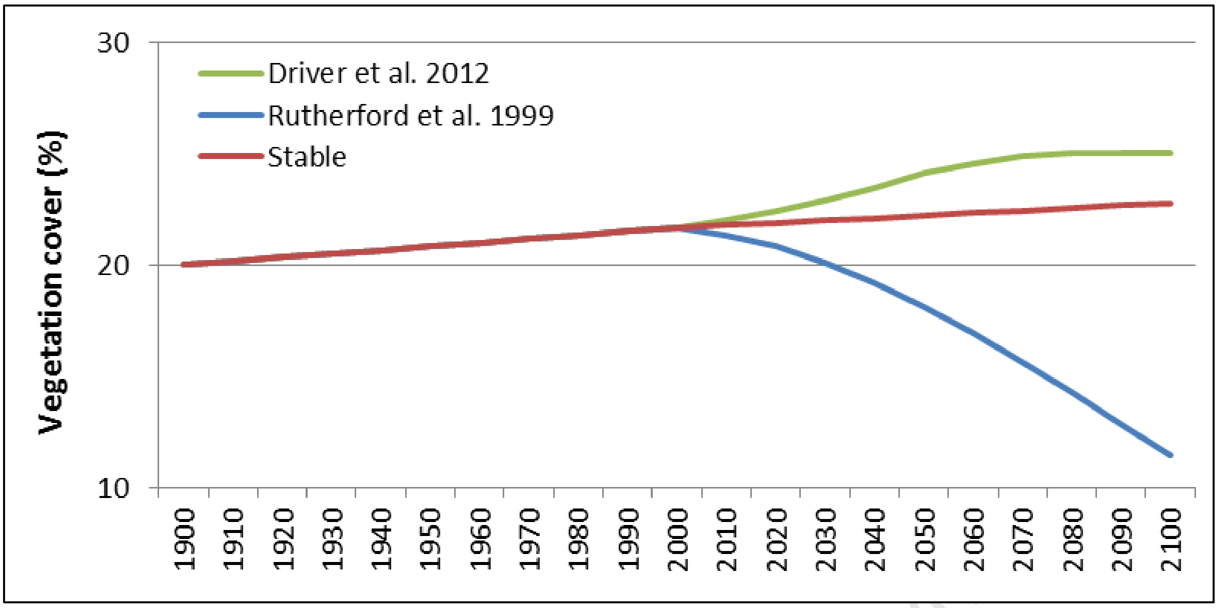


Figure 1.3: Theoretical framework of the critical pathways of future vegetation change in Namaqualand considering three possible scenarios (Rutherford et al. 1999; Driver et al. 2012). Current vegetation cover estimates are based on Anderson and Hoffman, Todd and Hoffman, and Samuels et al. (2009; 2007; 2007).

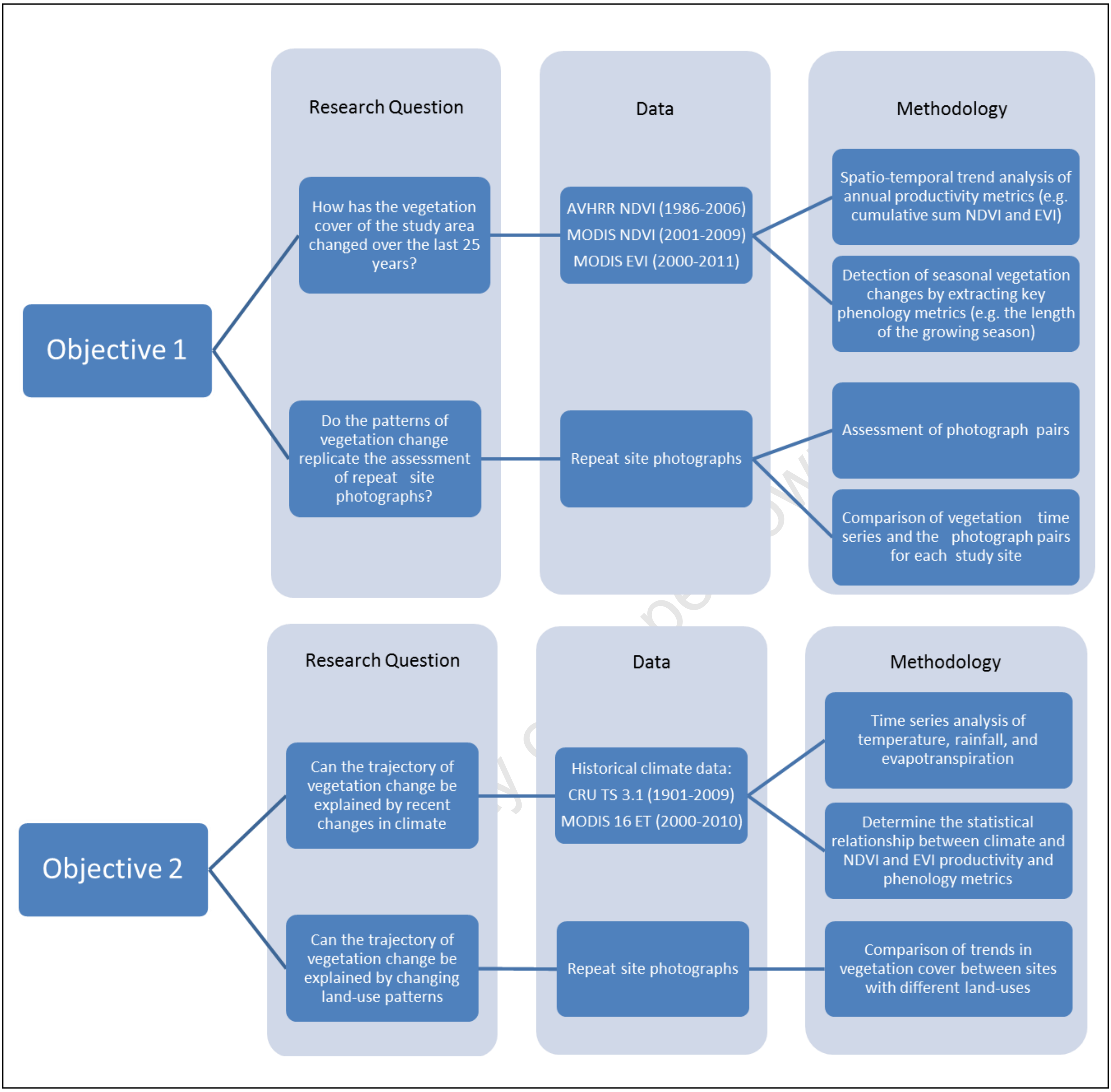


Figure 1.4: Conceptual flow chart of key research questions, data used and methodology employed in this study.

1.4. General approach and research design

The research was conducted on a landscape scale considering the semi-arid and arid winter rainfall region of Namaqualand, South Africa. Vegetation change was investigated at a relatively larger temporal and spatial extent, capturing large scale processes such as land use and climatic patterns. Figure 1.4 outlines the data used and the methodology employed in this study to address each research question.

Understanding the rate and extent of vegetation change in Namaqualand in response to land-use and climate changes, provides the necessary benchmarks against which future changes can be assessed. The first component of this research determined the extent, nature and rate of vegetation cover change in the region using two key approaches; remotely sensed vegetation indices and repeat photography. A comprehensive set of archival images taken since 1876 (Hoffman & Rohde 2010) was utilised in order to understand vegetation change in Namaqualand over long time scales from decades to centuries. Spatially-explicit time series analyses of remotely sensed vegetation indices and satellite-derived vegetation phenology were used to assess more recent changes in vegetation cover over the last 25 years. Vegetation cover change, defined here as changes in the vegetation indices (NDVI and EVI), is the most direct response of vegetation to climate changes and human activity (Zhao et al. 2012). The foundation for using vegetation indices in monitoring arid and semi-arid areas is based on a large body of research since the 1980's presented in the literature component of this chapter. The Normalised Difference Vegetation Index (NDVI) has been used as a proxy for vegetation productivity in numerous studies (for example Anyamba & Tucker 2005; Herrmann et al. 2005; Brown et al. 2010; Wessels et al. 2010; Eklundh et al. 2012; Vrieling et al. 2013).

A considerable amount of attention in this thesis was directed towards comparing the analysis of the remotely-sensed vegetation indices to the trends in vegetation derived from the repeat photography. There is a lack of long-term, scientific records for Namaqualand from which to verify remotely-sensed vegetation change and the option of utilising repeat photography is one such means which has been sufficiently investigated. Furthermore, a comparison of the outputs of these two approaches provides valuable information to determine spatial scale differences in vegetation change in Namaqualand.

Since vegetation production is directly correlated with the distribution of rainfall (Wessels et al., 2007) and responds to changes in land-use (Dahlberg, 1993), the second component of this study investigated recent trends in climate and land-use and related these patterns of change to the observed changes in vegetation productivity derived from the remotely-sensed time series. Historical climate data for Namaqualand was analysed to determine inter-annual variability and long-term trends. The relationship between climate and vegetation indices was statistically tested in order to assess the role of climate in driving recent changes in vegetation cover across the study area. Changes in land-use were inferred from the repeat site photographs and validated with the use of land cover and land tenure maps for the region. The link between rainfall, land use and vegetation change is important. For example, a higher frequency of drier spells or a lower critical rainfall season can affect vegetation cover with implications for both erosion processes and extensive livestock production (Archer & Tadross 2009).

This study is unique in the sense that it combines remotely sensed data with repeat site photography. Few international studies have utilised repeat photography in conjunction with detailed analysis of satellite imagery to provide a more robust measure of landscape change (de Mûelenaere et al. 2010; 2012; McClaren et al. 2000). The study presented here is the first of its kind to do so in Namaqualand as well as South Africa. There have been a few ground-based studies that have investigated long-term vegetation change in the Succulent Karoo biome (for example Rahlao et al. 2008) and a few that have investigated the phenology patterns (for example, Van Rooyen et al. 1979). A study by Fox et al. (2005) utilised the AVHRR NDVI time series to produce an overall description of the vegetation patterns of the Namaqualand region. The study presented here is the first of its kind to investigate recent changes in both vegetation productivity and phenology at a landscape scale in Namaqualand using remotely sensed vegetation indices.

It is hoped that this study will provide a baseline or reference for which future change can be assessed and that the approach taken in this study can guide future studies on the vegetation dynamics in Namaqualand. Understanding vegetation dynamics in the region and the processes that drive them is critical for effectively predicting the future trajectory of vegetation change, the development of long-term land management plans and the improvement of strategic adaptation responses to climate change.

1.5. Thesis outline

This thesis has been divided into eight chapters in order to describe the recent trends in vegetation productivity for Namaqualand and its drivers. Chapter (1) contextualizes the study and provides the general background and the study aims and research questions. Chapter (2) introduces Namaqualand, the study area, by describing its physical environment. Chapters' three to seven address the research questions of the study. Chapter (3) utilises climate data from CRU TS 3.1 dataset from 1901 to 2009 to investigate trends in local temperature and rainfall. Chapter (4) assesses the repeat photographs for each study site and provides information on the extent of vegetation change within different land tenure systems and for different land-use practises. Chapter (5) investigates the inter-annual trends in NDVI and EVI for the study area over the last 25 years and Chapter (6) investigates the seasonal changes in NDVI and EVI. The relationship between annual and seasonal productivity metrics and climate is statistically described in Chapters (5) and (6). Climate and land-use drivers are discussed in conjunction with trends in vegetation productivity investigated in Chapter (5) and (6). In Chapter (7) the observed trends in annual and seasonal vegetation productivity derived from the remotely sensed vegetation indices are compared with the assessment of repeat photographs for each study site. The final chapter (8) provides a brief synthesis highlighting the key findings of the study and gives some recommendations for future studies.

Chapter 2: Biophysical description of the study area

2.1. Introduction

The focus region of this study was determined by the locations of repeat photography sites (Hoffman & Rohde 2010; Hoffman & Rohde 2007; refer to Table A.1 and Figure A.1 in Appendix A) in Namaqualand, South Africa (Figure 2.1). Namaqualand forms part of the winter-rainfall region of the Succulent Karoo biome which is recognized internationally as one of only two biodiversity hotspots located within a desert environment (Myers et al. 2000; Van Jaarsveld 1987). Namaqualand extends from the Orange River in the north to Vanrhynsdorp and the Olifants River in the south (Desmet 2007; Cowling & Hilton-Taylor 1999). It is located west and south of the escarpment, 200–300 km inland of the west coast and covers a region of approximately 50 000 km^2 (Cowling et al. 1999), (Figure 2.1).

Namaqualand hosts approximately 3 500 species with about 25% of this flora being endemic to the region (Desmet 2007) and is well known for its flower displays in spring. One of the main reasons for this exceptional diversity is the relatively predictable annual rainfall amounts and moderate temperature regime throughout the year (Cowling et al. 1999). Agriculture, mainly livestock production, is the primary land use in Namaqualand and is practiced on both commercial and communal farmlands (Rohde et al. 2001).

The physical environment of Namaqualand has been described by numerous published sources from comprehensive regional scale reviews (Cowling et al. 1999; Desmet 2007; Driver & Maze 2002; Jürgens 1991; Cowling & Pierce 1999; Desmet & Cowling 1999) to fine scale, local studies (for example Allsopp et al. 2007; Shiponeni et al. 2011). In this chapter the study area is described in terms of topography, geology and soils, climate, land use, and vegetation.

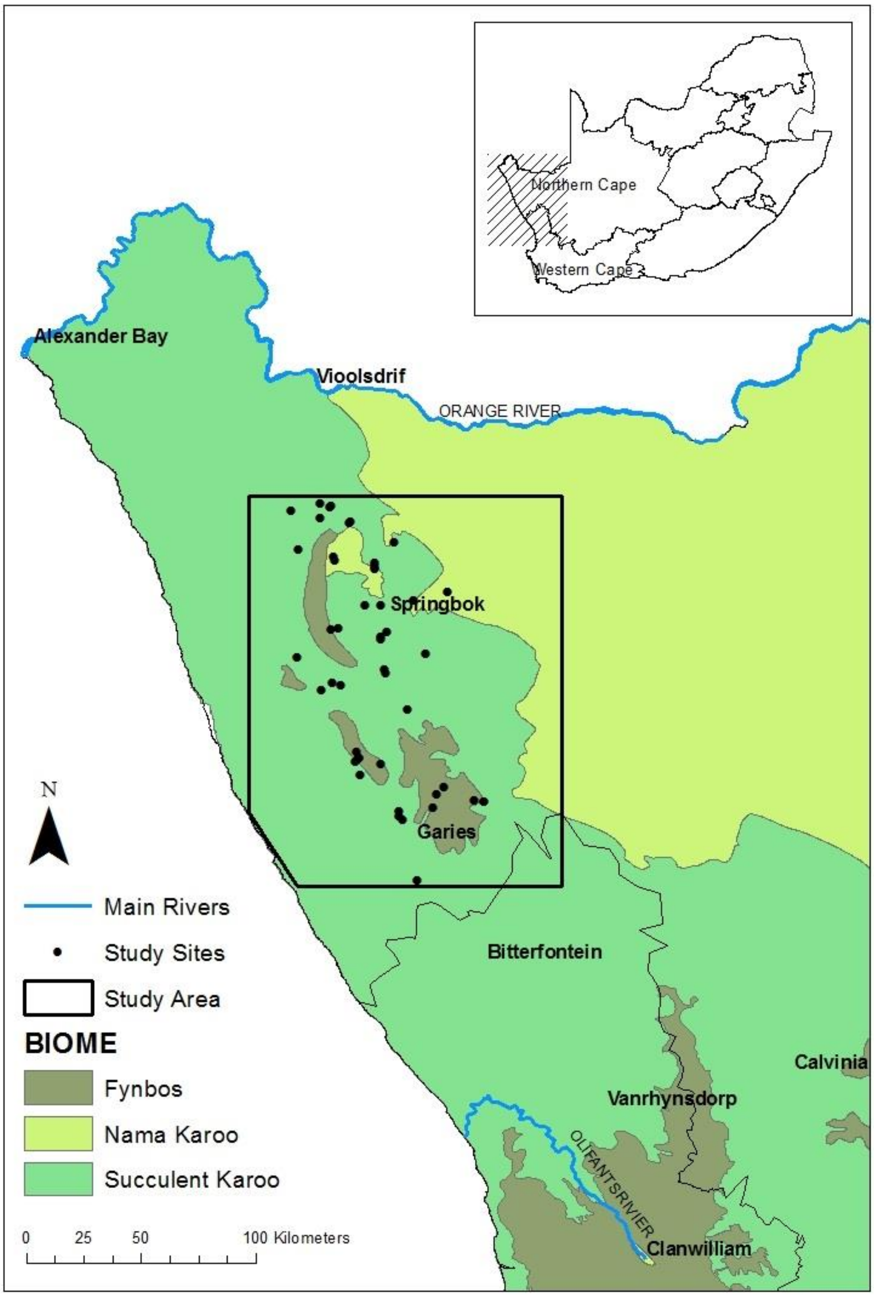


Figure 2.1: Map of Namaqualand with the boundaries of the Fynbos, Nama Karoo and Succulent Biomes (Mucina & Rutherford 2006). For this study Namaqualand has been defined as the area between the Orange River in the north and Olifants River in the south (Cowling et al. 1999). The location of the study area (black square) and the repeat photography sites (black dots) are shown as is the provincial boundary between the Western Cape in the south and the Northern Cape in the north.

2.2. Topography

The topography of Namaqualand is characterised by a relatively wide, gently undulating sandy coastal plain along the Atlantic coast grading up to the central granite massifs of the Kamiesberg Mountains where peaks reach 1 700 meters above sea level (Figure 2.2). The Kamiesberg Mountains run in a roughly north-south direction and are surrounded by a region of variously metamorphosed granite gneisses creating a landscape of rolling dome-shaped hills separated by sandy alluvial valleys. These valleys are dotted with heuweltjies, which are large termite-derived mounds (Desmet 2007). To the north of the Kamiesberg lies the Richtersveld Mountains and inland of the Kamiesberg are the wide-open Bushmanland plains occupying the high interior plateau (Figure 2.2).

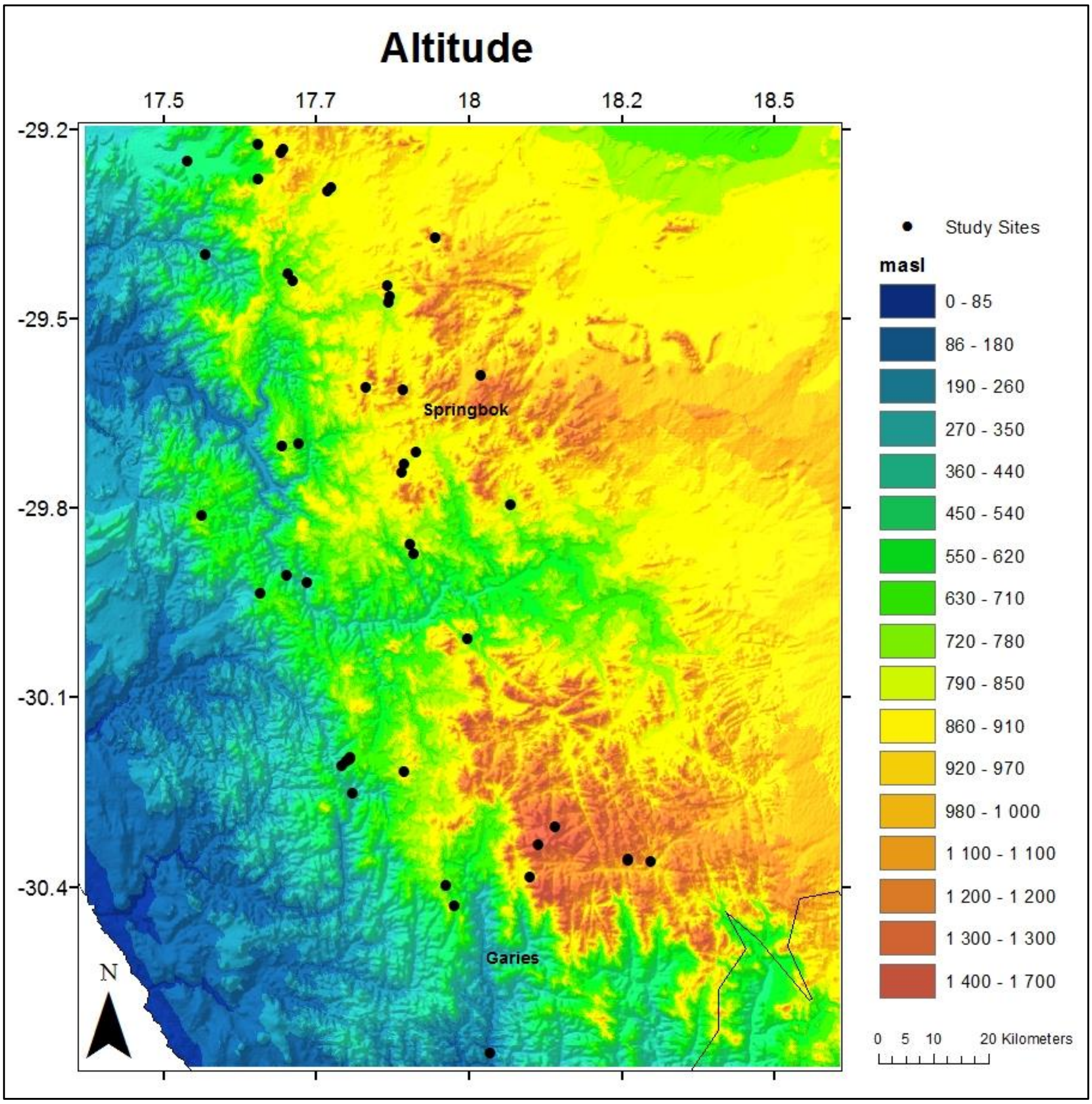


Figure 2.2: Digital Elevation Model (DEM, SRTM version 4, 250m) highlighting the topography of the study area. The repeat photography sites are indicated by the black dots and altitude is measured as metres above sea level (masl).

2.3. Geology and Soils

The stratigraphy and lithology of Namaqualand is complex (Cowling et al. 1999) and a more detailed discussion may be found in Watkeys (1999) and Meadows and Watkeys (1999). Along the west coast, Quaternary and Tertiary deposits are found which consist mainly of marine and windblown sands ranging from weathered to fine-grained deposits. Towards the interior the geology is made up by the Nama sequence, Namaqualand complex and Namaqualand Metamorphic Province. Rock types of the Nama sequence include sandstone, mudstone and limestone. The Namaqualand complex consists of metamorphic sedimentary rocks that are a product of intense folding and shearing along the southern and western edges of the Karoo (Meadows & Watkeys 1999). Hardpans of various siliceous and calcitic composition and metamorphosed rocks of the Namaqualand Metamorphic Province underlies most of the region. The granite and gneiss of the Namaqualand Metamorphic complex decay to form nutrient rich soils (Watkeys 1999).

The lack of moisture in Namaqualand results in less weathering and leaching giving rise to coarse, weakly developed soils that have little organic matter (Watkeys 1999). Weathering is limited to mechanical processes where thermal expansion breaks down parent material. Slow soil formation leads to coarse shallow soils with sharp boundaries between soil types. These arid soils are sensitive to soil degradation (Watkeys 1999).

The most common soils contain a predominantly sandy A horizon and are red and yellow in colour. Soils along the coast are mainly grey medium-grained sands derived from aeolian reworking of marine or fluvial deposits. Moving inland red, base rich soils derived from both coastal and inland sources predominate (Watkeys 1999; Desmet 2007). The escarpment zone and higher mountains of the Kamiesberg and Richtersveld are characterised by red to yellow shallow sands and sandy loams soils formed from in situ weathering of parent material. Soils have a high base status with neutral to high pH levels (Milton et al. 1997). The soils are free from waterlogging and in the west soils typically have less than 6% clay whereas in the east soils have between 6 and 15% clay (Watkeys 1999).

2.4. Climate

Namaqualand is classed as a semi-arid winter rainfall region with the majority of the area receiving less than 150 mm per annum (Figure 2.3a). The climate is determined primarily by the southern subtropical high pressure system and the circumpolar westerly airstream (Tyson & Preston-Whyte 2000). Geographic features, such as the mountains of the escarpment and the cold Benguela current, influence local scale climate.

More than 60% of the rainfall occurs during the winter months between May and September (Figure 2.3c) as a result of the cold, westerly fronts from the southern oceans (Tyson & Preston-Whyte 2000). Mean annual precipitation ranges from 50 mm in the north-west to 400 mm per annum in the Kamiesberg (Figure 2.3a). Peak rainfall amounts occur over the Kamiesberg Mountains as a result of the orographic effect (Kelso & Vogel 2007). Coastal lows are also common in winter. Compared to other winter rainfall deserts, mean annual precipitation is relatively predictable and reliable (Desmet 2007; Hoffman & Cowling 1987) and is expressed by low (less than 40%) coefficients of variation (CV) in Figure 2.3b. The diversity of life-forms and life-history strategies in Namaqualand can be attributed to these low but reliable rainfall patterns (Desmet & Cowling 1999). Rainfall is supplemented by heavy dewfalls experienced during mid-winter (July-August) and advective coastal fog experienced during the summer months. Fog is generated by the cold Benguela current of the Atlantic Ocean and occurs primarily along the coastal region for about 75 days of the year (Desmet & Cowling 1999).

Namaqualand is prone to droughts, which usually span a few successive years (Hoffman et al. 2009; Kelso & Vogel 2007). Recent evidence suggests that El Nino Southern Oscillation (ENSO) modulates rainfall in the region with El Nino (La Nina) years being associated with higher (lower) than normal rainfall amounts in May, June and July (Philippon et al. 2011). During ENSO events the rain-bearing systems are larger in extent and are located further north while during La Nina Southern Oscillation (LNSO) events they are smaller and located further south (Philippon et al. 2011).

Annual average temperatures for the study area are relatively mild throughout the year and range from 13°C to 21°C (Figure 2.4a) owing to the cold Benguela Current off the west coast of Namaqualand (Desmet 2007). Mean annual temperatures are highest inland of the west coast increasing northwards while the escarpment and high lying areas experience cooler temperatures (Figure 2.4a). Maximum temperatures only exceed 30°C when berg winds are blowing off the plateau to the west (Figure 2.4b). For the study area the average temperatures for January (summer) and July (winter) are 23°C and 13°C respectively (Figure 2.4c). With the exception of the coastal belt, the region experiences a large annual and diurnal range in temperatures (Kelso & Vogel 2007). Occasional frosts occur in the high lying areas of the escarpment and central plateau (Cowling et al. 1999).

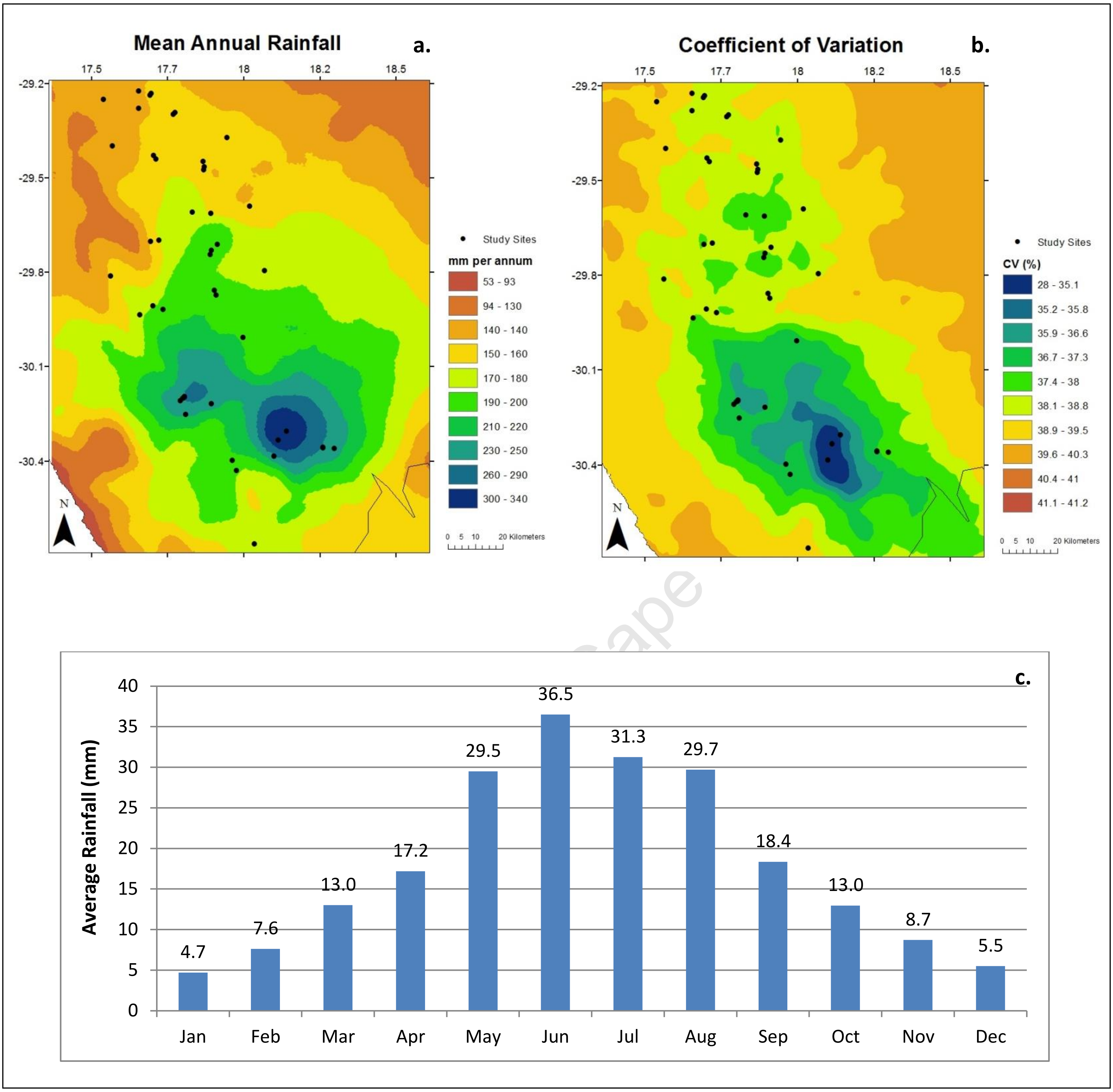


Figure 2.3: (a) mean annual rainfall, (b) coefficient of variation of mean annual rainfall for the study area (data source: Schulze 2008), and (c) median monthly rainfall for the Springbok weather station (data source: South African Weather Service). The repeat photography sites are indicated by the black dots in (a) and (b).

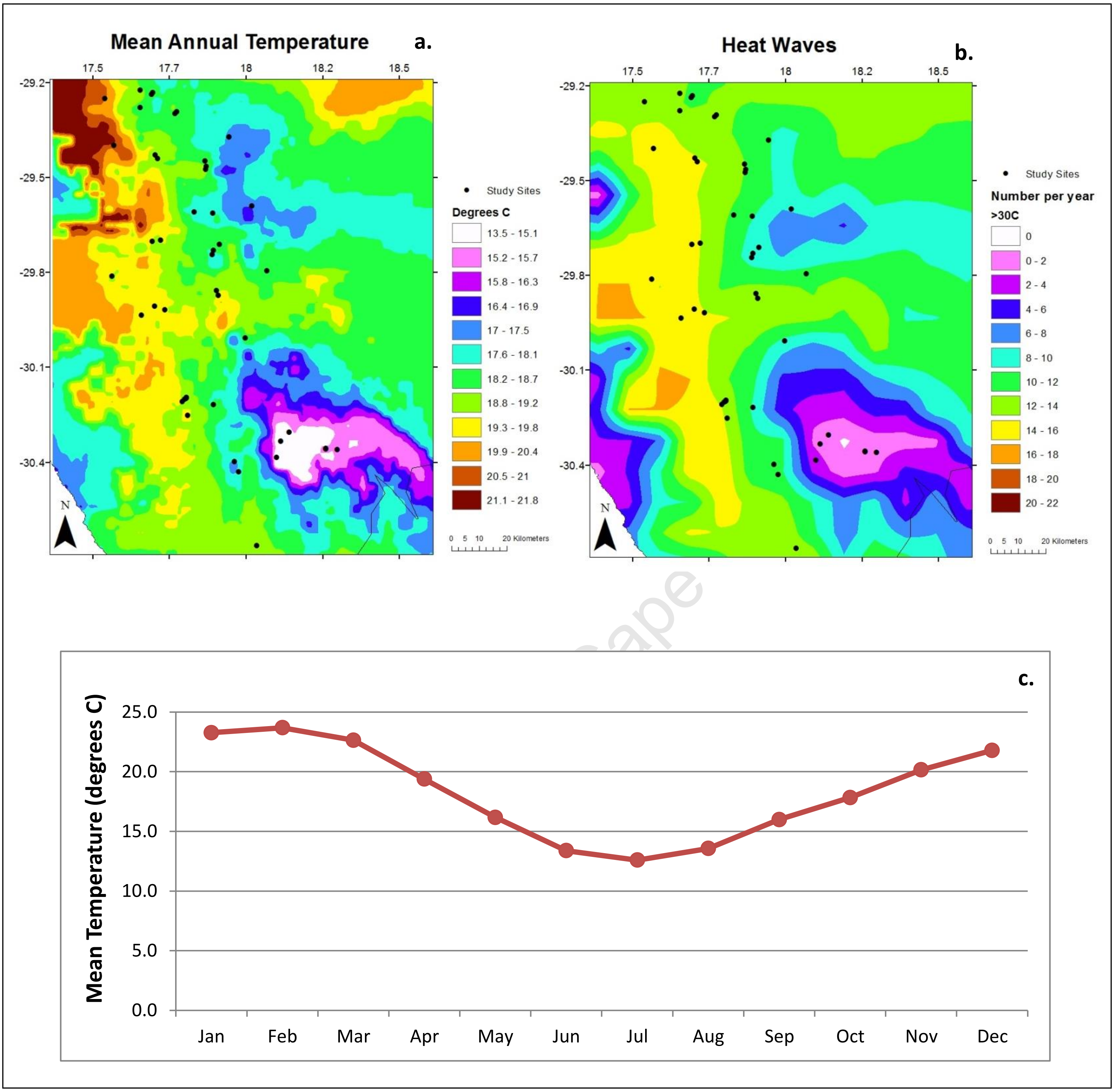


Figure 2.4: (a) mean annual temperature, (b) heat waves per year measured as the frequency of 3 or more days with maximum temperature greater than 30°C and (c) mean monthly temperature in the study area (data source: Schulze 2008). The repeat photography sites are indicated by the black dots in (a) and (b).

2.5. Land-Use

A detailed review of the land-use patterns and trends in Namaqualand can be found in Chapter 1 and a more comprehensive review of the history of land-use in the region can be found in Cousins et al. (2007) and Benjaminsen et al. (2006). This section provides an overview of the current land-use practises in the region.

The predominant land use in Namaqualand is small stock (sheep and goats) farming (Figure 2.5). The grazing capacity of the study area is closely related to mean annual rainfall (Todd & Hoffman 2000) where high rainfall areas are associated with a lower grazing capacity. Due to the aridity of the area, cultivation is not widespread and is predominantly associated with the higher rainfall areas of the Kamiesberg (Figure 2.5). There are two main agricultural production systems in Namaqualand which correspond to the communal and commercial tenure systems (Hoffman et al. 1999). There are four communal areas in the study area (Leliefontein, Concordia, Steinkopf and Kommaggas) which cover approximately 37% of the region (Figure 2.6). The largest part of the land in the study area belongs to private landowners (Figure 2.6).

Despite Namaqualand being a global conservation priority, the formal conservation status of the region is poor with only 3% currently being conserved (Desmet 2007). The Namaqua National Park and the Goegap Nature Reserve are located within the study area (Figure 2.6). Game farming is a relatively new land-use in the area with hunting and venison being the main income for these farms (SKEP, 2002). Mining for diamonds, gypsum, granite and heavy minerals occupy 10% of the region (Figure 2.5 and Figure 2.6).

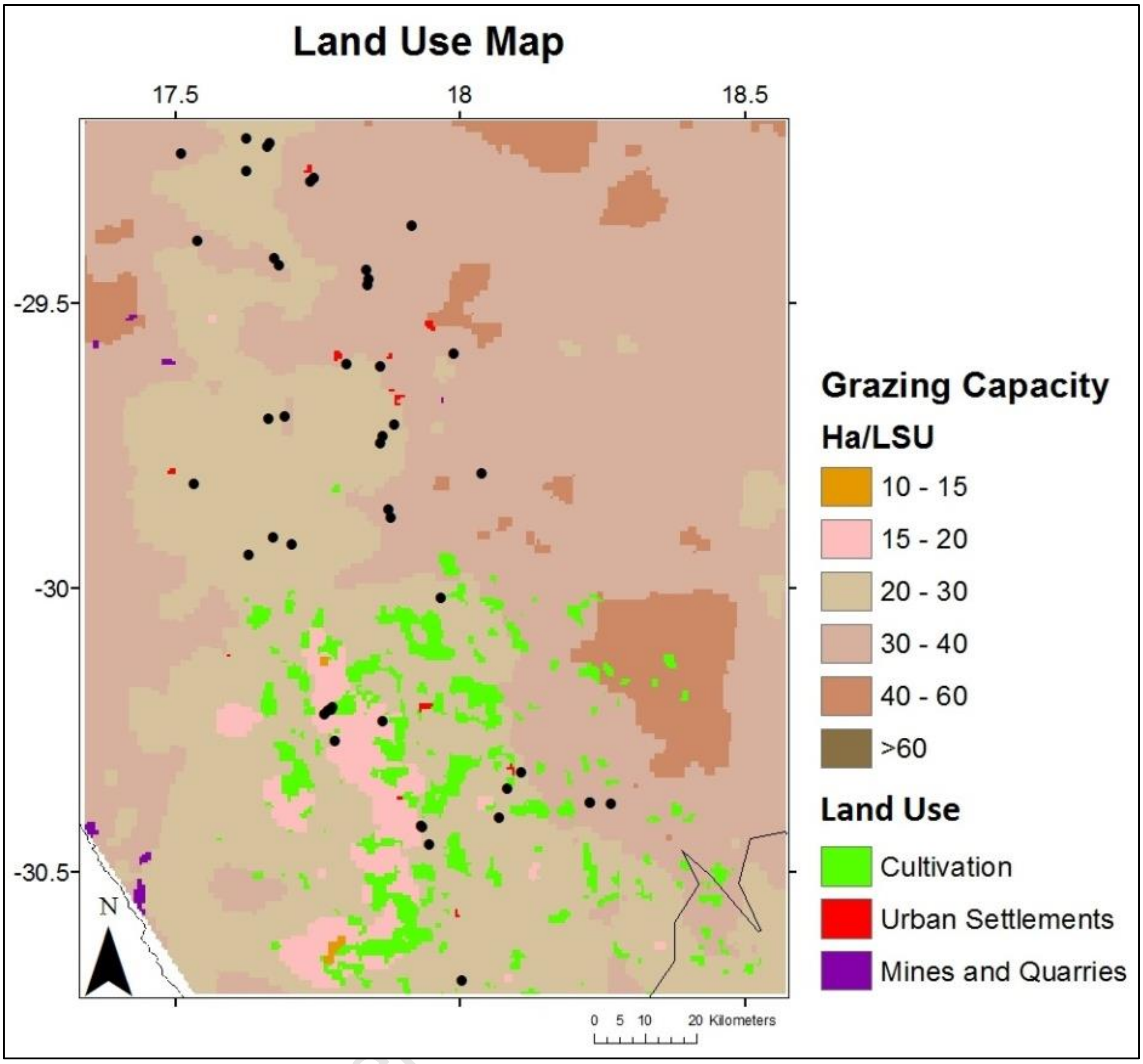


Figure 2.5: Broad land use map of the study area displaying areas used for livestock grazing (expressed as hectares per large stock unit, data source: ARC), cultivation, urban settlements, and mining (data source: National Land Cover Map 2009). The repeat photography sites are indicated by black dots.

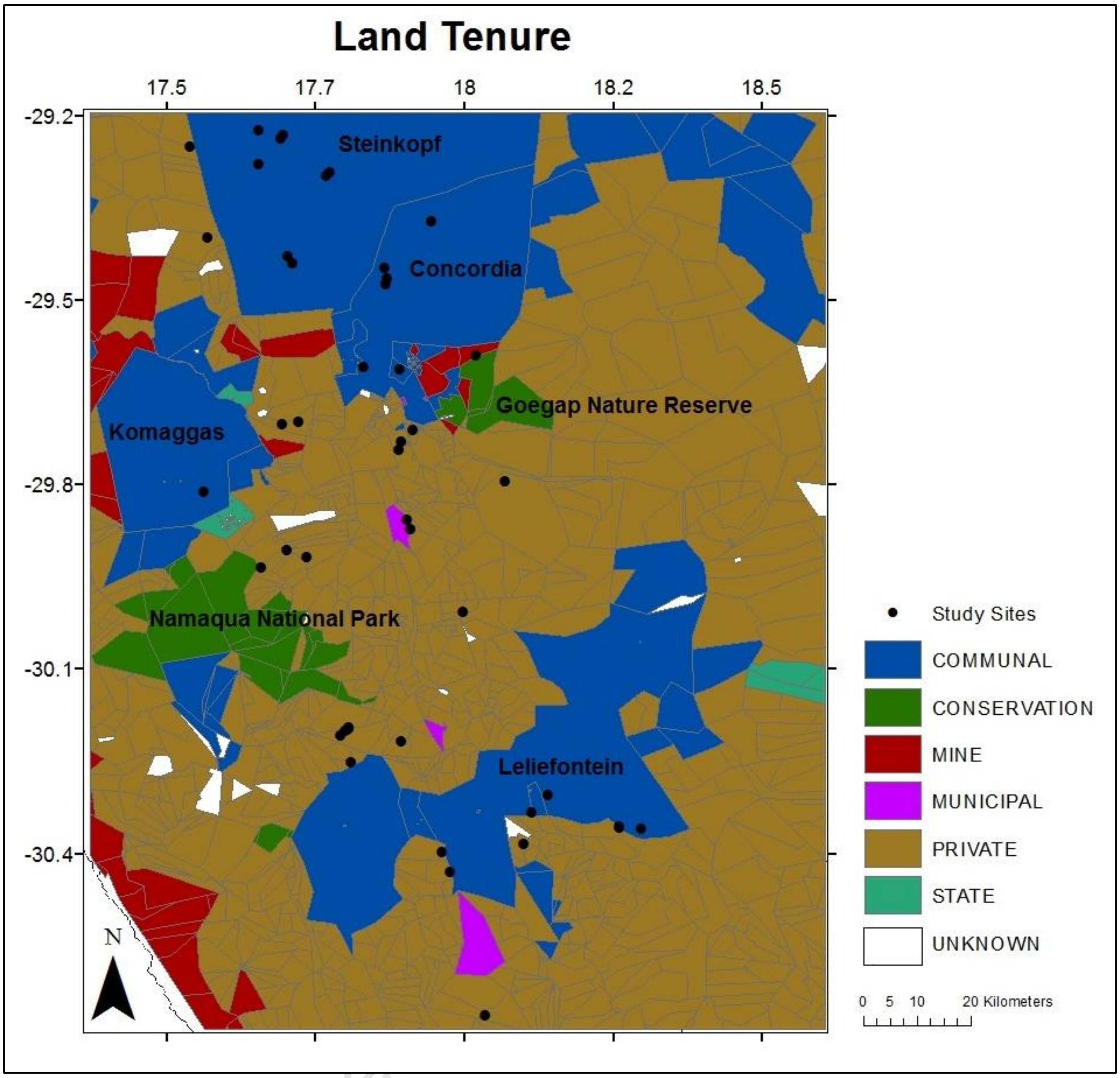


Figure 2.6: Land tenure map of the study area. Communal areas incorporate former Act 9 areas as well as land recently purchased as part of the national land reform programme (data source: Northern Cape Cadastral Data 2003). The repeat photography sites are indicated by black dots.

2.6. Vegetation types

Acocks (1953) produced one of the earliest maps defining veld types for the region. This was followed by Low and Rebelo (1996) who produced a new assessment for the area, as part of a new vegetation map for southern Africa. The recently revised South African vegetation map by Mucina and Rutherford (2006) offers the most detailed description of the vegetation types in Namaqualand (Figure 2.7). The study area encompasses a diverse range of vegetation types (Figure 2.7) which vary in association with the topographic and orographic gradients associated with the Kamiesberg Mountains. A comprehensive description of each vegetation type can be found in Mucina and Rutherford (2006). The dominant vegetation types in the study area include:

- Namaqualand Klipkoppe Shrubland which is characterised by a mix of succulent and woody shrubs and occurs in association with the rocky hills and domes separated by sandy pediments;
- Namaqualand Granite Renosterveld, located on the rocky upland areas is characterised by large stands of the woody shrub *Elytropappus rhinocerotis* and the grass species *Merxmuellera stricta*;
- Namaqualand Blomveld located on the low-lying areas; and
- Bushmanland arid grassland which signifies a shift from the winter rainfall region of the Succulent Karoo biome to the summer rainfall region of the Nama-karoo biome (Mucina and Rutherford 2006).

The highly predictable, low winter rainfall and moderate temperature regime have favoured leaf succulence with the Crassulacean Acid Metabolism (CAM) photosynthetic pathway and shallow root systems (Milton et al. 1997; Esler et al. 1999). The growing season extends through the wet winter months. The unique flora of the region can be described as shrubland dominated by leaf-succulents or deciduous-leafed woody perennial shrubs or dwarf shrubs (Desmet 2007). The succulent floras are characterized by a preponderance of plants particularly in the families Aizoaceae (Mesembryanthemaceae), Asteraceae, Crassulaceae, and Euphorbiaceae (Desmet 2007). Annual and geophyte species, which form the dominant component of the spring mass floral displays, are also abundant in Namaqualand. In large portions of the communal areas the unpalatable shrub *Galenia africana* has become dominant due to disturbance and overgrazing (Todd & Hoffman 2009; Todd & Hoffman 1999; Anderson & Hoffman 2007). Tall shrubs, trees and grasses are relatively rare in Namaqualand (Milton et al. 1997). There are relatively few invasive plant species in Namaqualand and in the Succulent Karoo biome in general (Rouget et al. 2004). The most prominent invaders include *Nicotiana glauca, Acacia cyclops* and *Prosopis* species (Henderson 2007).

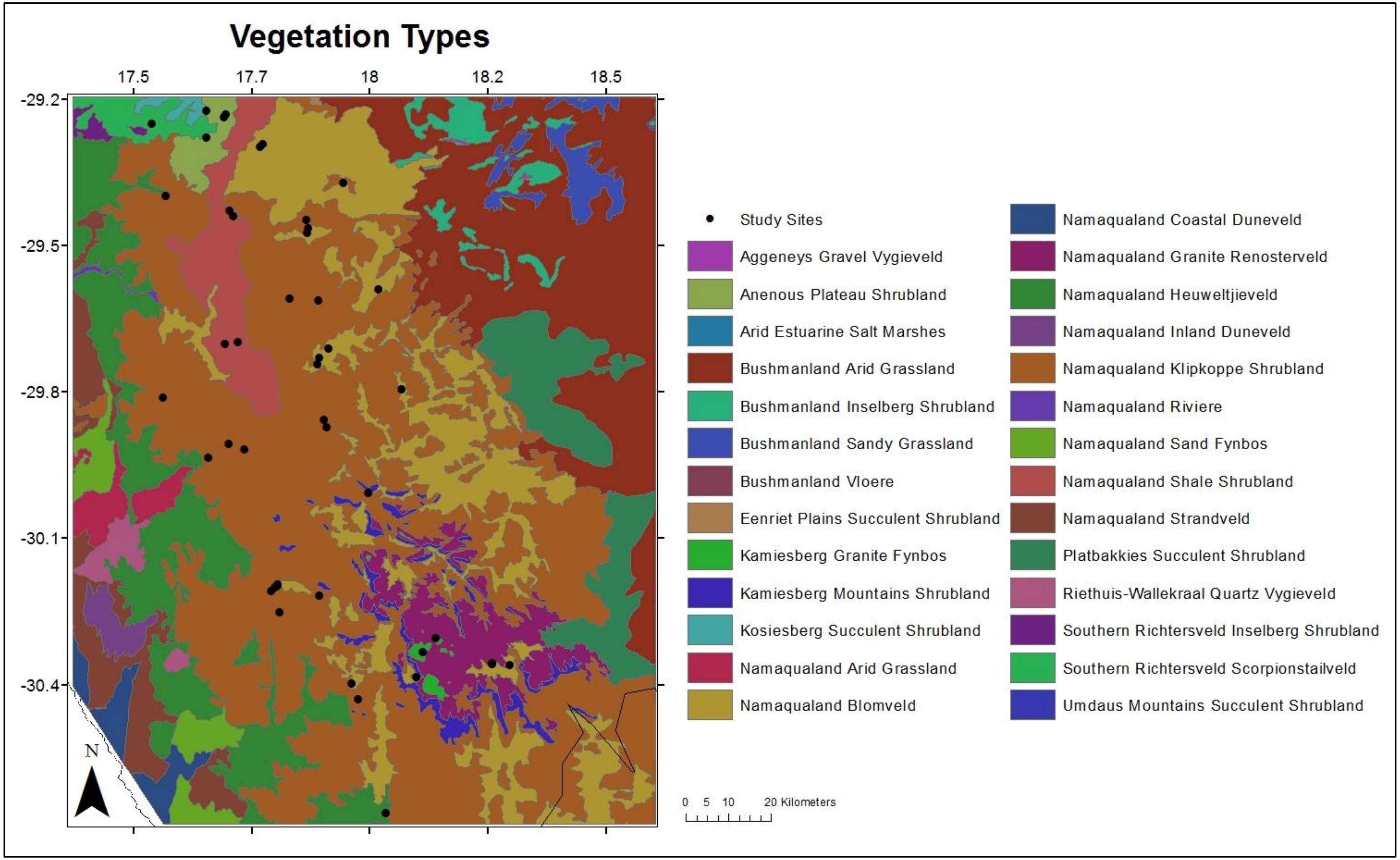


Figure 2.7: Vegetation types present in the study area (Mucina & Rutherford 2006). The repeat photography sites are indicated by the black dots.

Chapter 3: Observed trends in Namaqualand's climate

3.1. Introduction

One of the best ways of understanding how climate may change in future is to examine how it has changed in the past. While it is certainly possible that climate may change in ways not yet observed, reconstructions of past climatic fluctuations and evidence of more recent changes, based on available observational records, provide a good first indication of the direction and magnitude of possible future changes. This is particularly true of observational records in the form of weather station data which cover the most recent past (MacKellar et al. 2007). There are numerous regional studies of recent trends in temperature, rainfall and extreme weather events over Africa and southern Africa (Mason & Jury 1997; Mason et al. 1999; Hulme et al. 2001; Fauchereau et al. 2003; Kruger & Shongwe 2004; New et al. 2006; Haensler et al. 2010) but only 3 studies have focused explicitly on the recent climate changes of the Namaqualand region (MacKellar et al. 2007; Hoffman et al. 2009; Kelso & Vogel 2007). Various palaeoclimate studies in the winter rainfall zone of South Africa (Chase & Meadows 2007; Benito et al. 2011a; Benito et al. 2011b; Weldeab et al. 2013) have also contributed to the understanding of the long-term changes in climate in the region.

Detecting recent regional and local climate trends is considerably more difficult than doing so for global climate (Christensen et al. 2007). This is mainly due to the lack of an accurate, long-term, well-maintained and dense spatial network of observational stations to detect regional climate signals. This is particularly evident in Namaqualand where weather stations are sparsely distributed. Since each station represents only a single point, they may not be adequately representative of the surrounding region (MacKellar et al. 2007). Gridded climate data sets developed by interpolating weather station records help overcome this by approximating the true spatial and temporal variability of key climate variables (Hewitson & Crane 2005; Mitchell & Jones 2005; New et al. 2002). As discussed in more detail below, this chapter makes use of one such product in order to investigate the presence of climate trends over the last century.

Observed changes in the climate of the study area are presented in this chapter. The focus is on temperature and rainfall over the last century and evapotranspiration over the last decade. This chapter provides the necessary information to begin to answer the first research question of objective two: can the trajectory of vegetation change be explained by recent changes in climate?

3.2. Methodology

3.2.1. Data sources

Climate

Weather station data provided by the Climate Systems Analysis Group at the University of Cape Town (www.csag.uct.ac.za) and a high-resolution (0.5°x0.5°) gridded dataset provided by the Climatic Research Unit of the University of East Anglia (CRU TS 3.1) were used as sources of monthly temperature and precipitation data. When comparing these two datasets it was found that the local weather station dataset did not have the spatial and temporal resolution required for this study. There are only a limited number of long-term climate observations in South Africa and in Namaqualand. The Springbok weather station covers a relatively long period (1878-2002) but it is the only weather station located within the study area and is thus not fully representative of the full range of temperature and rainfall values experienced over the region. The gridded data, on the other hand, covers the entire study area and spans the required time-frame (1901-2009). The data has also been validated, better documented and homogenised and has been used previously to study trends in African climate (Hulme et al. 2001). A full review of the dataset can be found in Mitchell and Jones (2005). Gridded datasets are however, not as precise in some regions as others owing to a small numbers of weather stations included in the calculation of the gridded data and/or to the short period of some records.

In order to ensure that the CRU TS 3.1 dataset depicts the correct distribution and amounts of precipitation and temperature for the studied region, the gridded data set was compared to a local precipitation and temperature time series from the Springbok weather station. The correlation coefficients were statistically significant and high enough to confirm the similarity of the two datasets; 0.77 for rainfall, 0.7 for maximum temperature and 0.6 for minimum temperature. It is not recommended to use the CRU dataset to represent climate at a point (Mitchell & Jones 2005). Thus a regional trend analysis of temperature and precipitation was conducted and data was extracted for the study area as a whole rather than for each individual study site.

Evapotranspiration

In order to provide a more detailed understanding of changes in water availability, trends in evapotranspiration were also analysed. A direct measurement of evapotranspiration was not carried out in this study, but was derived from Moderate Resolution Imaging Spectroradiometer (MODIS) on-board NASA's Terra and Aqua satellites. The 8 day MOD16 Global Terrestrial Evapotranspiration dataset (MOD 16 ET)[1], has a 1 km^2 spatial resolution and covers the time period 2000 to 2010. The MOD16 Evapotranspiration datasets are

[1] (http://www.ntsg.umt.edu/project/mod16)

estimated using the improved evapotranspiration algorithm outlined in Mu et al. (2011) which is based on the Penman-Monteith equation (Monteith 1965).

3.2.2. Analysis of historical climate data

Figure 3.1 outlines the approach taken to determine and analyse the climatic trends for the study area based on the CRU TS 3.1 (1901-2009) and MODIS MOD16 ET (2000-2010) datasets. Trends in extreme climate were not investigated due to daily climate data not being available at the appropriate scale for this study. A time series of temperature and rainfall was extracted from the CRU dataset for the whole study area and a linear regression was performed to determine the presence of trends and the significance of those trends. Trends in each climatic variable were investigated at both an annual and seasonal time scale. Trends from 1960 to 2009 were investigated since this more closely matches the time period of the earth observational data utilised in Chapter 5 and Chapter 6. In addition, a piecewise regression analysis (Ryan & Porth, 2002), also referred to as a segmented regression, was performed on the temperature and humidity data. The slope of the linear regression line assumes that the trend is occurring at a constant rate since the beginning of the analysis period (Mason, 1996) whereas piecewise regression identifies when a change (termed the break-point) in climate has begun (Ryan & Porth, 2002).

To describe inter-annual temperature variability, annual minimum and maximum temperature anomalies (temperature in year *t* minus the long-term mean annual temperature) were calculated. The World Meteorological Organisation (WMO) recommends that the long-term climatology average should be calculated from a 30 year period based on the decades 1960-1990 (Hulme 1992; Houghton et al. 2001).

Rainfall variability is examined through the anomaly of the coefficient of variation (Jurkovic & Pasaric 2012). The standardized precipitation index (SPI) (McKee et al. 1993) was used to detect drought periods and wet periods. SPI is based on the probability of precipitation for a given time period and is widely used to detect short-term droughts. The SPI index ranges between -3 (extremely dry) and 3 (extremely wet) and the more the index value departs from zero, the drier or wetter an event lasting six months (for 6 month SPI) is when compared to the long-term climatology. A drought is defined whenever the SPI reaches a value of –1.00 and continues until the SPI becomes positive again. In low rainfall areas SPI values for short time periods (1 - 3 month) can be misleading (Prudhomme & Farquharson 2003) and as such 6 and 12 month SPI values were calculated for the study area in order to capture both short-term and long-term drought.

Interannual trends for evapotranspiration were assessed spatially using the Earth Trend Modeler in Idrisi Taiga (Eastman 2009). The Earth Trend Modeler provides tools, which are unaffected by the presence of outliers, to determine the presence of linear and non-linear trends as well as their significance (Eastman 2009). The statistical techniques use area, length, proximity, orientation and spatial relationships in their mathematics and thus provide more information than traditional (non-spatial) techniques (Fischer & Getis 2009). The non-parametric Mann-Kendall statistic (Kendall 1938) was used, which makes no assumptions about the distribution of the data or the linearity of any trends (Hollander & Wolfe 1973). This is a non-linear trend indicator that measures the degree to which a trend is consistently increasing or decreasing. Kendall's correlation coefficient ranges from -1 to +1 where a value of +1 indicates a trend that consistently increases and never decreases and the opposite is true of a value of -1. A value of 0 indicates no consistent trend (Eastman 2009). Since Kendall's statistic does not give an indication of the magnitude of trend, linear trends were calculated using the median trend (Theil-Sen) method. This is a robust non-parametric trend operator which determines the slope between every pairwise combination and the median slope value (Eastman 2009). The result is a spatially-explicit expression of the rate of change per year in evapotranspiration where pixels with significant negative (positive) slopes indicate areas that have experienced a decline (increase). A significance image of the observed trends, expressed as p-values, was also produced.

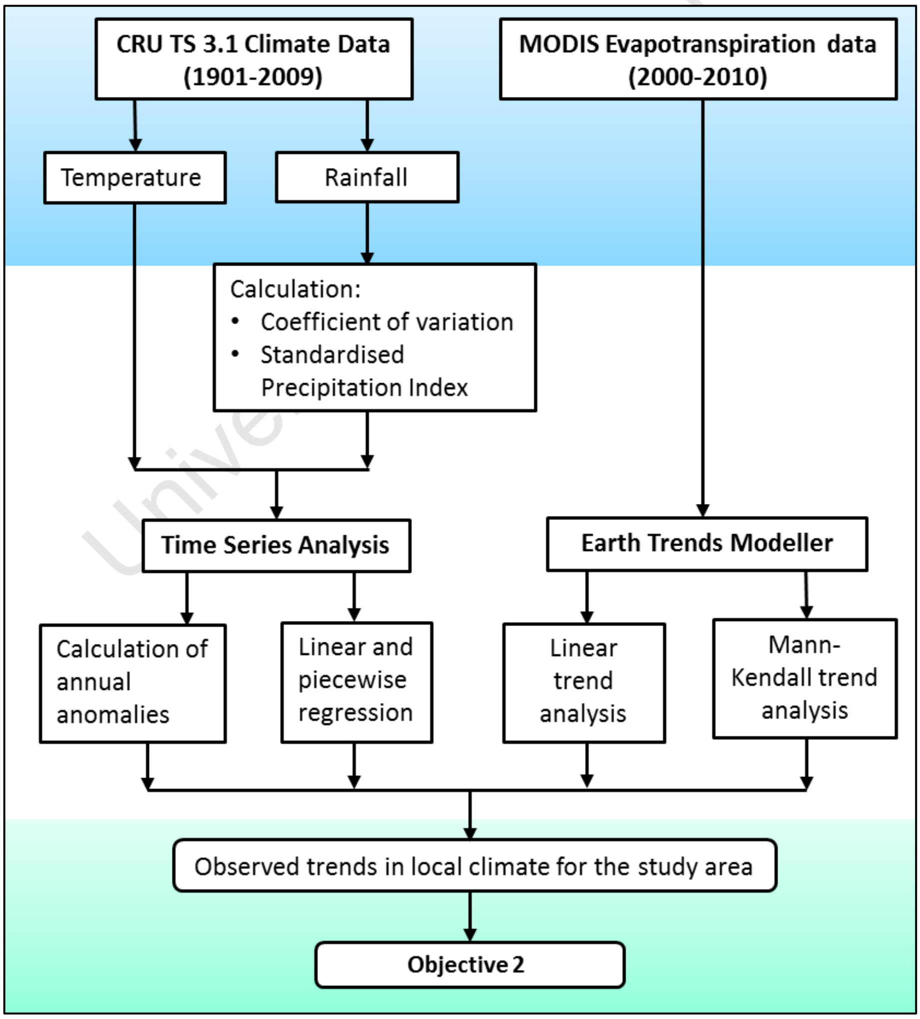


Figure 3.1: Flow diagram illustrating the approach taken to analyse trends in Namaqualand's climate

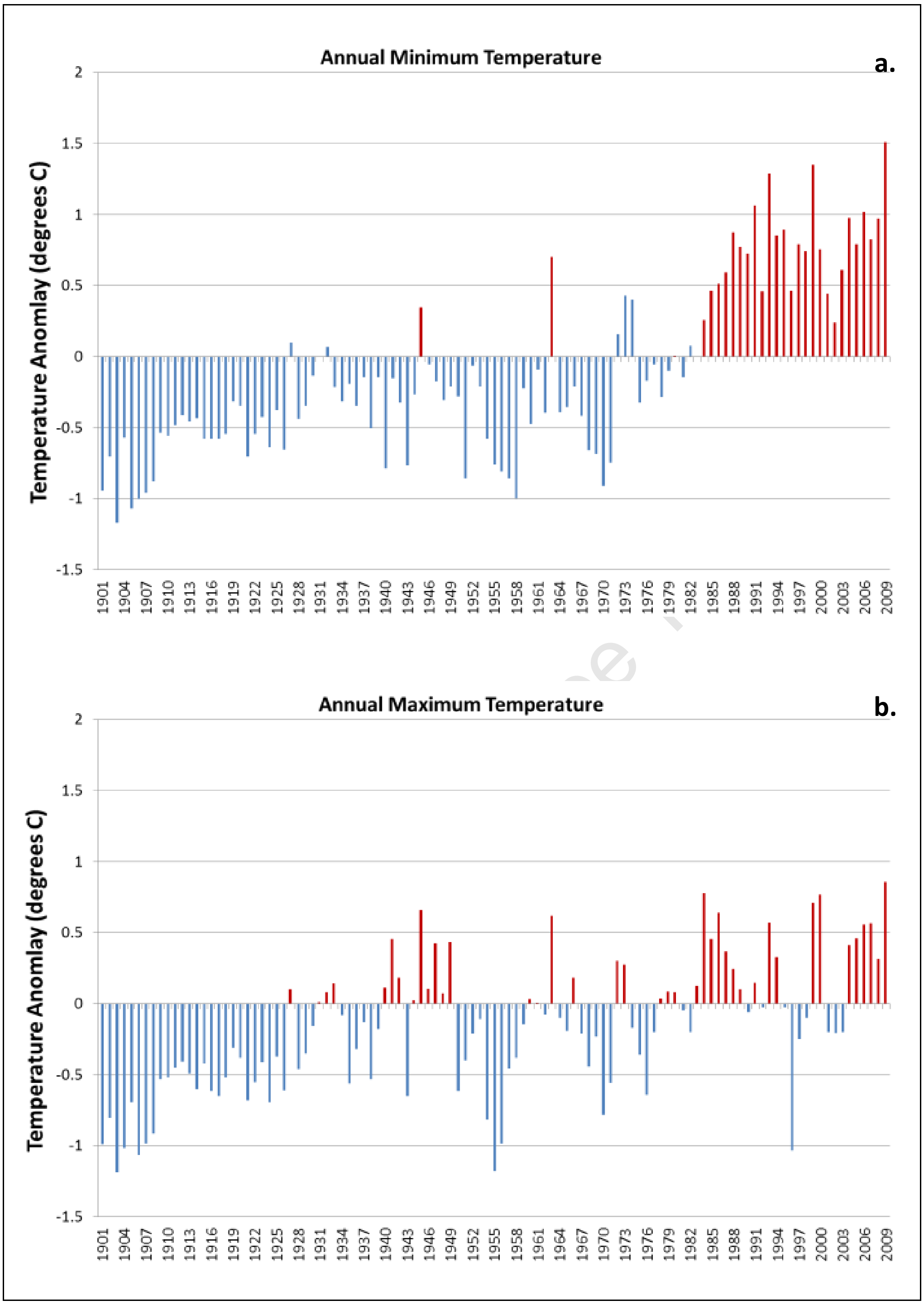
3.3. Results

The following section details the results from the analysis of the temperature and rainfall high-resolution gridded dataset (1901 to 2009) provided by the Climatic Research Unit of the University of East Anglia (CRU TS 3.1) as well as the 8 day MOD16 evapotranspiration dataset. No significant trend in relative humidity was found and thus the results from this analysis are not presented here (refer to Appendix B Figure B.1 and B.2 for annual and seasonal trends in relative humidity).

3.3.1. Temperature

There is strong evidence, based on analysis of minimum and maximum temperature trends, that the region is getting warmer. The trends are displayed as departures (or anomalies) from the 1961-1990 average, in Figure 3.2. After 1984, the anomalies for minimum temperature are all positive; approximately 0.75°C above the 1961-1990 average (Figure 3.2a). For maximum temperature the occurrence of positive anomalies becomes more frequent post 1983 with only a few years displaying negative temperature anomalies (Figure 3.2b). The change in maximum temperature is not as pronounced as with minimum temperature. The magnitude of both maximum and minimum temperature anomalies appears to be larger in more recent years, suggesting that the rate of increase in temperature is increasing. Results from the piecewise regression (Figure 3.3) reveal that the period of most rapid warming in minimum temperature occurred post 1970. This demonstrates that minimum temperatures have begun to rise more steeply during the latter years of the 20th century and the first decade of the 21st century. The piecewise regression analysis of maximum temperature was not statistically significant.

Trend analysis of temperatures for the study area reveals that annual minimum and maximum temperatures have increased at an average rate of 0.33˚C per decade ($p<0.001$) and 0.1˚C per decade ($p<0.05$) respectively between 1960 and 2009. At a seasonal time scale, minimum temperatures have increased significantly ($p<0.001$) across all seasons whereas maximum temperatures have only increased significantly during summer (December-January-February) and autumn (March-April-May), (Table 3.1 and Figure B.3 in Appendix B). Minimum temperatures have experienced the greatest rate of change during autumn (March-April-May) and winter (June-July-August) with an increase of 0.35˚C and 0.3˚C per decade respectively between 1960 and 2009 (Table 3.1 and Figure B.3 in Appendix B). As with the annual trends, the rate of increase in seasonal minimum temperatures is greater than that of maximum temperatures.



<u>Figure 3.2:</u> Annual (a) minimum and (b) maximum temperature anomalies for the study area (1901-2009) based on CRU TS 3.1 dataset. Red represents positive anomaly and blue a negative anomaly in temperature with respect to the long-term average climatology (1961-1990 mean).

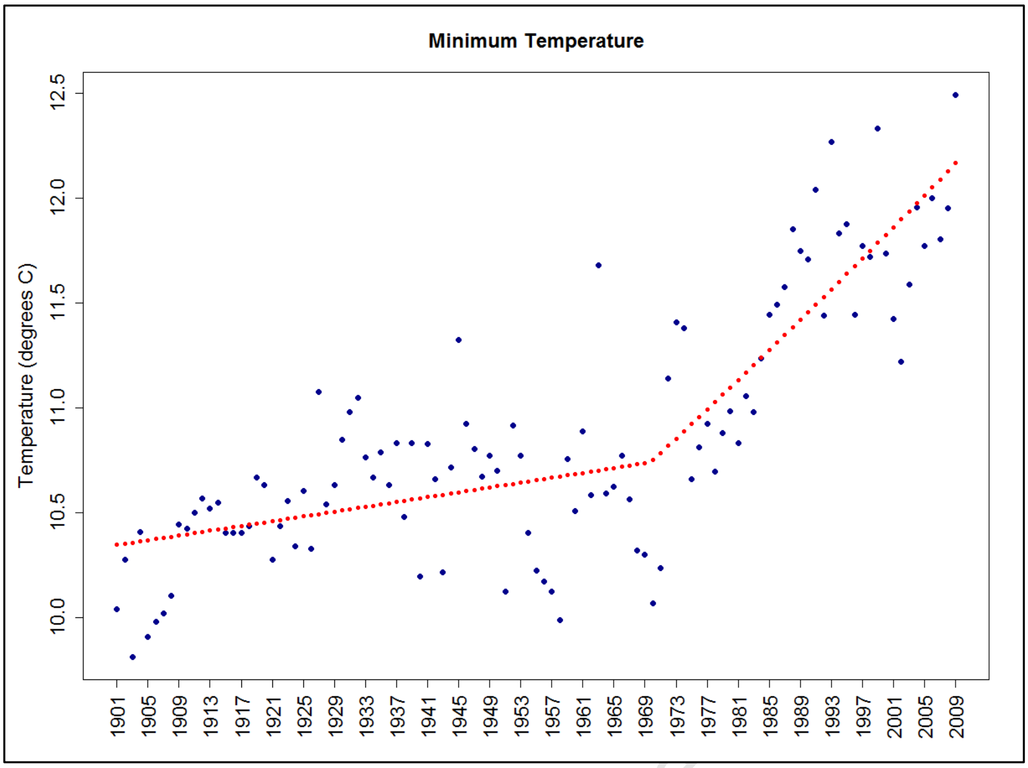


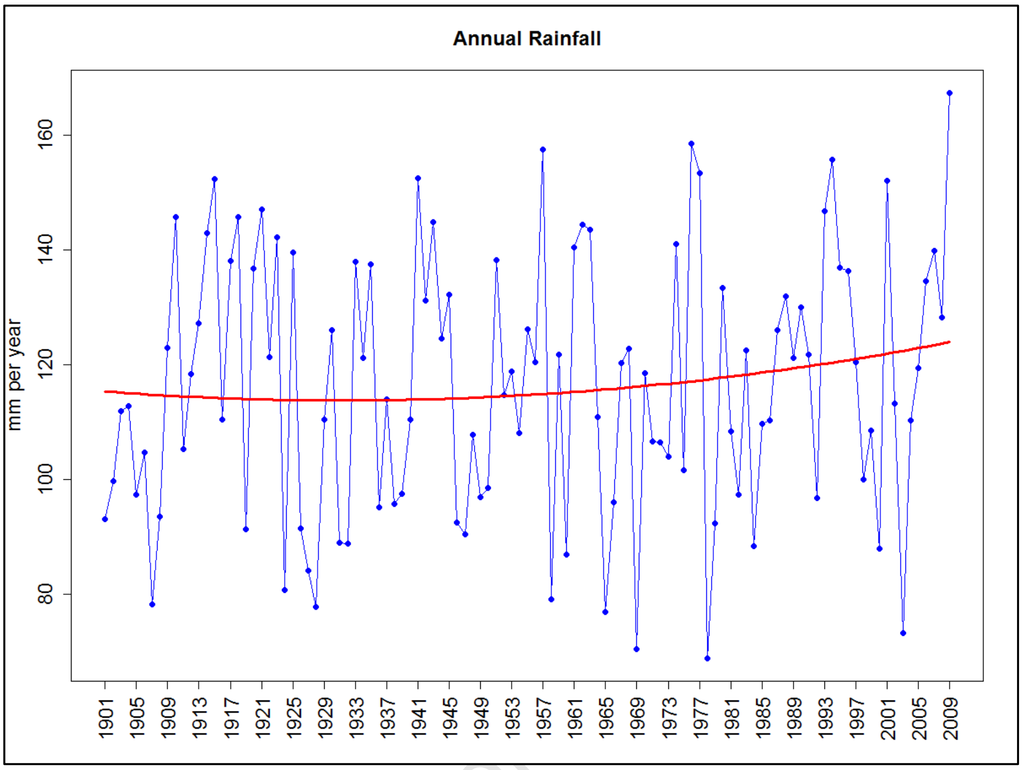
Figure 3.3: Time series of annual minimum temperature (1901-2009) based on CRU TS 3.1 dataset. The dotted red line represents the segmented regression.

Table 3.1: Rates of seasonal change in minimum and maximum temperature given as degrees Celsius per decade (1960-2009) based on CRU TS 3.1 dataset. Significance values are given as: ***=p<0.001, **= p< 0.01.

Season	Minimum Temperature	Maximum Temperature
December-January-February	0.28***	0.15***
March-April-May	0.35***	0.15**
June-July-August	0.30***	0.09
September-October-November	0.24***	0.11

3.3.2. Rainfall

Trend analysis of rainfall (1901-2009) for the study area reveals very little change at the annual (Figure 3.4) and seasonal time scales (refer to Appendix B Figure B.4). The trend shown in Figure 3.4 indicates a slight initial drying trend of 6.7 mm per decade from 1901-1950 and a slight wetting trend of 6.8 mm per decade from 1951-2009 but this is statistically insignificant. The anomalies of the coefficient of variation demonstrate considerable inter-annual variability in rainfall for the study area with some years deviating from the long-term mean by up to 28% (Figure 3.5). There was no significant trend in the coefficient of variation suggesting that the inter-annual rainfall variability for the study area has remained unchanged. Oscillating wet and dry climatic conditions are evident from the 12 month Standardised Precipitation Index (Figure 3.6). The time series for the 12 months highlights major droughts periods (for example 2002-2004) as well as wet periods (for example 1996-1997), (Figure 3.6).



<u>Figure 3.4:</u> Mean annual rainfall (mm per year) for the study area (1901-2009) based on CRU TS 3.1 dataset. The red line represents the fitted 2nd order polynomial regression line.

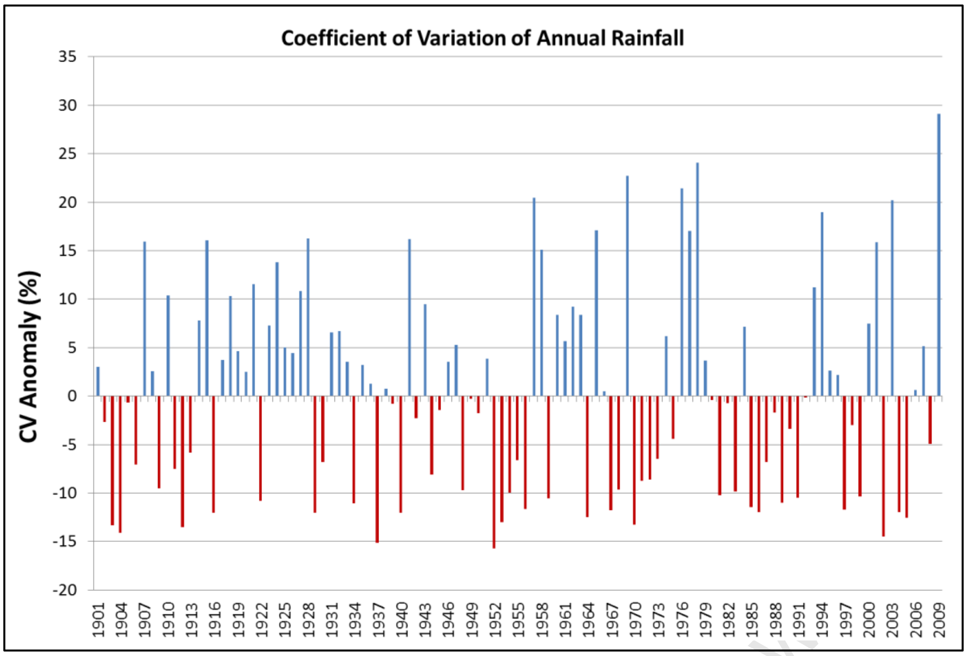


Figure 3.5: Annual coefficient of variation anomalies for the study area (1901-2009) based on CRU TS 3.1 dataset. Red represents positive anomaly and blue a negative anomaly in the annual coefficient of rainfall with respect to the long-term average climatology (1961-1990 mean).

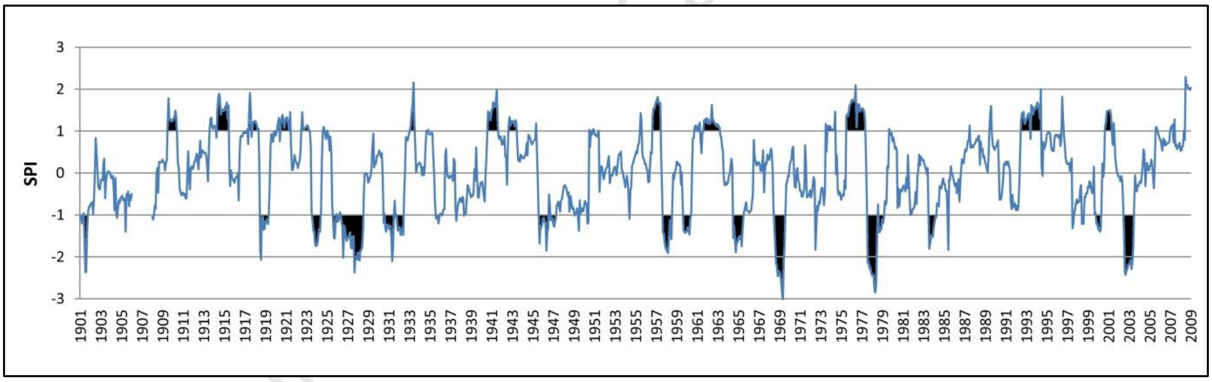


Figure 3.6: Standardised Precipitation Index (SPI) values for the study area based on CRU TS 3.1 rainfall data for the period 1900–2000. SPI values are for a 12-month period. The extended dry and wet periods are shown by the shaded black areas.

3.3.3. Evapotranspiration

The study area displays a relatively high evaporative demand with an average evapotranspiration of 5 mm per day in the dry season and 3.7 mm per day in the wet season. For 2009, for example, the total evapotranspiration was 192 mm, which is 25 mm higher than the annual rainfall for that year (refer to Appendix B Figure B.5 for the graphical trend in evapotransipration). Evidence from the analysis of MOD16 indicates that some parts of the study area have undergone an increase in evapotranspiration and others a decrease (Figure 3.7). The spatial pattern of change for evaporation is characterised by a steepening inland-coastal gradient where areas along the coast show a significant ($p<0.01$) increase in evapotranspiration of up to 7 mm per year (Figure 3.7). Small patches to the north east of the study have experienced a significant decrease in evapotranspiration of 1.7 mm per year (Figure 3.7). The seasonal time series analysis revealed that evapotranspiration has significantly ($p<0.01$) decreased by 0.66 mm during winter (JJA), (refer to Appendix B Figure B.6). Trends in evapotranspiration for the other seasons are not statistically significant.

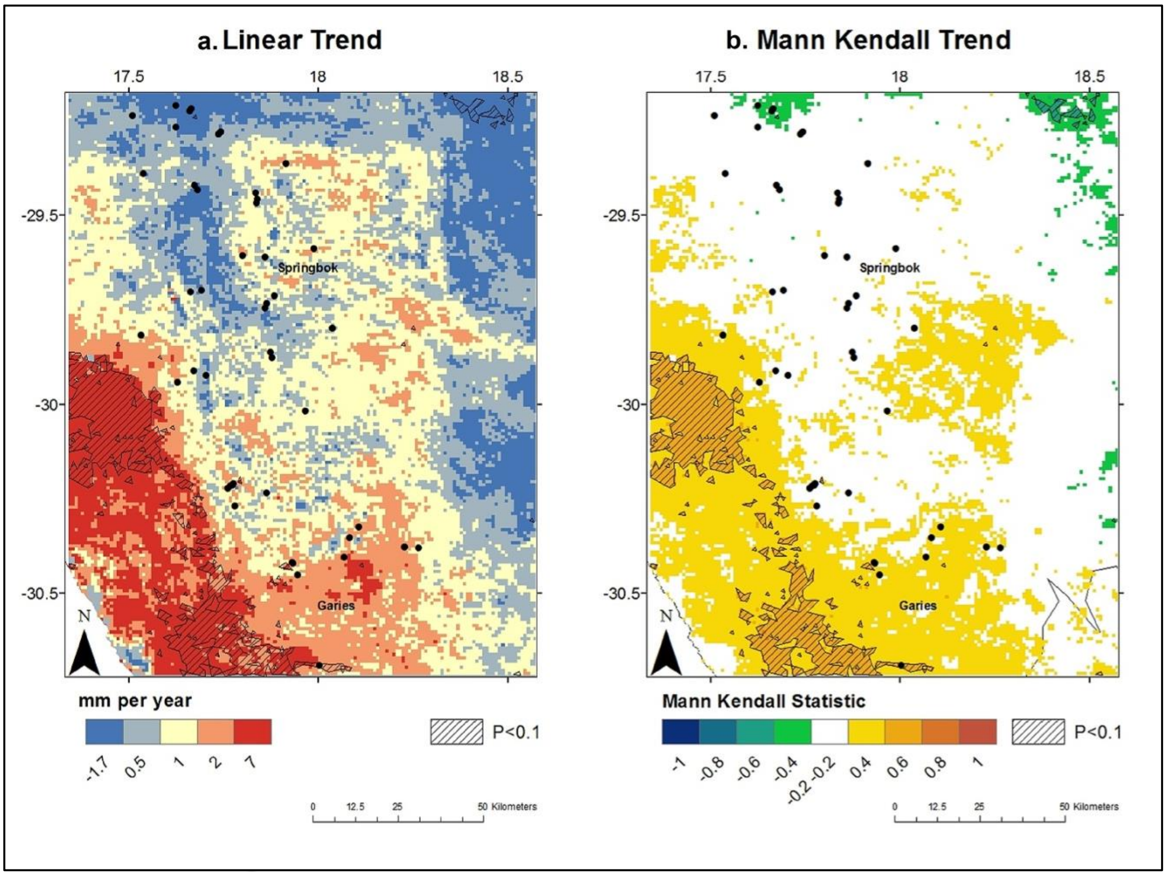


Figure 3.7: (a) Linear trend and (b) Mann-Kendall trend analysis of evapotranspiration for the study area (2000-2010) based on the MOD16 ET dataset. Blue colours indicate a decreasing trend and red colours indicate an increasing trend. Areas of significance ($p < 0.01$) are shown by the shaded areas. The repeat photography sites are indicated by the black dots.

3.4. Discussion

There is good evidence, from the results presented, to suggest that temperatures in the study area have been increasing over the last century, and that the rate of warming has been increasing – most notably in the last two decades. The trends in temperature are consistent with detected increases in global (Christensen et al. 2007; Hansen et al. 2006), continental (Hulme et al. 2001), and regional (Kruger & Shongwe 2004; Haensler et al. 2010; Hughes & Balling Jr 1996) annual air temperatures. Projections of future temperature change for South Africa (Archer et al. 2010), show that temperatures are expected to continue to increase. As presented here, studies have also shown that minimum temperature is increasing at a faster rate than the maximum (Easterling et al. 1997) and that the rate of warming in minimum temperature has increased since 1970 (Blunden et al. 2012). Karl et al. (1993) report that the increase in minimum temperature has occurred at a rate three times that of maximum temperature during the period 1951 to 1990. This has resulted in a decrease in the diurnal temperature range for many parts of the globe (Easterling et al. 1997). Temperature trends were found to be inconsistent across seasons where the highest temperature trends were observed in summer and autumn and the lowest in spring. This is consistent with the findings of Kruger and Shongwe (2004).

Changes in rainfall are typically harder to detect due to the fact that rainfall varies based on location and from year to year across southern Africa (Hoffman & Vogel 2008; Fauchereau et al. 2003). Evidence from regional studies have shown that inter-annual rainfall variability over southern Africa has increased since the late 1960s and that droughts have become more intense and widespread in the region (Fauchereau et al. 2003; New et al. 2006; Qin et al. 2007). Evidence for Namaqualand suggests that while annual rainfall has increased significantly in some areas it has decreased in others (MacKellar et al. 2007), 20th century climates have been little different from 19th century climates in terms of the frequency of drought and wet periods (Kelso and Vogel 2007). Palaeoflood studies in Namaqualand (Benito et al. 2011a; Benito et al. 2011b) provide evidence of a decrease in the magnitude and frequency of floods in the Buffel's river. Paleoflood discharges for the period 1500-1921 were five times greater than the largest modelled floods during the period 1965-2006 (Benito et al. 2011a; Benito et al. 2011b). Palaeoclimate studies in the winter rainfall region of South Africa demonstrate a continuous aridification trend and evidence of a poleward shift of the austral mid-latitude westerlies (Weldeab et al. 2013).

From the results presented here, no clear evidence exists for a significant change in mean annual rainfall, and the rainfall time series remain dominated by oscillating wet and dry conditions. This finding is supported by Hoffman et al (2009) who found no evidence for a significant change in mean annual rainfall for the Succulent Karoo but did however, suggest a slight drying trend (1901-1950) followed by a slight wetting trend (1951-2009) which is replicated in the results presented above. A study conducted by Haensler et al (2010) also found no significant trend in annual rainfall for the western region of South Africa. In addition, the strong inter-annual variability in rainfall presented here follows that demonstrated by Hoffman et al (2009) for the Springbok weather station and Haensler et al (2010) for the western region of South Africa.

There is currently no literature on the trends in evapotranspiration for the Succulent Karoo or the Namaqualand region. Hoffman et al (2011) found that pan evaporation declined significantly at an average rate of 9.1 mm per annum at 16 weather stations located in the Cape Floristic Region of South Africa as a result of a decline in wind run. Trends in coastal fog for the region are also lacking and since rainfall is supplemented by fog a true indication of the change in water availability of the region cannot be definitively determined.

The analysis of trends and variability of recent historical climate in the Namaqualand, presented in this chapter, provides a foundation for the interpretation of trends in vegetation production presented in Chapter 5 and 6. In these chapters the relationship between climate and vegetation indices will be statistically tested in order to assess the role of climate in driving recent changes in vegetation cover across the study area.

Chapter 4: Assessment of vegetation change in Namaqualand based on historical repeat photographs

4.1. Introduction

Repeat photography is a valuable research tool for evaluating long-term landscape and land use change (Webb et al. 2010) as it provides high quality information within a limited area (Rhode 1997). Since photography become widespread in the late 1800s, repeat photography studies are able to assess change over longer time periods than aerial photography (which is available for Namaqualand from the 1950s only) and satellite remote sensing (Landsat 1 was launched in 1972), (Kull 2005). The repeat photography methodology involves the retaking of photographs from the same camera spot and of the same subject several times and then comparing the photographs in order to identify changes (Kull 2005; Nyssen et al. 2010). There is currently a lack of software available to assist with the comparison of repeat photographs and comparisons are typically conducted using manual methods that involve visually comparing the images and then scoring the degree of change (Hall 2002; Nyssen et al. 2009). As outlined in Chapter 1, repeat photography has been used in numerous studies worldwide, many of which were conducted in semi-arid environments (Kull 2005; Hastings & Turner 1965; Shantz & Turner 1958; Nyssen et al. 2009; Rohde & Hoffman 2012; Bahre 1991). In South Africa, repeat photography has been used to address questions of vegetation change in the eastern Karoo (Hoffman & Cowling 1990), Namaqualand (Hoffman & Rohde 2010; Hoffman & Todd 2010) and in the dry savannas near Kimberley (Ward et al. 2012). The majority of these studies are based on historical photographs from the late 1800s and early 1990s and thus the interval between photographs can be multiple decades up to a century or more (Kull 2005).

Utilising a comprehensive set of archival images taken since 1876 (Hoffman & Rohde 2010), this chapter investigates the following key question: what has been the extent of change in vegetation cover in Namaqualand within different land tenure systems and in response to different land- use practices? This chapter addresses both objective one and two of this study.

4.2. Methodology

4.2.1. Repeat photographs

Following the approach outlined by Rhode (1997), Hoffman and Rohde (2010) re-located 233 historical images taken in Namaqualand between 1875 and 1971 and re-photographed them between 1998 and 2007 (Figure 4.1). Each photograph typically covered an area of between 5 and 50 hectares and the average number of years between the photograph periods was 60 and ranged between 33 and 100 years (Hoffman and Rohde 2010). Each repeat photograph is accompanied by field notes describing the general condition of the site as well as the major changes in land-use and vegetation cover evident between the two periods.

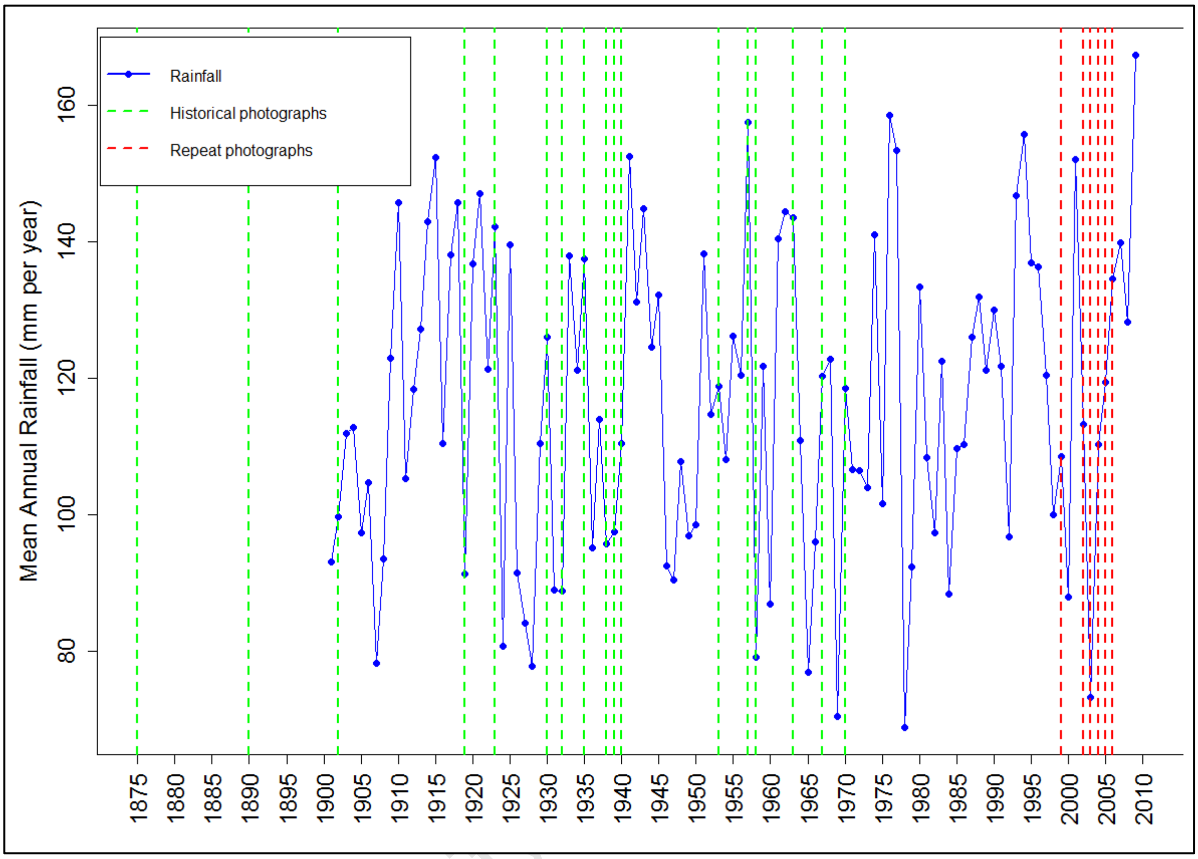


Figure 4.1: Mean Annual Rainfall (solid blue line) based on CRU TS 3.1 dataset from 1901 to 2009 with the years the historical images were captured (dashed green line) and the years when the repeat photographs were taken (dashed red line).

4.2.2. Selection of repeat photography sites

Study sites were selected from the 233 repeat photography sites (Hoffman & Rohde 2010) based on a qualitative and quantitative assessments of each image (see Figure 4.2 for the methodological approach). Firstly, the qualitative process identified the attributes (land tenure, land-use and land-form) of each site and removed sites that did not provide for a good assessment of vegetation change, for example urbanised sites and disturbed sites dominated by bare ground. The repeat photograph pairs as well as land use and land cover maps (see Chapter 2 Figures 2.5 and 2.6), and a DEM (Digital Elevation Model) of the study area were used to categorise each photography site stating whether or not the attribute, such as a cultivation, was present. The distance between adjacent sites was also calculated and a matrix was created in order to remove sites that were closer than 2 km. The decision on which site to be removed was made based on the quality and amount of information in the repeat photographs.

Secondly, the quantitative process investigated the mean annual NDVI derived from AVHRR and MODIS NDVI data sets (refer to Chapter 5 for a detailed description) and mean annual rainfall characteristics (Schulze 2008) for each site to ensure that the sites selected were representative of the full range of NDVI and rainfall values for the study area and reflected the spatial patterns of both variables. The relationship between NDVI and rainfall for each site was plotted graphically and demonstrated a significant linear relationship (AVHRR: R^2=0.626, $p<0.005$; MODIS: R^2=0.427, $p<0.05$) between the two variables. A spatial trend analysis further revealed that mean annual NDVI and mean annual rainfall decreased from south to north and from west to east. Sites with a mean annual NDVI value of less than 0.1 were removed from the selection since the NDVI signal at these sites would be dominated by soil surface properties rather than by the presence of vegetation (Camberlin et al. 2007) and would thus not produce plausible results (Heumann et al. 2007).

Utilizing both the NDVI and rainfall information for each site, a k-means cluster analysis and a spatial outlier analysis using the Anselin Local Moran's I statistic (Anselin 1995) was performed in order to identify unique sites. The cluster analysis identified 6 clusters and the outlier analysis identified statistically significant ($p<0.05$) concentrations of high values (HH) and low values (LL), (Figure 4.3). These unique HH sites were retained for further analysis with earth observational data.

Forty six study sites (see Chapter 2 Figure 2.1 and Table A.1 and Figure A.1 in Appendix A) were selected that met all the criteria described above and which were representative of the full range of NDVI and rainfall values experienced across the repeat photography sites.

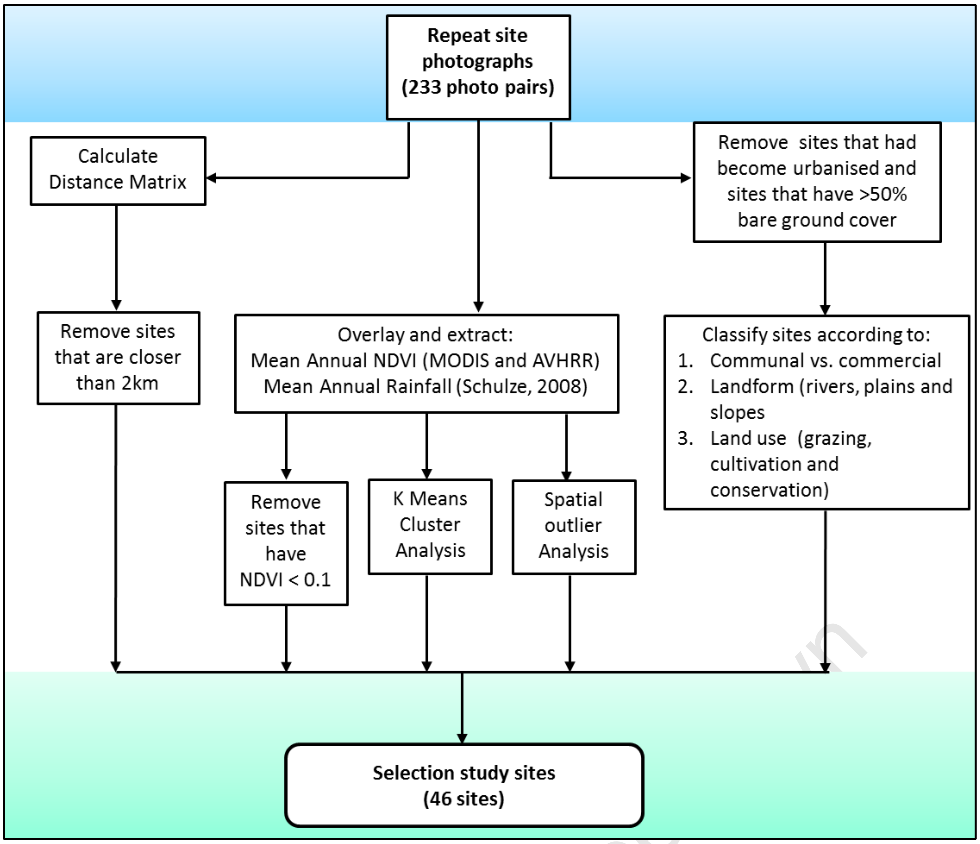


Figure 4.2: Flow diagram illustrating the methodological approach taken to select the study sites

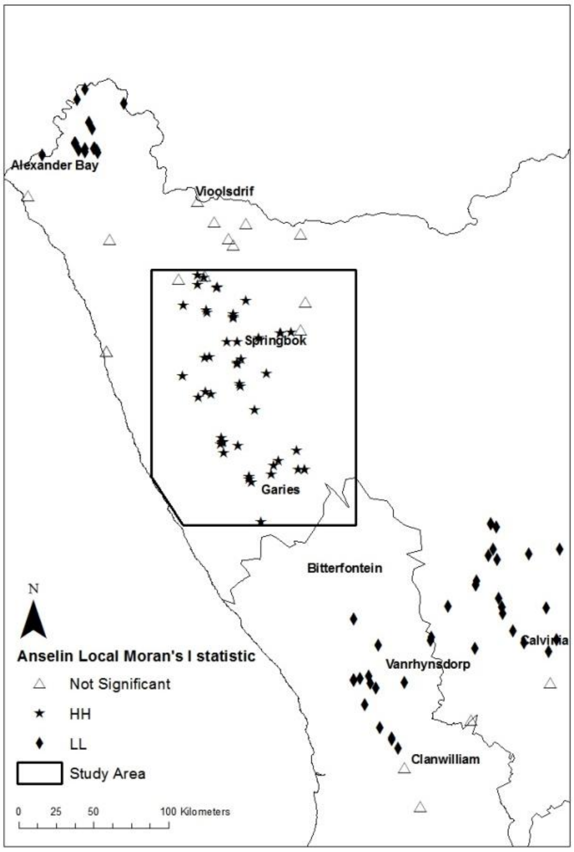


Figure 4.3: Location of 233 repeat photography sites in Namaqualand with the results of the spatial outlier analysis (Anselin Local Moran's I statistic) where the black stars represent concentrations of significantly high NDVI values (HH) and black diamonds the concentrations of significantly low NDVI values (LL). The triangles indicate sites that were not statistically significant. The study area encompassing the selected study sites is shown by the black square.

4.2.3. Analysis of individual repeat photographs

In order to assess the changes in vegetation cover, the images were digitised and matched exactly using standard image analysis software Adobe Photoshop CS4 (Hoffman & Rohde 2007; Photoshop 2005). Using the matched images, the change in annual and perennial plant cover was visually assessed according to a five point scale (Nyssen et al. 2009; Hoffman & Rohde 2010):

- −2: substantial decrease,
- −1: slight decrease,
- 0: no change,
- 1: slight increase,
- 2: substantial increase.

The median score for each land use (grazed or cultivated) under the different land tenure system (commercial, communal and conservation) was calculated and the deviation of the averages from zero (no change) was tested using the Wilcoxon signed-rank test (Nyssen et al. 2009). In order to establish the influence of changes in land-use on vegetation change, sites that showed evidence of changes in land-use practises such as an increase in grazing pressure or a reduction in cultivation were noted.

4.3. Results

The analysis of the repeat photograph pairs clearly demonstrates a significant reduction in annual cover and a slight increase in perennial cover in all three land tenure systems (Table 4.1). The recovery of perennial vegetation cover was more pronounced in commercial land tenure sites that had been previously cultivated but which have remained fallow for several decades (refer to site 350 in Figure 4.4). Approximately 70% of the sites under commercial land tenure showed a reduction in the area cultivated. A few commercial land tenure sites utilised for livestock grazing as well as the conservation site located in the Goegap Nature Reserve demonstrated a similar shift in vegetation cover from annuals to perennials (refer to site 372 Figure 4.5 and Table 4.1). The major perennial species which re-colonised these sites were *Lebeckia sericea*, *Stipagrostis brevifolia, Drosanthemum hispidum, Galenia africana* and *Elytropappus rhinocerotis.* These species are widespread in Namaqualand and are early colonisers of disturbed areas (Hoffman & Rohde 2010).

In the communal areas, however, where the sites are still relatively heavily grazed, old cultivated fields remained barren and were dominated by one or two unpalatable shrubs such as *Galenia africana* and *Elytropappus rhinocerotis* (refer to site 131 in Figure 4.6). In a few cases, perennial cover decreased as a result of increased grazing and in others the vegetation cover remained fairly stable (refer to site 352 in Figure 4.7). Approximately 36% of the communal sites showed a decrease in cover, presumably as a result of an increase in grazing pressure. At sites with views of river systems there was evidence of an increase in riverine vegetation cover, particularly *Acacia karroo* (Table 4.1 and refer to site 210a in Figure 4.9).

Table 4.1: Interpretation of vegetation change in terms of annual and perennial cover for different land use types (grazed or cultivated) under different land management systems (commercial, communal and conservation)

Land Tenure	Category	*n*	Score	Change
A. Commercial				
Grazing	Annuals	12	-2*	Substantial decrease
	Perennials	26	1*	Slight increase
Cultivated	Annuals	9	-2*	Substantial decrease
	Perennials	12	2*	Substantial increase
B. Communal				
Grazing	Annuals	5	-2*	Substantial decrease
	Perennials	14	0	No change
Cultivated	Annuals	5	-2*	Substantial decrease
	Perennials	9	1	Slight increase
C. Conservation	Annuals	1	-2	Substantial decrease
	Perennials	1	2	Substantial increase
All land tenure systems	Annuals	24	-2*	Substantial decrease
	Perennials	47	1*	Slight increase
	Riverine vegetation	9	1*	Slight increase

n = number of sites where the category was applicable; score = median of the scores given to each of the interpreted sites, ranging from -2 (substantial decrease) to +2 (substantial increase), with the level of significance for the deviation from a test value zero (no change) (*significant at 0.05 level); change = comparison of the photograph pairs

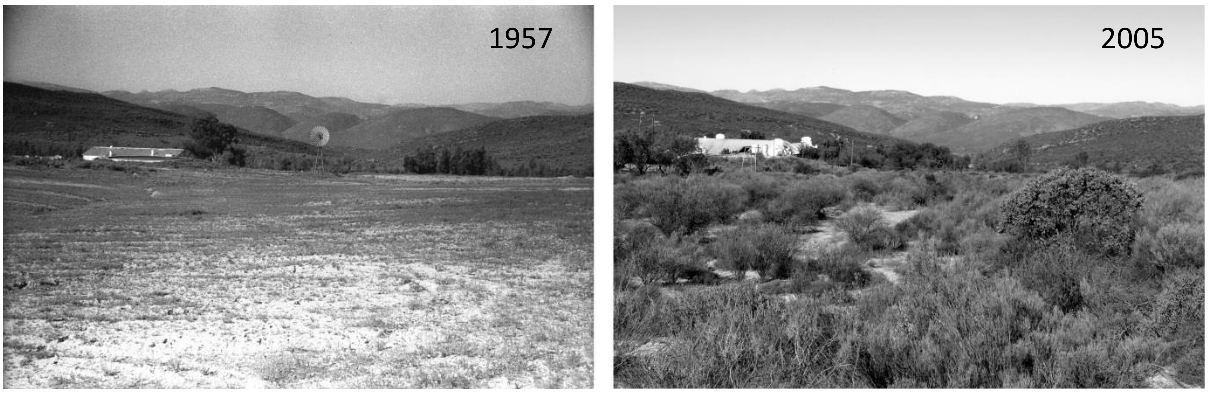


Figure 4.4: Site 350 located on a commercial farm located approximately 27 km west of Springbok was first photographed by John Acocks in 1957. When it was re-photographed in 2005 the old field had been lying fallow for several decades and was dominated by *Elytropappus rhinocerotis* and Galenia *africana*, which are both early successional shrubs. Photograph on the left courtesy of the South African National Biodiversity Institute and photograph on the right courtesy of Hoffman and Rohde.

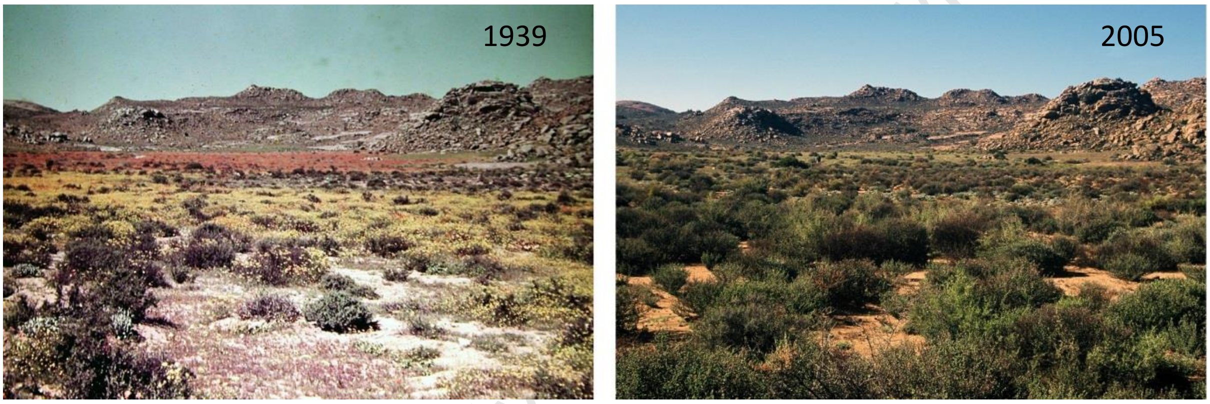


Figure 4.5: Site 372 is located in the Geogap Nature Reserve and has been protected for 35 years. It is the only site included in this study that has been formally protected. When the site was re-photographed in 2005 it was dominated by *Drosanthemum hispidum* and *Ruschia robusta.* The latter species was larger and more abundant than in 1939. Photograph on the left courtesy of H. Herre and photograph on the right courtesy of Hoffman and Rohde.

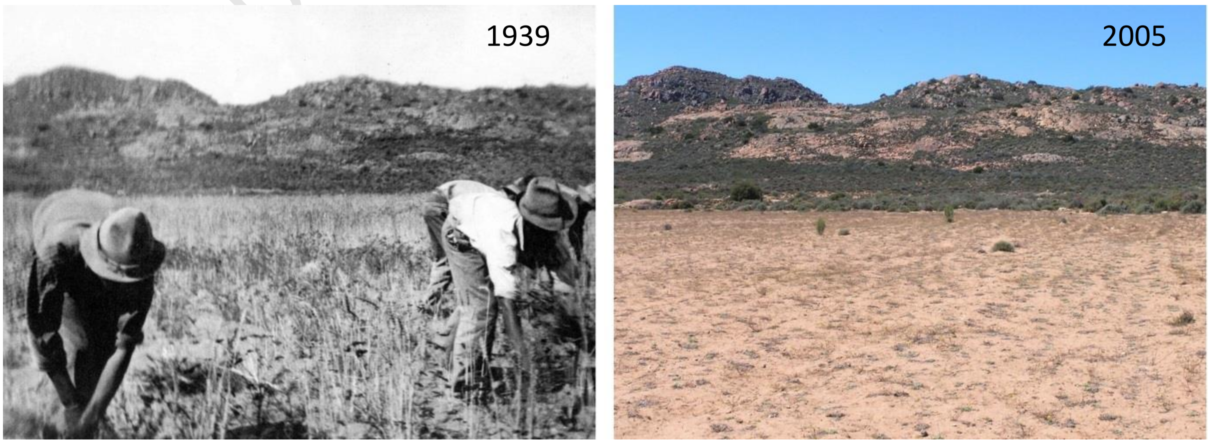


Figure 4.6: Site 131 located in Paulshoek, a town in a communal area has shown a substantial reduction in annual species since it was first photographed in 1939. The lowlands in the 2005 photograph have been severely impacted by cultivation and grazing. Photograph on the left courtesy of A.J Andrews and photograph on the right courtesy of Hoffman and Rohde.

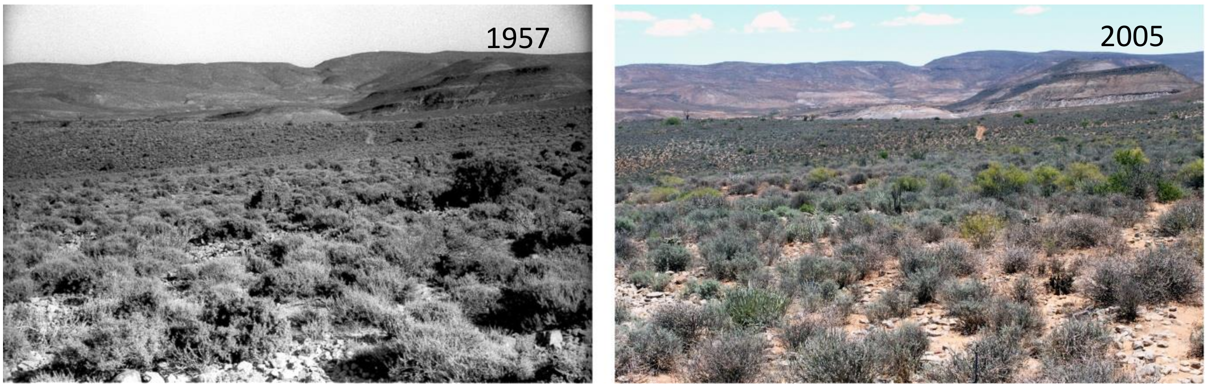


Figure 4.7: Site 352 located west of Bulletrap town in the communal area of Steinkopf has shown little change in vegetation since John Acocks first photographed the site in 1957. Photograph on the left courtesy of the South African National Biodiversity Institute and photograph on the right courtesy of Hoffman and Rohde.

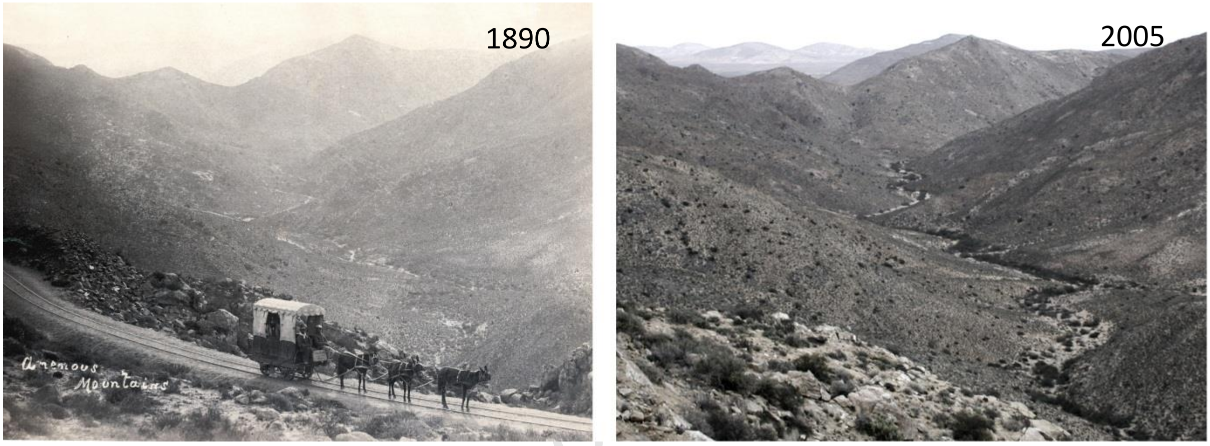


Figure 4.8: Site 210a is located on commercial land and the 2005 photograph shows that there has been an increase in vegetation cover, specifically *Acacia karroo*, along the non-perennial river. Photograph on the left courtesy of the Moffat Collection and photograph on the right courtesy of Hoffman and Rohde.

4.4. Discussion

4.4.1. Major changes in the vegetation of the study area

This chapter has demonstrated that changes in land use practices, namely cultivation and livestock grazing, have an important influence on the cover and species composition of the study area. The most important trend has been for perennial cover to increase on previously cultivated fields, under both commercial and communal management. In Namaqualand, the area used for the cultivation of wheat, oats, barley and rye crops peaked in 1971 and since then the area under cultivation has declined by nearly two-thirds (Hoffman & Rohde 2007; Rohde et al. 2003). This is largely a result of the large-scale abandonment of wheat farming in marginal, low rainfall areas where it is no longer economically viable (Hoffman & Rohde 2007). Cultivation in the communal areas has also declined significantly since the 1960s (Rohde et al. 2003). The repeat photographs have demonstrated that indigenous perennial species have been able to recolonise these abandoned fields resulting in an improvement in vegetation cover and composition of the sites. This improvement is limited in the communal areas particularly where sites have been subject to heavy grazing pressure over a long period of time. The successional processes remain slow and sites are often dominated by only one or two disturbance-tolerant species such as *Elytropappus rhinocerotis* and *Galenia africana.* In general, there is a higher grazing pressure on communal lands than adjacent commercial farms (Hoffman & Ashwell 2001; Benjaminsen et al. 2006) and this prevents an increase in palatable, productive shrubs (Anderson & Hoffman 2007). At some communal sites however, vegetation cover and composition has remained fairly stable, possibly as a result of agricultural subsidies and greater access to land which are a focus of land reform processes in the region (Hoffman & Rohde 2007; Cousins et al. 2007). In addition, the expansion of conservation areas such as the Goegap Nature Reserve in the region (Hoffman & Rohde 2007) has facilitated the recovery of perennial plant cover. This interpretation that vegetation and cover composition has improved in the study area is however, confounded by the fact that many of the early photographs were taken when the land was used extensively for subsistence agriculture (Acocks 1988).

The repeat photographs provided evidence of an increase in *Acacia karroo*, an indigenous tree, along rivers and small tributaries. This could be a recolonization of the area following the harvesting of the tress for firewood and charcoal in the beginning of the 20th century or a result of destructive floods which cleared the vegetation along the rivers (Benito et al. 2011a; Benito et al. 2011b; Hoffman & Rohde 2011). Increases in tree cover may also be partially the result of CO_2 fertilization and an increase in moisture availability (Bond & Midgley 2000). Hoffman and Rohde (2007) found that in some areas of Namaqualand, the alien trees *Prosopis glandulosus* and *Nicotiana tabacina* have also started to invade drainage areas.

4.4.2. The use of repeat photography to detect changes in vegetation

This chapter has demonstrated that repeat photography is a useful tool for change detection but that there are some limitations to this approach. A key strength of repeat photography lies with the relatively long time period covered by the images as well as the level of detail provided in each image. The repeat photographs have provided important information on the trends of vegetation cover, key changes in community composition as well as changes in land-use practices for the study area. The photograph pairs, however, only represent two, rarely three, snapshots in time and are thus not likely to be representative of the average vegetation cover experienced at that site. In addition, the location of the photography sites are based on the available historical material and the purpose of such photographs were not necessarily to monitor vegetation.

The results from this chapter provide a foundation for the interpretation of trends in vegetation cover derived from remotely sensed vegetation indices presented in Chapters 5 and 6 of this thesis. Chapter 5 investigates the main trends in vegetation observed at an inter-annual time scale and Chapter 6 presents phenological information such as the amplitude of the annual vegetation cycle and the time of the occurrence of the annual maximum vegetation cover. The hypothesis that the perennial cover and biomass is increasing at the study sites will be tested in these following chapters.

Chapter 5: Analysis of inter-annual trends in satellite derived vegetation indices for Namaqualand between 1986 and 2011

5.1. Introduction

Considerable attention has been directed towards understanding the future trajectory of vegetation change in the arid and semi-arid regions across the globe in the face of climate change (Zhang et al. 2013). In Namaqualand, vegetation productivity is of great importance since there is a high dependence on livestock and crop production but there is considerable debate regarding the future stability of the Succulent Karoo biome (Rutherford et al. 1999; Driver et al. 2012). There is very little documented evidence in Namaqualand of the extent and rate of changes in vegetation against which future responses can be assessed. Therefore, spatially and temporally explicit long-term data on the changes and trends in vegetation productivity for the Namaqualand region are of great importance.

Coarse resolution satellite data (250 m to 1 km pixel size) covering the last 3 decades are routinely used to estimate the photosynthetic activity of vegetation at synoptic scales (Wessels et al. 2007; de Jong et al. 2011b; Fensholt et al. 2013; Tucker et al. 1991). As demonstrated in Chapter 1, many studies in semi-arid regions have successfully used satellite derived vegetation indices to monitor trends in primary production for the purposes of assessing land degradation. Vegetation indices use the contrast in the reflectance between the visible and infrared wavelengths to provide an estimate of photosynthetically active vegetation (Tucker et al. 1991). Vegetated areas will generally yield high values because of their relatively high near infrared reflectance and low visible reflectance. Vegetation indices are often used as a proxy for terrestrial vegetation productivity because it is strongly correlated with leaf area index (LAI), aboveground biomass and primary production (Prince 1991; Tucker et al. 2005; Myneni et al. 1997; Wessels et al. 2006).

The Normalised Difference Vegetation Index (NDVI) derived from the Advanced Very High Resolution Radiometer (AVHRR) sensor is the most commonly used tool for detecting long-term vegetation changes at global, continental and regional scales. The AVHRR sensor, however, was not initially designed to monitor vegetation and several studies have revealed certain drawbacks with using NDVI which can complicate the attribution of vegetation change (Archer, 2004). In semi-arid areas NDVI is highly sensitive to seasonal rainfall variability since variability in rainfall directly affects vegetation cover and production in the region (Li et al. 2004; Richard & Poccard 1998). In addition, in regions where the vegetation cover is not continuous the reflectance of bare soil results in a certain proportion of NDVI values representing the background soil brightness (Sebego et al., 2008). The MODIS Enhanced Vegetation Index (EVI) developed by Huete et al. (2002) can be used to circumvent these problems as this index reduces the sensitivity to atmospheric and soil effects but remains sensitive to a wide range of variation in canopy density (Zhang et al.

2005). The EVI, however, is more sensitive to topographic conditions (Matsushita et al. 2007) than the NDVI, which successfully retains the ability to minimise topographic effects (Eastman, 2003). Huete et al (2002) thus maintain that the two VIs complement each other in global vegetation studies and improve upon the detection of changes in vegetation and the extraction of canopy biophysical parameters.

In this chapter both the Normalised Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI) were used as a proxy for vegetation productivity in order to investigate inter-annual trends in vegetation across a subset of the Namaqualand region of South Africa from 1986 to 2011. This study relies on the combined use of time series data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Very High Resolution Radiometer (AVHRR) sensors. Changes in vegetation productivity were identified by trends in key NDVI and EVI productivity metrics, namely annual maximum, cumulative sum and coefficient of variation.

Comparable trends in rain-use efficiency (Nicholson et al. 1998; Prince et al. 1998) and standardised residuals (RESTREND) (Wessels et al. 2007; Archer 2004; Evans & Geerken 2004) were produced in order for rainfall-related trends to be distinguished from human-induced land degradation. Linear least square regression trend techniques (Herrmann et al. 2005; Olsson et al. 2005; Helldén & Tottrup 2008; Fensholt et al. 2009), non-parametric trend analyses (Fensholt et al. 2012; de Jong et al. 2011a) and piecewise regressions (Verbesselt et al. 2010a; Zhang et al. 2013) were used to determine the intensity, rate and timing of changes in vegetation production. It is hypothesised that a statistically negative slope in NDVI or EVI indicates areas that have experienced a decline in vegetation production and possibly also an increase in degradation (Anyamba & Tucker 2005; Wessels et al. 2007; Evans & Geerken 2004; Weiss et al. 2001). This chapter provides the necessary information to answer the first research question of objective one: How has the vegetation cover of the study area changed over the last 25 years?

5.2. Methodology

Figure 5.1 outlines the approach taken to analyse inter-annual vegetation dynamics for Namaqualand. Three methods were utilised to detect long-term changes in vegetation:

1. Trends in key productivity metrics: annual maximum NDVI and EVI, annual cumulative sum NDVI and EVI, and coefficient of variation of NDVI and EVI;
2. Trends in Rain-use efficiency;
3. Residual trends of NDVI and EVI (RESTREND)

Details of the data used and the analytical methods are provided in the sections below.

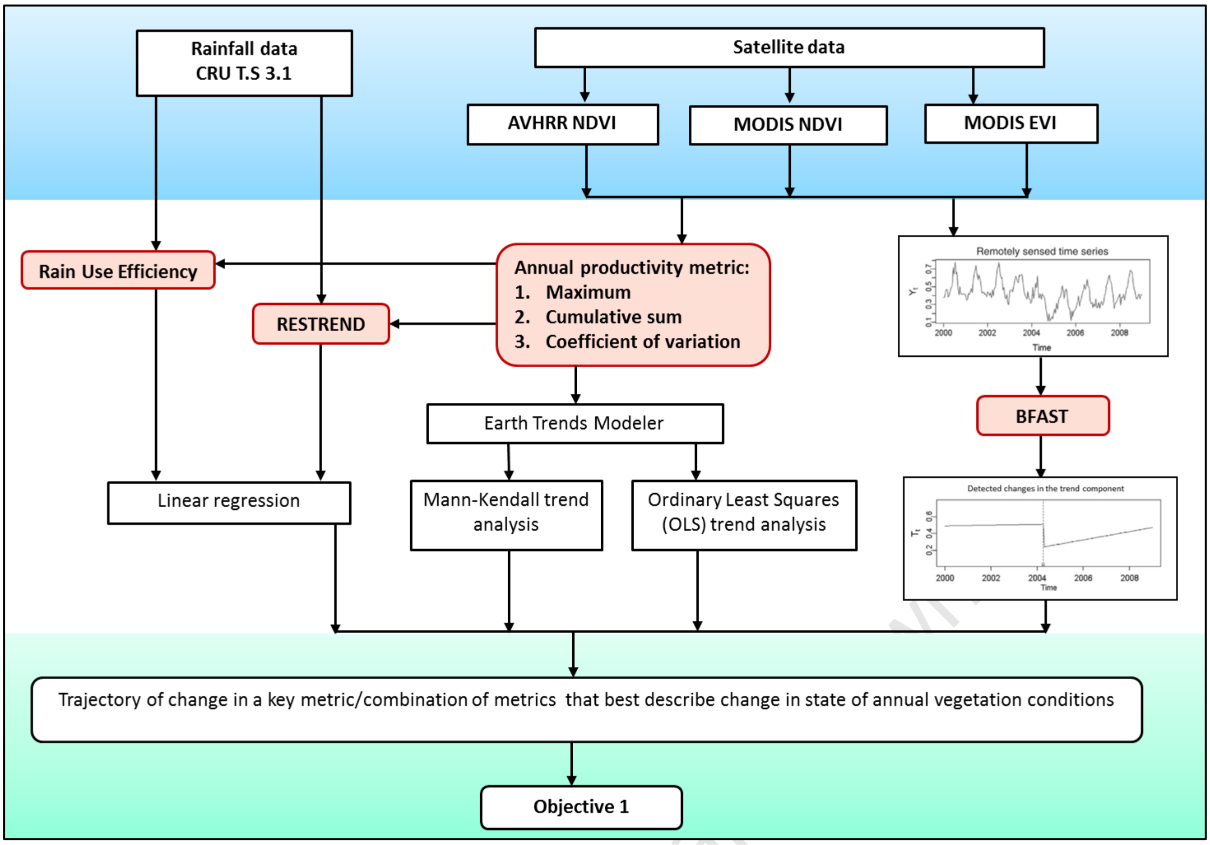


Figure 5.1: Flow diagram illustrating the methodological approach taken to determine inter-annual trends in NDVI and EVI. BFAST images taken from Verbesselt et al (2010a; 2010b).

5.2.1. Satellite datasets and pre-processing

Vegetation productivity was estimated with NDVI derived from Advanced Very High Resolution Radiometer (AVHRR) data and NDVI and EVI derived from Moderate-resolution Imaging Spectroradiometer (MODIS) data (Table 5.1). The AVHRR NDVI data set has the advantage of a long-term data record (the early 1980s to the present) while the more recent MODIS data sets have greater spectral and spatial resolution as well as other technical improvements (Huete et al. 2002). MODIS data is referred to as the "continuity index" to the existing 20 plus year AVHRR NDVI time series, which is extended by MODIS data to provide a longer data record for use in vegetation monitoring studies (Huete et al. 2002). The MODIS NDVI and EVI data sets will be used in this study to firstly provide a longer data record to evaluate vegetation change and secondly to validate the trends observed in the AVHRR NDVI time series. A crossplot from the two sensors (Figure 5.2) shows a linear relationship between the data sets. Efforts are underway by NASA's Land Long Term Data Record (LTDR) project (Pedelty et al. 2007) and others (Zhang et al. 2013; Swinnen & Veroustraete 2008) to create a multi-sensor long-term data record by reprocessing the older AVHRR and more recent MODIS and SPOT VEGTATION in such a way that their NDVI data are potentially comparable through time.

Table 5.1: Description of the satellite data utilised in this study (data made available by the South African National Space Agency and processed by CSIR-Meraka Institute http://wamis.meraka.org.za)

Sensor	Platform	Indicator	Time Range	Spatial Resolution	Temporal Resolution
AVHRR	NOAA (7, 9, 11, 14 and 16) polar orbiting satellite	NDVI	January 1986 to December 2006	1 km^2	10 day
MODIS	Earth Observing System-Terra platform	NDVI	January 2001 to December 2009	500 m	16 day
MODIS	Earth Observing System-Terra platform	EVI	January 2000 to December 2012	500 m	8 day

AVHRR NDVI data

Daily AVHRR NDVI data have been recorded by the South African National Space Agency (formally known as the Satellite Application Centre) since 1985 (Wessels et al. 2012). The data has been processed and calibrated by the Institute for Soil, Climate and Water at the Agricultural Research Centre (ARC-ISCW) to correct for sensor degradation and sensor changes (Rao & Chen 1995; 1996). The dataset could, however, not be corrected for atmospheric effects due to the unavailability of the required atmospheric data (Wessels et al. 2012). In order to minimise the impact of clouds and other atmospheric effects, a statistical filter was applied through time to interpolate pixels that were covered or affected by atmospheric aerosols. Ten-day maximum value composites were calculated from the daily data. Data for 1994 was unavailable due to the failure of NOAA-13 shortly after its launch. Therefore, the 21 year period investigated (1985-2006) only contained 19 full growing seasons. For further information on the processing of AVHRR NDVI dataset see Wessels et al (2006).

MODIS NDVI and EVI data

MODIS NDVI 16-day composite grid data (MOD13Q1) was made available by the South African National Space Agency. The MODIS EVI 8 day data set (Schaaf et al. 2002) was processed by CSIR-Meraka Institute (2011)[2]. EVI values were linearly interpolated for pixels that were affected by clouds. For further information on the processing of the MODIS vegetation indices see Huete et al. (2002; 1999).

[2] http://afis.meraka.org.za/wamis/products/long-term-time-series

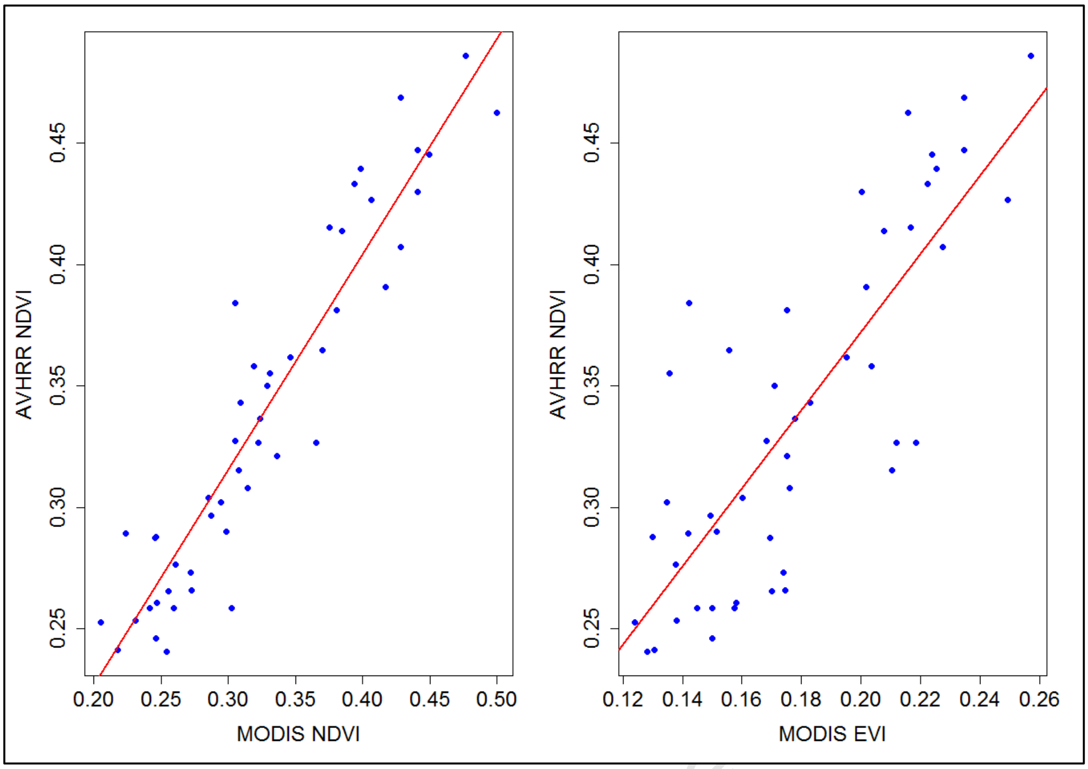


Figure 5.2: Crossplot of annual average AVHRR NDVI and (left) MODIS NDVI (R^2 = 0.88, p<0.0001) and (right) MODIS EVI (R^2 = 0.68, p<0.0001) with the linear regression line shown in red. Each data point (blue) represents a study site (n=46). The average VI for each study site is based on data from 2001 to 2006.

5.2.2. Identifying long-term trends in NDVI and EVI

Three key productivity metrics were calculated for each sensor data set (i) annual maximum NDVI and EVI, (ii) annual cumulative sum NDVI and EVI (hereafter referred to as ∑NDVI and ∑EVI), and (iii) coefficient of variation of NDVI and EVI. Using the Earth Trend Modeler in Idrisi Taiga (Eastman 2009), ordinary least squares (OLS) regression and Mann-Kendall non-parametric trend analysis were used to investigate the spatial-temporal trends of each NDVI and EVI productivity metric. The Earth Trend Modeler provides tools, which are unaffected by the presence of outliers, to determine the presence of linear and non-linear trends as well as their significance (Eastman 2009). The spatial statistical techniques provide more information than traditional (non-spatial) techniques (Fischer & Getis 2009).

A piecewise regression model, Breaks For Additive Seasonal and Trend (Verbesselt et al. 2010a; Verbesselt et al. 2010b), was applied to detect the timing and magnitude of the changes in the AVHRR NDVI, MODIS NDVI and MODIS EVI time series. This technique does not assume monotonic trends throughout the time-series but instead decomposes the time-series into gradual trends and abrupt changes at breakpoints (Wessels et al. 2012).

Linear trend analysis (OLS)

The ordinary least squares (OLS) regressions between each productivity metric (maximum, cumulative sum and coefficient of variation) versus time were applied per pixel for each sensor data set (AVHRR NDVI, MODIS NDVI and MODS EVI). The output is a spatially explicit expression of the slope of the regression expressed as the rate of change per year in each productivity metric as well as the associated statistical significance (expressed as the p-value).

Non-parametric Mann-Kendall Analysis

The rank based, non-parametric Mann-Kendall method (Kendall 1938) was applied to each productivity metric (maximum, cumulative sum and coefficient of variation) for each sensor data set (AVHRR NDVI, MODIS NDVI and MODS EVI). This is a non-linear trend indicator that measures the degree to which a trend is consistently increasing or decreasing. The Kendall's correlation coefficient ranges from -1 to +1 where a value of +1 indicates a trend that consistently increases and never decreases and the opposite is true of a value of -1. A value of 0 indicates no consistent trend (Eastman 2009).

Detecting breakpoints using Breaks for Additive Seasonal and Trend (BFAST)

The key concepts of the method for detecting Breaks For Additive Seasonal and Trend (BFAST) are explained below, but for technical elaboration please refer to Verbesselt et al (2010a; 2010b). BFAST is an additive decomposition model that iteratively fits a piecewise linear trend to a time series. It is given by the equation (Verbesselt et al. 2010b):

$$\boldsymbol{Y_t = T_t + S_t + e_t\,(t = 1, \dots, n)}$$

$\boldsymbol{Y_t}$ is the observed data at time t

$\boldsymbol{T_t}$ is the trend component

$\boldsymbol{S_t}$ is the seasonal component

$\boldsymbol{e_t}$ is the remainder or noise component

The BFAST model was run using the time series data derived from the AVHRR NDVI, MODIS NDVI and MODIS EVI datasets. Each time series was generated by extracting data from all three sensor data sets for each study site using a 2 km^2 grid and then averaging all the study site data. The 2 km^2 grids were created for each study site (n=46) based on the direction in which the repeat photograph was taken so as to include the corresponding area covered by the photograph (refer to Figure C.1 in Appendix C for an example of the methodology used). The BFAST model was run in the statistical software program R using the R code developed by the authors (Verbesselt et al. 2010a; Verbesselt et al. 2010b).

Various settings were tested and set prior to the analysis. These included the seasonal model used to fit the seasonal component, the maximum number of breaks that would be estimated and the maximum number of iterations for the calculation of the breakpoints in the components. The data was run using the harmonic seasonal model, the maximum number of breaks was set at default and the maximum number of iterations was 1.

5.2.3. RUE and RESTREND methods

In semi-arid regions, vegetation production is strongly correlated with rainfall and one of the biggest challenges is distinguishing inter-annual variability and trends in rainfall from human-induced impacts on vegetation (Wessels et al. 2007; Archer 2004; Evans & Geerken 2004). Satellite derived indices of rain-use efficiency and residual trends have been utilised in conjunction with vegetation indices. Both methods are based on the concept that land degradation causes a reduction in vegetation production per unit rainfall.

Rainfall data (1901 to 2009) obtained from the Climatic Research Unit of the University of East Anglia (CRU TS 3.1) was utilised in this chapter (refer to Chapter 3 section 3.2.1 for a full description of the dataset). The spatial resolution of the CRU TS 3.1 dataset (50 km grids) was insufficient to conduct a trend analysis at the scale of the entire study area and therefore RUE and standardised residuals were averaged across the study area. The analysis was only conducted up to and including 2009 since there is currently no CRU TS data for 2010, 2011 and 2012.

Relationship of NDVI and EVI with rainfall

In general there is a strong linear relationship between vegetation production and rainfall. A Log_e transformation was applied to the rainfall data and linear regression analysis was used to characterise the relationship between Log_eRainfall and both ∑NDVI and ∑EVI. A linear regression analysis was also conducted between the CV of rainfall and ∑NDVI and ∑EVI for each study site.

Rain-Use Efficiency

Annual rain-use efficiency (RUE) was estimated as the ratio of ∑NDVI to the total annual rainfall and a decrease in this efficiency is assumed to occur in association with land degradation (Wessels et al. 2007; Prince et al. 1998). For this analysis the rainfall data were not Log_e transformed in order to retain the original units; NDVI mm^{-1} or EVI mm^{-1}. The average annual RUE for the study area was calculated and then regressed over time in order to investigate trends in RUE. The slope of the regression and the associated p-value were the primary outputs of the analysis. The trend in RUE was compared across the three different data sets; AVHRR NDVI, MODIS NDVI and MODIS EVI.

Residual trend analysis

The Residual Trend Analysis (RESTREND) method assumes a linear relationship between ∑NDVI and the natural logarithm of rainfall (Log_e rainfall), (Wessels et al. 2007; Nicholson & Farrar 1994; Camberlin et al. 2007). The RESTREND method outlined by Wessels et al (2007; 2011) was followed in this study. Firstly, the regression between ∑NDVI and Log_e rainfall was calculated using the ordinary least squares (OLS) regression method. Secondly, the residuals (difference between the observed ∑NDVI and the predicted ∑NDVI from the rainfall) as well as the standardised residuals (expressed as standard deviations) were calculated. The standardised residuals across the study area were then regressed over time and an average time-series produced. The slope of the regression and the associated p-value were the primary outputs of the analysis. The trends in the residuals represent trends in vegetation production independent of rainfall (Wessels et al. 2007; Evans & Geerken 2004) where a negative RESTREND may indicate land degradation and a positive RESTREND improvement in vegetation biomass and cover. The trend in standardised residuals were compared across the three different data sets; AVHRR NDVI, MODIS NDVI and MODIS EVI.

5.3. Results

5.3.1. Spatial patterns of NDVI and EVI

Figure 5.3 shows the average amount of vegetation production that occurs over one year (expressed as the long-term average maximum NDVI and EVI and the cumulative sum NDVI and EVI) and how that growth varies, (expressed as the long-term average coefficient of variation). The orange and red colours indicate lower NDVI or EVI values and a low amount of vegetation growth throughout the year and the blue and green colours indicate higher NDVI or EVI values and higher production throughout the year.

The AVHRR NDVI and MODIS NDVI and EVI datasets (Figure 5.3) demonstrate a similar spatial pattern of vegetation growth with the areas along the escarpment of the Kamiesberg mountain range (see Chapter 2 Figure 2.3) displaying higher maximum values. The annual cumulative sum provides an indication of the total production in the study area in an average year and ranges from 3 units in north-eastern Bushmanland to 15 units along the Kamiesberg mountain range and the coastal belt. The AVHRR dataset however, tends to overestimate the annual cumulative sum of NDVI. The coefficient of variation in NDVI and EVI is also shown to be affected by topographic features with the higher altitude areas having a greater inter-annual variation in NDVI and EVI than the inland and coastal areas. In addition, the spatial distribution of NDVI generally follows that of rainfall (refer to Chapter 2 Figure 2.4).

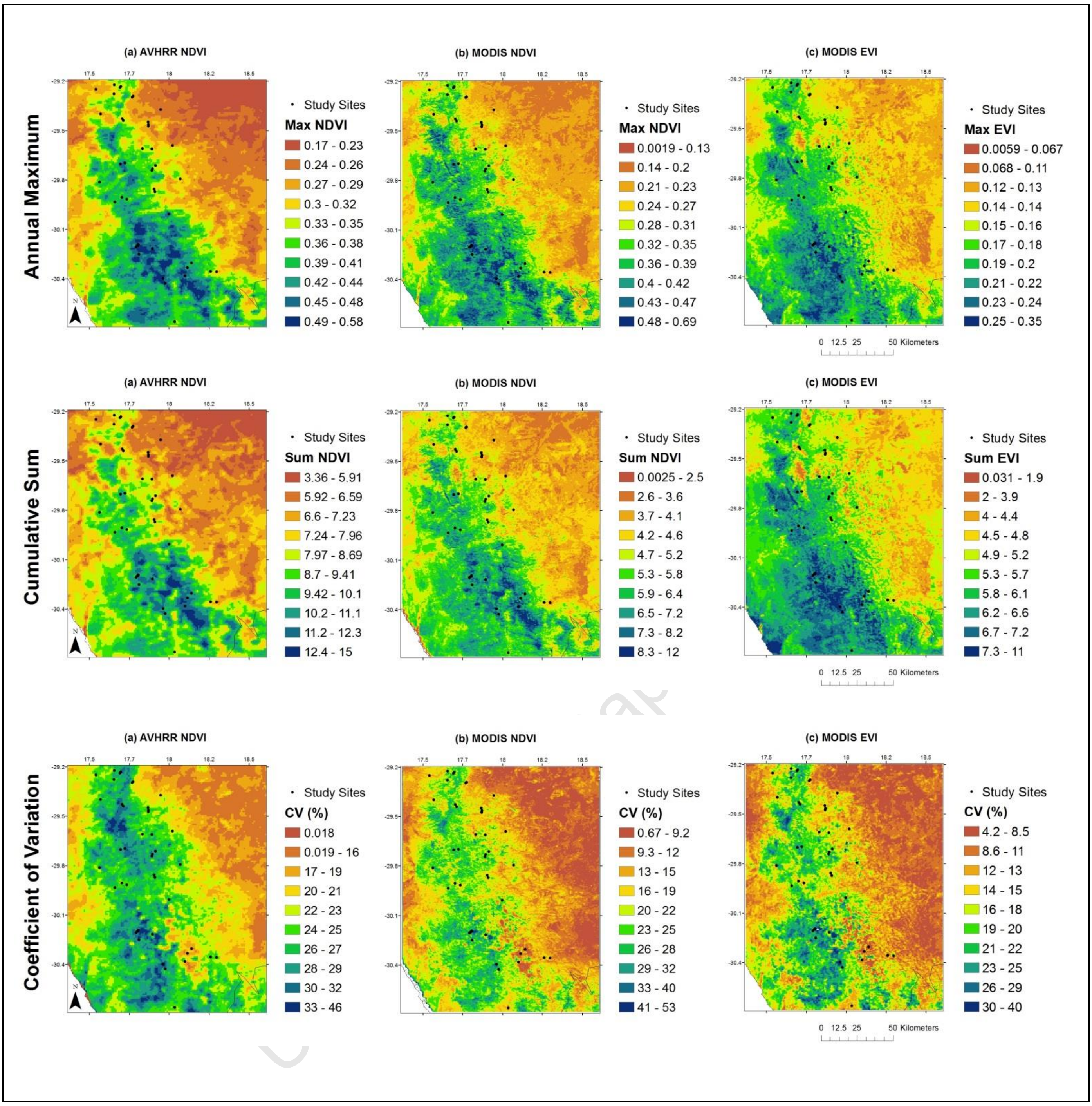


Figure 5.3: Long-term average annual maximum, cumulative sum, and coefficient of variation of NDVI and EVI derived from (a) AVHRR NDVI, (b) MODIS NDVI and (c) MODIS EVI datasets for the 1986-2006, 2001-2009 and 2000-2011 periods respectively. The repeat photography sites are indicated by the black dots.

5.3.2. Long-term trends in NDVI and EVI

In this results section spatially explicit trends as well as average trends for the study sites are discussed. The ordinary least squares (OLS) regression and the Mann-Kendall trend analysis indicate a significant decrease in annual maximum AVHRR NDVI over the escarpment and Kamiesberg mountain range (Figure 5.4 and Figure 5.5). The spatial trends analysis of the MODIS datasets however, indicates an increase in annual maximum NDVI and EVI over the central regions of the study area. The trends in annual cumulative sum of NDVI and EVI demonstrate a similar spatial pattern (Figure 5.6 and Figure 5.7).

The spatial trend analysis also reveals a significant decrease in annual maximum AVHRR NDVI and MODIS EVI over the north-eastern region of the study area that forms part of Bushmanland (Figure 5.4 and Figure 5.5). This observation is more noticeable in the trend analysis of annual cumulative sum of NDVI and EVI where a significant decreasing trend is observed in all three datasets (Figure 5.6 and Figure 5.7). Furthermore, a significant increase in cumulative sum of AVHRR NDVI and MODIS NDVI is observed along the coastline and further northwards (Figure 5.6 and Figure 5.7). Noticeable increases along the river courses are also observed in the spatial trend analysis of the cumulative sum of MODIS NDVI (Figure 5.6 and Figure 5.7).

A significantly decreasing trend in the coefficient of variation of AVHRR NDVI is observed across the entire study area (Figure 5.8 and Figure 5.9) whereas significant increase in the coefficient of variation of MODIS NDVI and EVI is observed over the Kamiesberg (Figure 5.8 and Figure 5.9).

The Breaks For Additive Seasonal and Trend (BFAST) method adds considerable value to the interpretation of the differing trends observed over the escarpment region derived from the AVHRR and MODIS sensor datasets. Figure 5.10 illustrates the detected trend changes within the AVHRR NDVI (1986-2006), MODIS NDVI (2001-2009), and MODIS EVI (2000-2011) time series. A positive trend is observed in both the AVHRR and MODIS datasets during overlapping years (for example 2000-2006). This suggests that the spatial trends presented previously are dependent on the start and end dates of the time series. A comparative ordinary least squares (OLS) regression and Mann-Kendall spatial trend analysis of all three datasets between 2000 and 2006 revealed similar trends over the central escarpment region of the study area. The BFAST decomposition demonstrates a statistically significant decreasing trend of -0.010 and -0.018 in AVHRR NDVI between 1985 and 1993 and between 1993 and 1997 respectively (Figure 5.10). Consequently, the addition of years to the beginning of the AVHRR NDVI dataset results in an overall negative trend observed in the spatial outputs. Lastly, the BFAST decomposition detected a recent decline in MODIS NDVI and EVI after 2006.

The time series of NDVI and EVI metrics for the communal and commercial study sites demonstrate trends similar to those describe previously (refer to Figure C.2 in Appendix C). In addition, there was no difference in trends between north-facing and south facing slopes (refer to Figure C.3 in Appendix C).

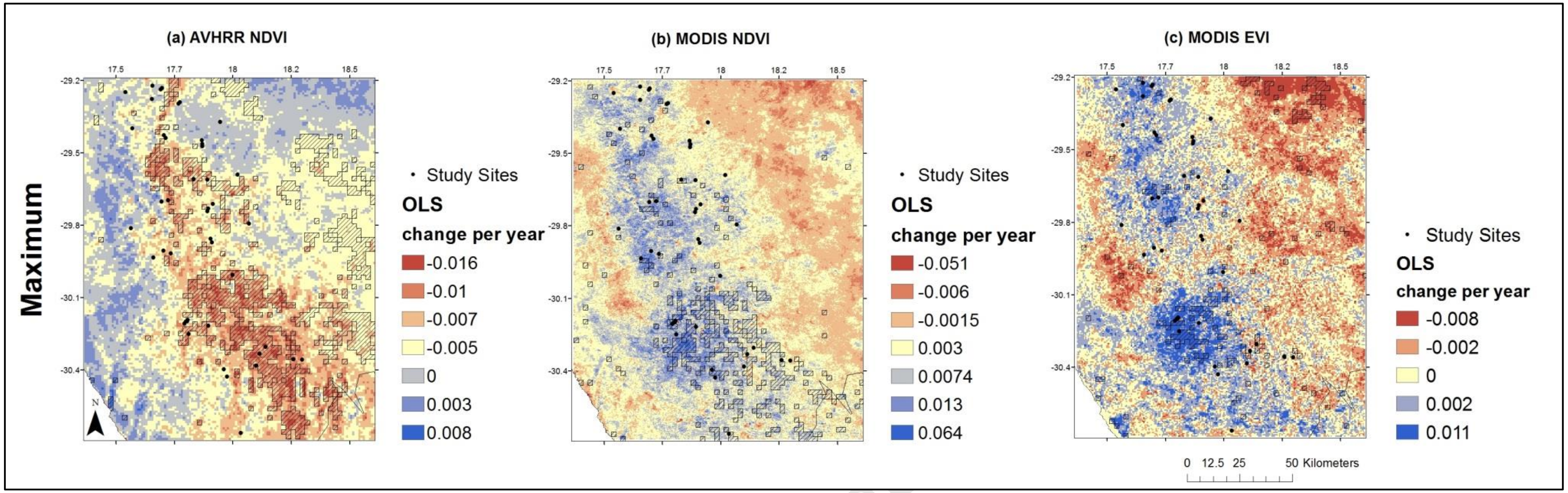


Figure 5.4: Ordinary Least Squares analysis of maximum (a) AVHRR NDVI, (b) MODIS NDVI, and (c) MODIS EVI. Red colours indicate negative change and green colours indicate positive change. Shaded areas highlight areas of significance. The repeat photography sites are indicated by the black dots.

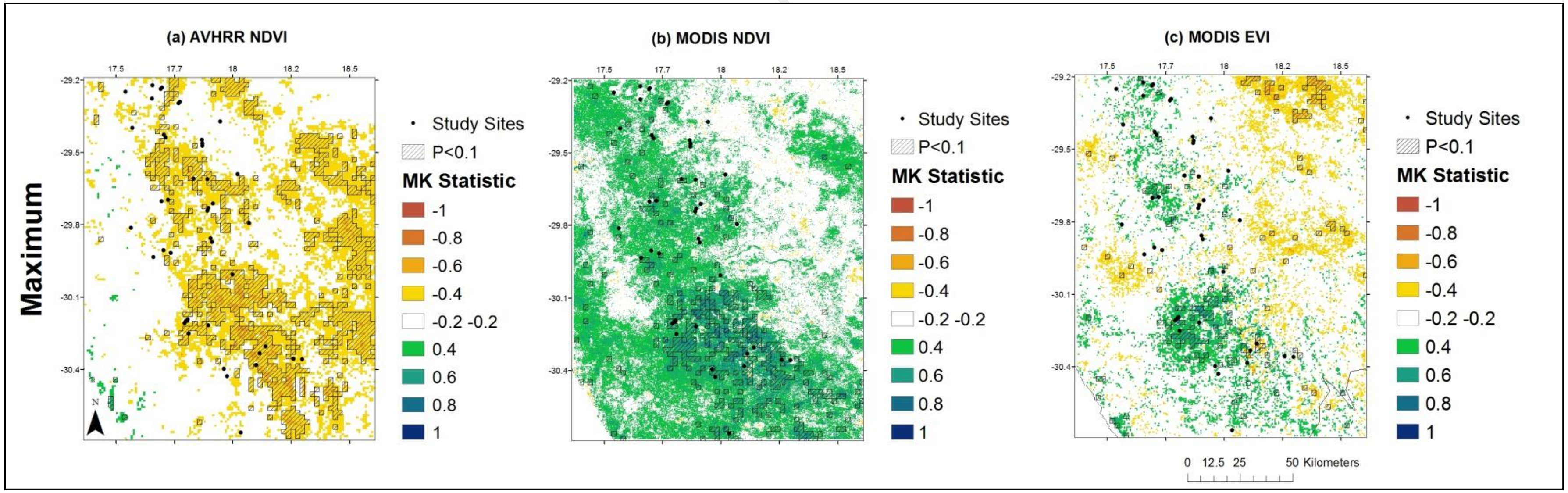


Figure 5.5: Mann-Kendall trend analysis of maximum (a) AVHRR NDVI, (b) MODIS NDVI, and (c) MODIS EVI. Red colours indicate negative change and green colours indicate positive change. Shaded areas highlight areas of significance. The repeat photography sites are indicated by the black dots.

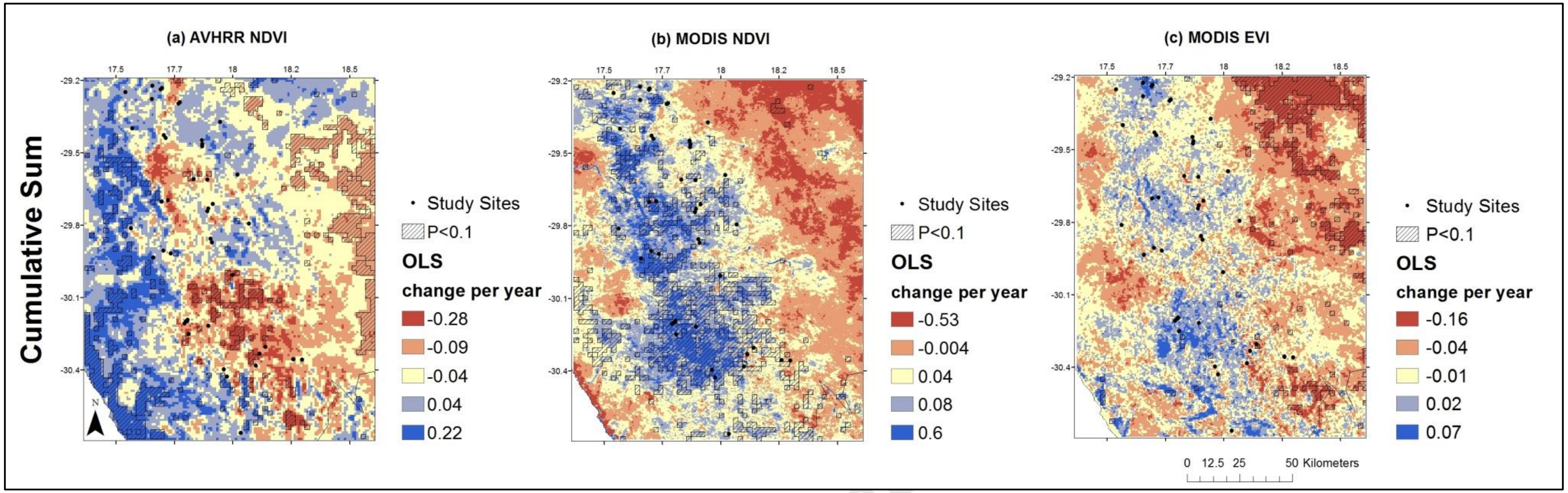


Figure 5.6: Ordinary Least Squares analysis of cumulative sum (a) AVHRR NDVI, (b) MODIS NDVI, and (c) MODIS EVI. Red colours indicate negative change and green colours indicate positive change. Shaded areas highlight areas of significance. The repeat photography sites are indicated by the black dots.

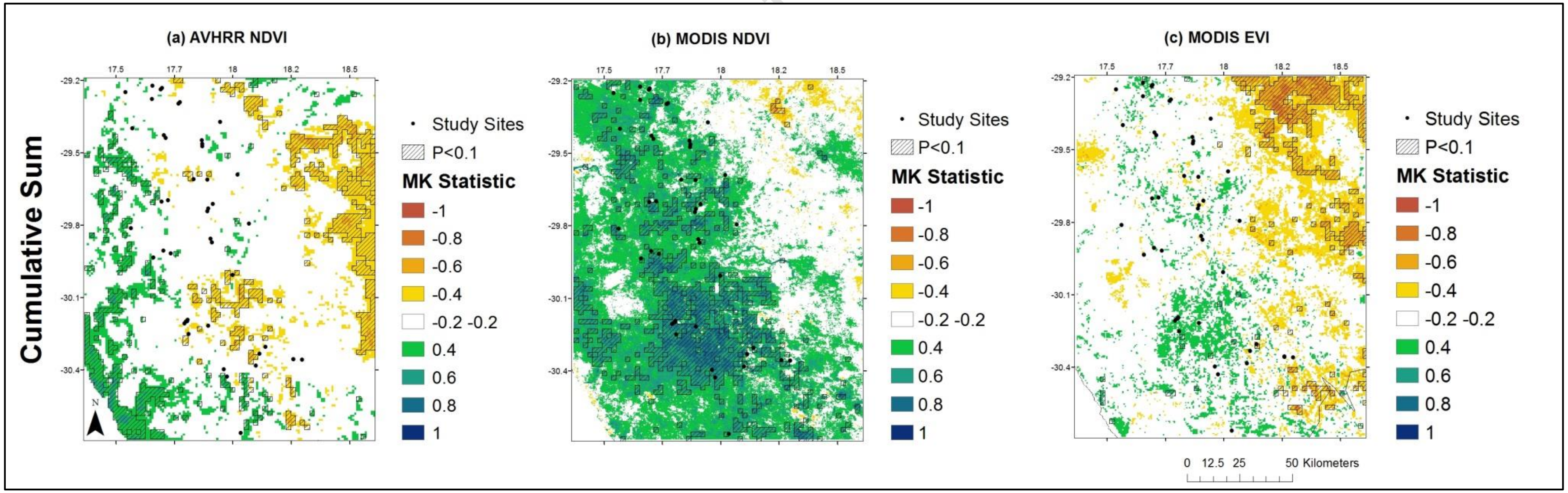


Figure 5.7: Mann-Kendall trend analysis of cumulative sum (a) AVHRR NDVI, (b) MODIS NDVI, and (c) MODIS EVI. Red colours indicate negative change and green colours indicate positive change. Shaded areas highlight areas of significance. The repeat photography sites are indicated by the black dots.

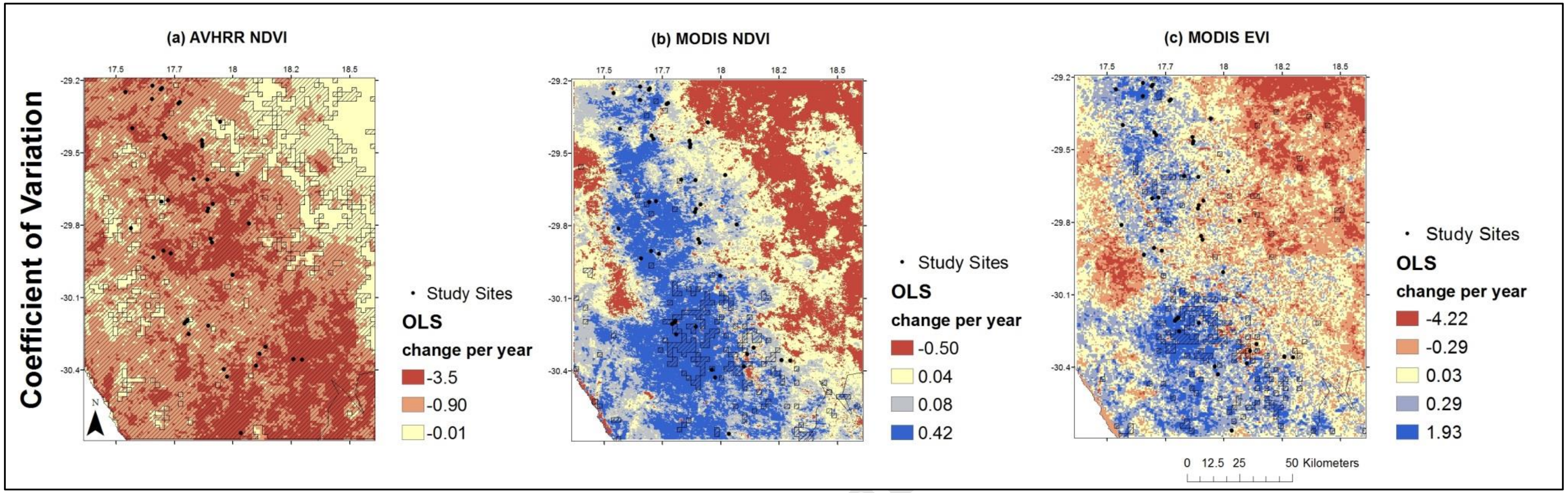


Figure 5.8: Ordinary Least Squares analysis of coefficient of variation (%) in (a) AVHRR NDVI, (b) MODIS NDVI, and (c) MODIS EVI. Red colours indicate negative change and green colours indicate positive change. Shaded areas highlight areas of significance. The repeat photography sites are indicated by the black dots.

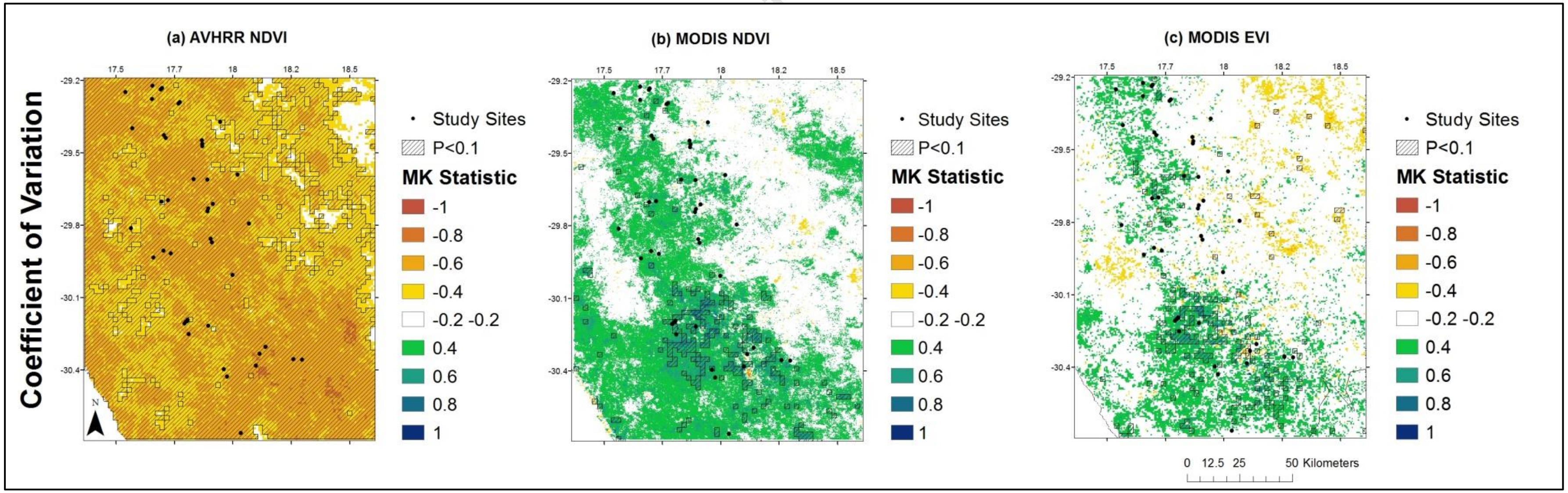
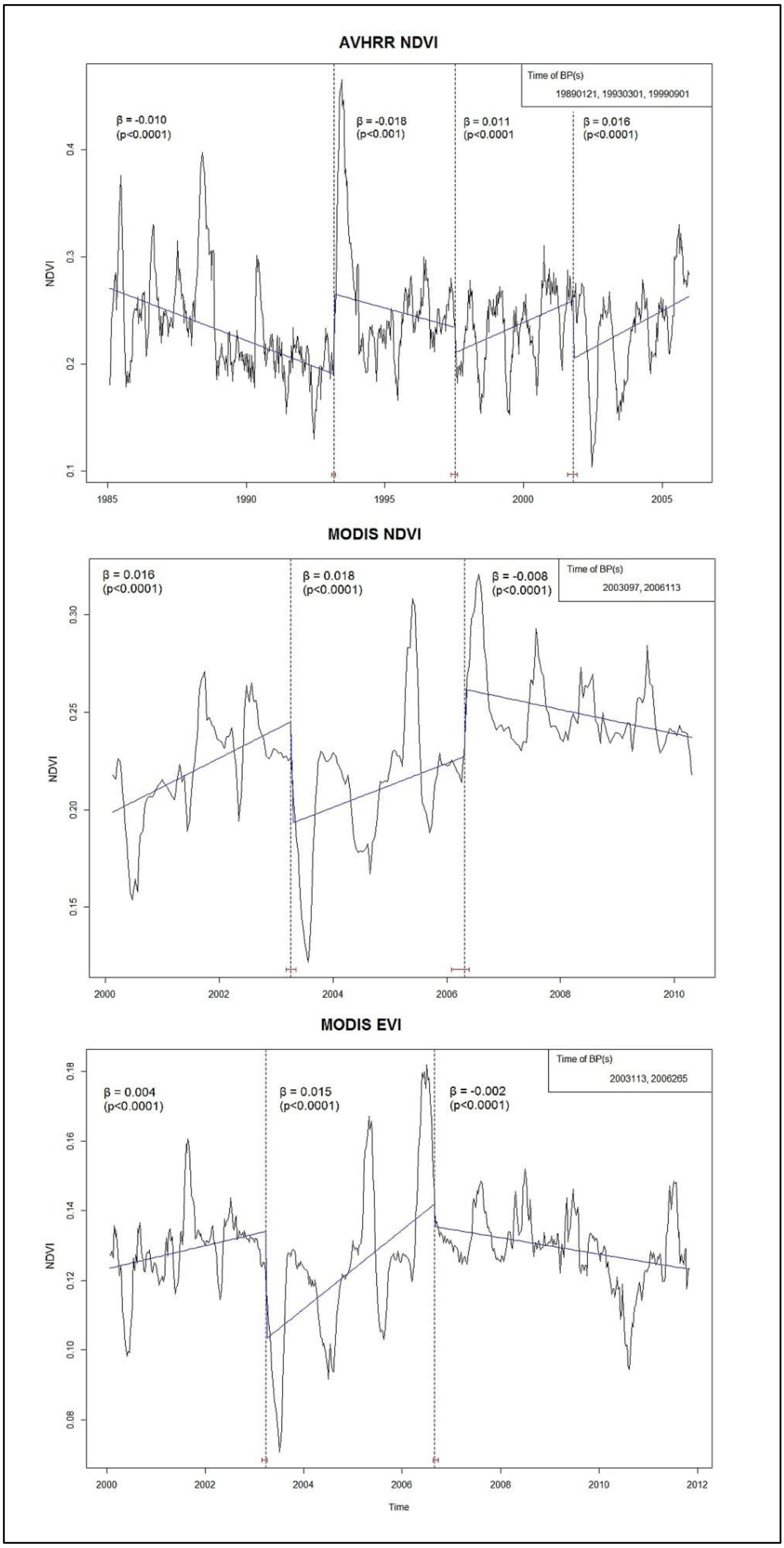


Figure 5.9: Mann-Kendall trend analysis of coefficient of variation (%) in (a) AVHRR NDVI, (b) MODIS NDVI, and (c) MODIS EVI. Red colours indicate negative change and green colours indicate positive change. Shaded areas highlight areas of significance. The repeat photography sites are indicated by the black dots.



<u>Figure 5.10:</u> Detected changes in the trend component (blue) of 16-day AVHRR NDVI data series between 1986 and 2006, 10 day MODIS NDVI data series between 2000 and 2010, and 8 day MODIS EVI data series between 2000 and 2011. Each data series (black) has been averaged across the study sites (n=46). The time of the change (---) together with its confidence intervals are also shown (|-|). The date of the breakpoints (BPs) is given in the top left corner of the graph. The slope coefficients (β) and the associated significance value (p) are given for the trend component.

5.3.3. RUE and trends in residuals (RESTREND)

Relationship of ∑NDVI and ∑EVI with rainfall

The Rainfall-∑NDVI and Rainfall-∑EVI relationships (Figure 5.11) differed in strength but showed very similar patterns. The correlation between AVHRR NDVI (R^2 = 0.45; p<0.0001) and the Log_e rainfall time series was the strongest indicating a strong relationship between rainfall and vegetation response patterns. The Rainfall-∑NDVI relationship for the MODIS dataset was slightly weaker but still significant (R^2 = 0.30; p<0.01). The Rainfall-∑EVI relationship (R^2 = 0.13; p=NS) was the weakest indicating that this vegetation index has not accounted for the influence of rainfall on vegetation growth. There was a strong negative relationship between the CV of rainfall and ∑NDVI for both the AVHRR (R^2 = 0.68; p<0.0001) and MODIS (R^2 = 0.54; p<0.0001) datasets as well as ∑EVI (R^2 = 0.24; p<0.0001).

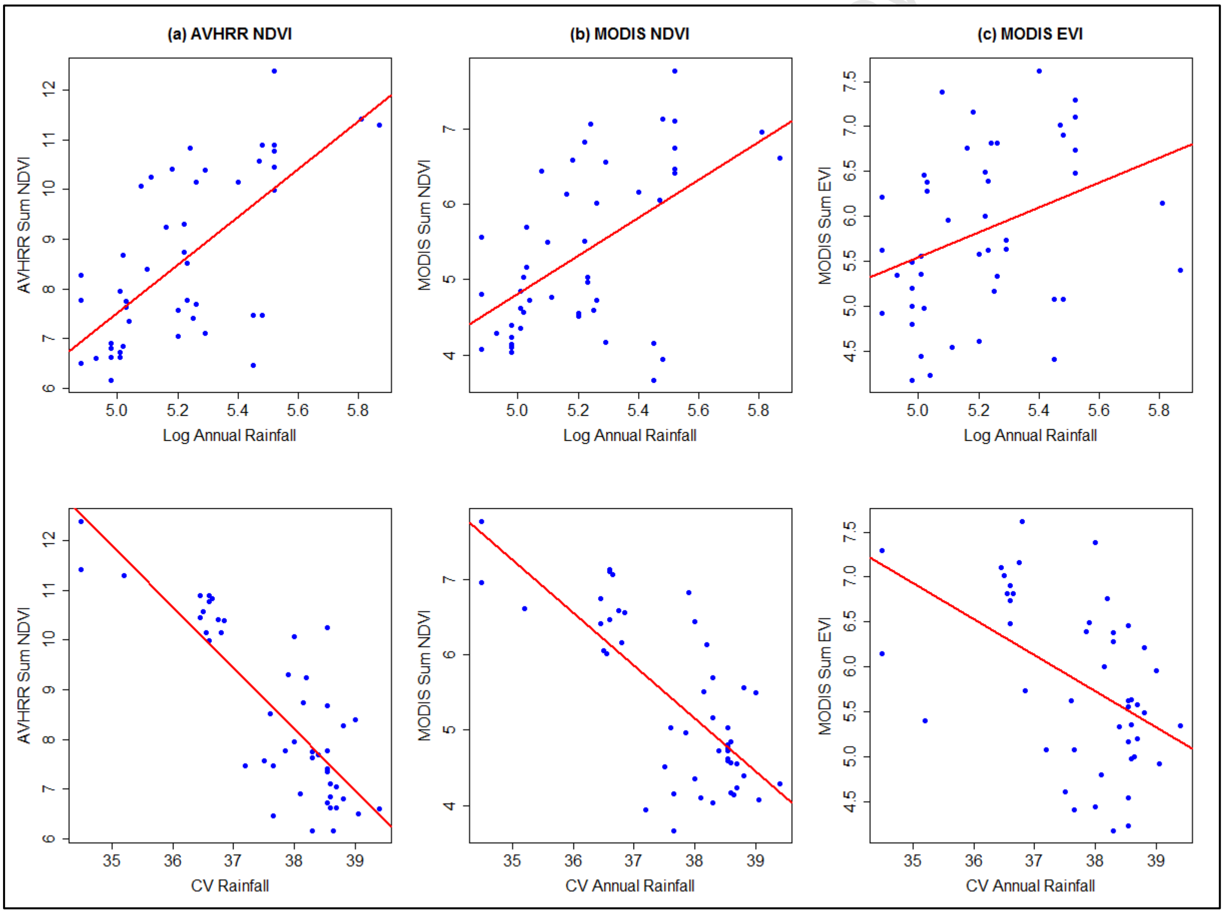


Figure 5.11: Relationship between cumulative sum (a) AVHRR NDVI, (b) MODIS NDVI, and (c) MODIS EVI and Log_e mean annual rainfall and coefficient of variation of rainfall. Each data point (blue) represents a study site (n=46).

Rain-Use Efficiency

The long-term average rain-use efficiency (RUE) derived from AVHRR NDVI and MODIS NDVI and EVI datasets for the study area is shown in Figure 5.12. Average annual RUE is low over the south-eastern part of the study area and increases westwards over the Kamiesberg towards the coastline. Figure 5.13 demonstrates that there has been very little change in RUE over time. The only statistically significant trend in RUE is that derived from the MODIS EVI dataset of an increase of 0.056 EVI mm^{-1} per year ($p<0.05$). The sensor datasets compare well where similar trends in RUE are observed during overlapping years. As with the trends in annual maximum and cumulative sum of NDVI and EVI presented above, the AVHRR data set tends to overestimate RUE (Figure 5.12 and Figure 13).

Residual trend analysis

The long-term average standardised residuals (expressed as standard deviations) demonstrate a similar spatial pattern of vegetation productivity to average RUE with the higher altitude regions demonstrating higher vegetation productivity and the north-eastern Bushmanland region exhibiting lower vegetation productivity values (Figure 5.14). In Figure 5.14, the negative standard deviations (shades of red) depict areas of lower vegetation productivity is lower than it should be, while positive standard deviations (shades of blue) depict areas that have higher vegetation productivity. Average standardised residuals from the three sensor data sets agree well (Figure 5.14). The time series of annual standardised residuals averaged across the study sites remains relatively constant for all indices demonstrating very little change in vegetation productivity between 1986 and 2009 (Figure 5.15).

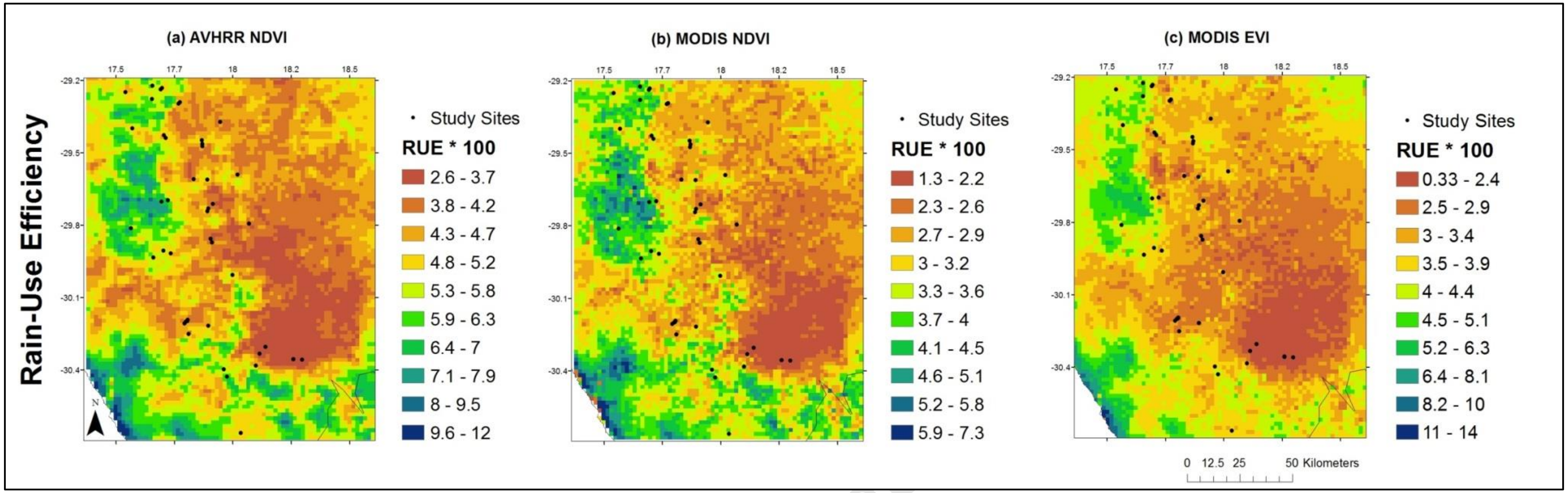


Figure 5.12: Long-term average rain-use efficiency (RUE) derived from the (a) AVHRR NDVI, (b) MODIS NDVI, and (c) MODIS EVI datasets for the 1986-2006, 2001-2009 and 2000-2011 periods respectively. The repeat photography sites are indicated by the black dots.

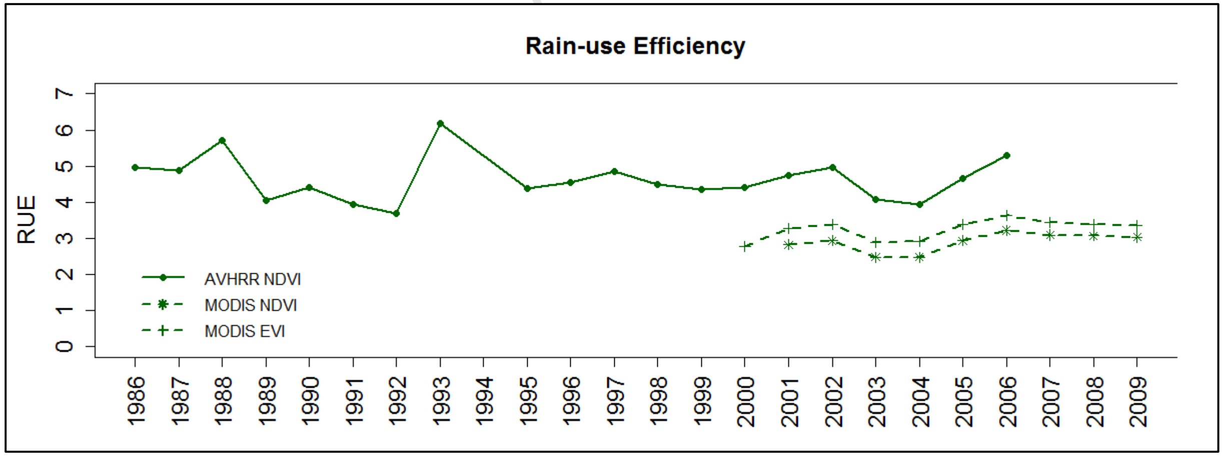


Figure 5.13: Time series of rain-use efficiency (RUE) averaged across the study sites (n=46) for the AVHRR NDVI, MODIS NDVI and MODIS EVI datasets for the 1986-2006, 2001-2009 and 2000-2009 periods respectively. RUE is expressed as the ratio of ∑NDVI to annual rainfall multiplied by 100.

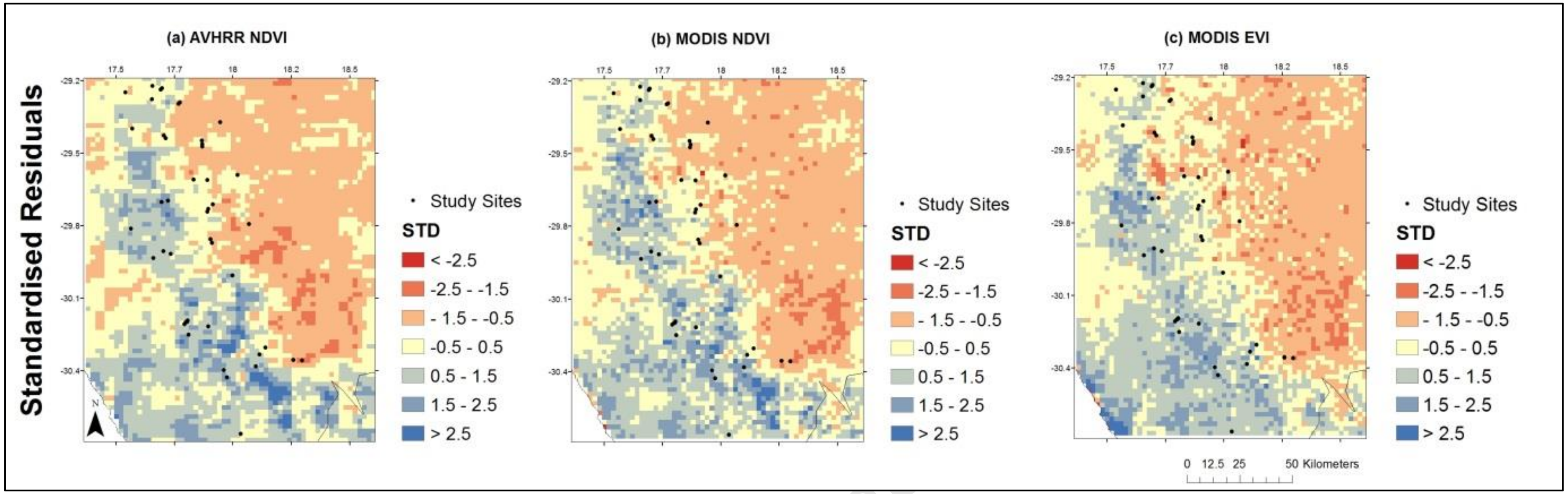


Figure 5.14: Long-term average standardised residuals derived from the AVHRR NDVI (left), MODIS NDVI (middle) and MODIS EVI (right) datasets for the 1986-2006, 2001-2009 and 2000-2011 periods respectively. The repeat photography sites are indicated by the black dots.

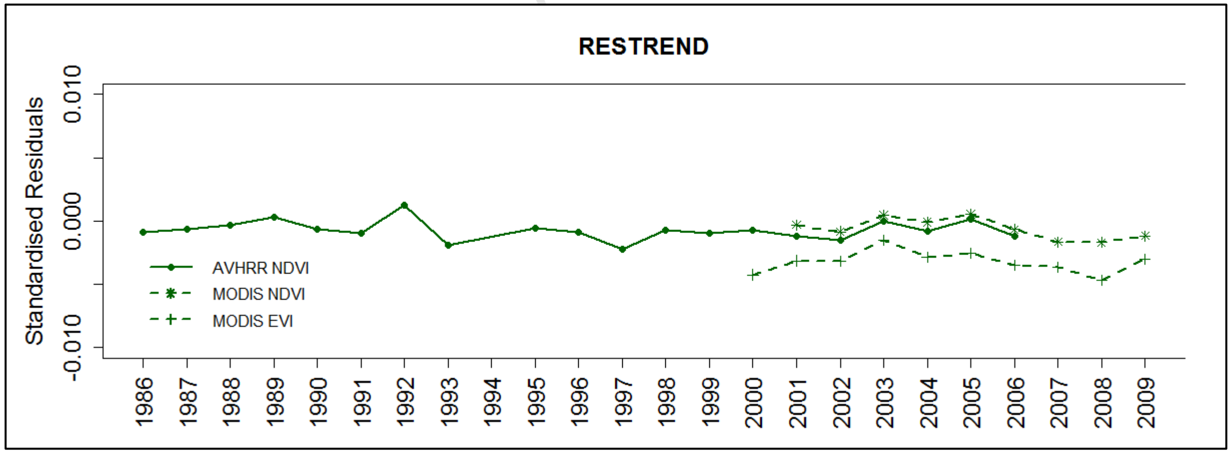


Figure 5.15: Time series of standardised residuals averaged across the study sites (n=46) for the AVHRR NDVI, MODIS NDVI and MODIS EVI datasets for the 1986-2006, 2001-2009 and 2000-2009 periods respectively.

5.4. Discussion

In this chapter, the AVHRR NDVI and MODIS NDVI and EVI datasets provided a useful indication of the spatial and temporal variability of vegetation in Namaqualand over the last 25 years. In general, the vegetation productivity in the study area is considerably variable both spatially and temporally.

The results demonstrate that the amount of vegetation production reflected by the magnitude of the NDVI and EVI values is strongly associated with altitudinal and rainfall gradients. The high rainfall and high elevation sites along the Kamiesberg escarpment have higher NDVI and EVI values whereas the low rainfall and low lying areas towards the eastern region of the study area have a low NDVI and EVI signal throughout the year. For Namaqualand, Fox et al. (2005) found similar spatial patterns in AVHRR NDVI and Anderson et al. (2010) found plant biomass to vary significantly in relation to the altitudinal and rainfall gradients. The correlation between rainfall and cumulative sum NDVI derived from AVHRR and MODIS was positive and significant (R=0.45 and R=0.3) indicating a close relationship between rainfall and vegetation growth in the region. This relationship is comparable to those reported elsewhere (Wessels et al. 2007; Fox et al. 2005). Others have also found that the NDVI signal responds positively to changes in rainfall (Anyamba & Tucker 2005; Evans & Geerken 2004; Olsson et al. 2005; Fensholt & Rasmussen 2011; Zhao et al. 2011). There was no significant relationship between MODIS EVI and mean annual rainfall for the study area.

To date, no assessments of vegetation change using remote sensing have been conducted for the Namaqualand region of South Africa. Bai et al. (2008) calculated linear trends in the sum of NDVI derived from AVHRR dataset for South Africa but the methods and conclusions of the study has been strongly criticized (Wessels 2009). The time-series analysis of AVHRR NDVI presented in this chapter demonstrated a general decline in vegetation productivity for the period 1986-2006 over the higher altitude regions. The time series analysis also suggests that the AVHRR sensor tends to overestimate NDVI. This is likely due to the spectral reflectance of soil that may indicate vegetation where there is none (Prince et al. 2004; Saltz et al. 1999). Between 2000 and 2011 the trends in MODIS NDVI and EVI demonstrate an improvement in vegetation conditions with the most pronounced increases occurring over the Kamiesberg. This recent increase in vegetation productivity is unlikely to be a result of changes in rainfall since no significant trends in mean annual rainfall were found in Chapter 3. The assessment of the repeat photographs at sites located along the escarpment (for example site 350 in Chapter 4) indicates an increase in vegetation production as a result of the abandonment of cultivation on commercial and communal farms. This suggests the role of smaller-scale factors, such as land-use, driving vegetation change in the study area.

Time series trends for the eastern part of the study area towards Bushmanland, derived from both AVHRR and MODIS datasets, show a consistent reduction in vegetation productivity. In Namaqualand, the loss of plant biomass in the low-lying communal areas is principally a result of heavy grazing practises (Anderson et al. 2010). The repeat photographs have shown that vegetation cover at sites located in these areas has been significantly impacted by both cultivation and grazing practises over long periods of time (for example site 131 in Chapter 4). The spatial trend analyses of the MODIS datasets also highlight distinct increases in vegetation cover along the river courses. The assessment of repeat photographs demonstrate that this increase is most likely consisting of invasive woody species such as *Acacia karoo* (refer to site 210a in Chapter 4).

A key limitation of the spatial trend analyses applied in this chapter is that they are based on a limited time-series where vegetation change occurring within the first or last two years of the time series is very difficult to detect (Wessels et al. 2007). The shorter time series from the MODIS datasets limits the statistical power of the linear trend analyses and thus the ability to detect trends in vegetation productivity. Unfortunately, the start date of the time series is determined by the beginning of the satellite record and there is a clear trade-off between the longer time series of the older AVHRR sensor with a lower resolution and higher noise when compared to the MODIS sensor with a shorter time series but higher resolution and less noise. Efforts to calibrate the MODIS data with the coarser resolution AVHRR data will allow for more comprehensive analyses of vegetation productivity over time. The period of assessment also has a large influence on the detection of linear trends and thus the results from the trend analyses presented above is only applicable to a certain period and trends may change following the addition of years to the time series. The AVHRR and MODIS time-series for overlapping years (2000-2006) display similar trends in vegetation production but over the full period of assessment they display differing trends demonstrating that the overall trend is strongly influenced by the length of the time series and the specific window observed.

The piecewise linear trends (Verbesselt et al. 2010a; Verbesselt et al. 2010b) technique, BFAST, was more applicable in this case since it does not assume monotonic trends throughout the time-series but instead decomposes the time-series into gradual trends and abrupt changes at breakpoints (Wessels et al. 2012). Considering the full AVHRR NDVI and MODIS NDVI and EVI time series, the BFAST results highlighted three periods of change in the vegetation productivity of the region. A decreasing trend was observed between 1985 and 1997, followed by an increasing trend between 1997 and 2006 and then a decreasing trend between 2006 and 2011. The recent declining trend in NDVI and EVI highlights the importance of continued monitoring. The analysis of historical rainfall records in Chapter 4 showed no significant change and thus this recent declining trend in NVDI and EVI is unlikely to be a result of a reduction in rainfall. This finding however needs further investigation.

The changes in the coefficient of variation of annual NDVI and EVI presented in this chapter could imply that changes in vegetation productivity are occurring at a seasonal time scale. This is especially the case over the escarpment region of the study area, which has shown dramatic shifts in the amount of inter-annual variation in vegetation production as expressed by the coefficient of variation. The assessment of the repeat photographs in Chapter 4 suggests that the majority of the change in vegetation observed in the region is principally a result of shift in dominance from annual and perennial plant species. This highlights the importance of understanding the phenology of the vegetation in the study area and determining whether the phenological response curve shows an amplitude shift as predicted by Thompson et al. (2009). The program TIMESAT is used in Chapter 6 to investigate the shifts in annual and perennial plant species.

The results from the trends in the cumulative sum NDVI and EVI can only provide possible indicators of vegetation improvement or degradation where a negative (positive) trend in greenness may not necessarily imply land degradation (land improvement). The RESTREND method and RUE should be more sensitive to detecting change in vegetation than the cumulative sum NDVI since it is expected to correct for rainfall variations and trends (Wessels et al. 2012; Prince et al. 2004). The trends in RUE and the standardised residuals were considerably smaller than those observed over the north-eastern part of South Africa (Wessels et al. 2007).

A key criticism of RUE is that it is strongly correlated with rainfall and in the short term it explains more about rainfall fluctuation than land degradation (Wessels et al. 2007; Prince et al. 2007). From the results lower RUE is more common in lower rainfall areas and thus the decline in RUE presented for some sites could be caused by a lower frequency of precipitation events in these areas. Wessels et al. (2012) note that RESTREND can only be performed where a strong relationship ($R > 0.4$) exists between sum NDVI and rainfall. The correlation between AVHRR NDVI and rainfall is stronger ($R=0.45$) than that between MODIS NDVI and EVI and rainfall ($R=0.3$ and $R=0.13$) highlighting that the RESTREND results derived from the MODS dataset may be less reliable. Furthermore, the weak relationship between rainfall and ∑EVI indicates that this index has not accounted for the influence of rainfall on vegetation production and thus may be a better indicator of land degradation than NDVI.

Chapter 6: Using satellite derived vegetation indices to detect changes in vegetation seasonality for Namaqualand between 1986 and 2011

6.1. Introduction

Vegetation phenology refers to the timing of seasonal biological events (for example bud burst, leaf unfolding, flowering, vegetation growth, and leaf senescence) and the abiotic and biotic forces that control these (Schwartz 2003). Vegetation phenology is strongly linked to climatic factors (e.g. temperature, rainfall) as well as changes in land cover (Heumann et al. 2007). Consequently phenology studies are utilised to identify and quantify climate related changes such as an earlier spring green up dates in the northern latitudes as well as the appearance and impact of land use changes (Zhao et al. 2012; Myneni et al. 1997; Van Den Bergh et al. 2012; Reed 2006). These studies are often limited in that field data only provide information for particular species and specific locations (Schwartz 2003; Wessels et al. 2011). Furthermore, there are only a few studies investigating phenological patterns in Namaqualand and even South Africa utilising remotely sensed information (Wessels et al. 2010; Fox et al. 2005).

Satellite derived phenology data provides spatially explicit information on the vegetation dynamics and patterns and allows for the monitoring of vegetation on a regional and global scale (Justice et al. 1985; Reed 2006). Even in arid areas with low NDVI values, phenology metrics are able to capture the spatial patterns of vegetation dynamics including seasonality, productivity and inter-annual variability (Heumann et al. 2007; Wessels et al. 2011). More specifically, remotely sensed phenology data have the potential to detect changes in the phenological cycle (expressed a the shift in the time of maximum growth and the trend of the seasonal amplitude) which can indicate changing proportions of functional vegetation types. For the Succulent Karoo, Thompson et al. (2009) hypothesise that degraded land would be dominated by annual plants which demonstrate spring growth pulses in NDVI.Intact vegetation, however, is dominated by a diverse array of perennial plants which produce a NDVI curve showing stable year-round growth. The historical repeat photographs, presented in Chapter 4, detected a shift in the dominance of annual and perennial plants suggesting that the vegetation composition in Namaqualand has improved over the last 100 years. A more thorough analysis of the trends in phenology is required in order to provide a quantitative indication of the change in annual versus perennial vegetation cover for Namaqualand.

A number of numerical methods have been developed to extract vegetation phenology from long-term satellite vegetation index data (de Jong et al. 2011b; Eklundh et al. 2012; Vrieling et al. 2013; Jönsson & Eklundh 2004; Zhang et al. 2003; Reed 2006; De Beurs & Henebry 2005). These methods fit mathematical functions to the time-series data and then extract various phenology metrics from these models, such as the start, end and length of the growing season from which seasonal vegetation productivity can be estimated (Wessels et al. 2011). The time-series analysis program, TIMESAT has been widely used to calculate phenology metrics from AVHRR and MODIS data (Wessels et al. 2010; Heumann et al. 2007; Olsson et al. 2005; Jönsson et al. 2010; Tan et al. 2011). TIMESAT fits a smooth continuous curve to the time-series data using Savitzky-Golay filtering, asymmetrical Gaussian, or double logistic functions (Jönsson & Eklundh 2004). These robust models are able to distinguish seasonal vegetation signals from the noise caused by cloud and atmospheric contaminations to reconstruct a clean time series for each image pixel (Wessels et al. 2010). The threshold method used by TIMESAT provides a robust and computationally simple method for identifying the start and end of the growing season (Wessels et al. 2010). The high degree of phenological variability between years however, demonstrates the necessity of distinguishing long-term phenological change from temporal variability. The Breaks For Additive Season and Trend (BFAST) method decomposes a time-series into seasonal variation, gradual trends and abrupt changes. BFAST estimates the time and number of changes in a time-series and characterises this change by its magnitude and direction (Verbesselt et al. 2010a; Verbesselt et al. 2010b). This approach is suited for detecting phenological changes in specific segments of the full time-series (Wessels et al. 2011).

This chapter utilises both the time-series program, TIMESAT, and the seasonal change detection method, BFAST, to further address the first research question of objective one: How has the vegetation cover of the study area changed over the last 25 years? This analysis adds value to that presented in Chapter 5 by providing a more detailed approach to investigating the long-term trend in vegetation patterns for Namaqualand which include seasonality, productivity and inter-annual variability.

6.2. Methodology

Figure 5.1 outlines the approach taken to analyse the trends in vegetation phenology for Namaqualand derived from Advanced Very High Resolution Radiometer (AVHRR) NDVI data and Moderate-resolution Imaging Spectroradiometer (MODIS) NDVI and EVI data (Refer to Chapter 5 section 5.2.1 for a full description of the satellite datasets utilised). The two approaches, BFAST and TIMESAT, utilised in this chapter to detect the changes in vegetation phenology are detailed in the following sections.

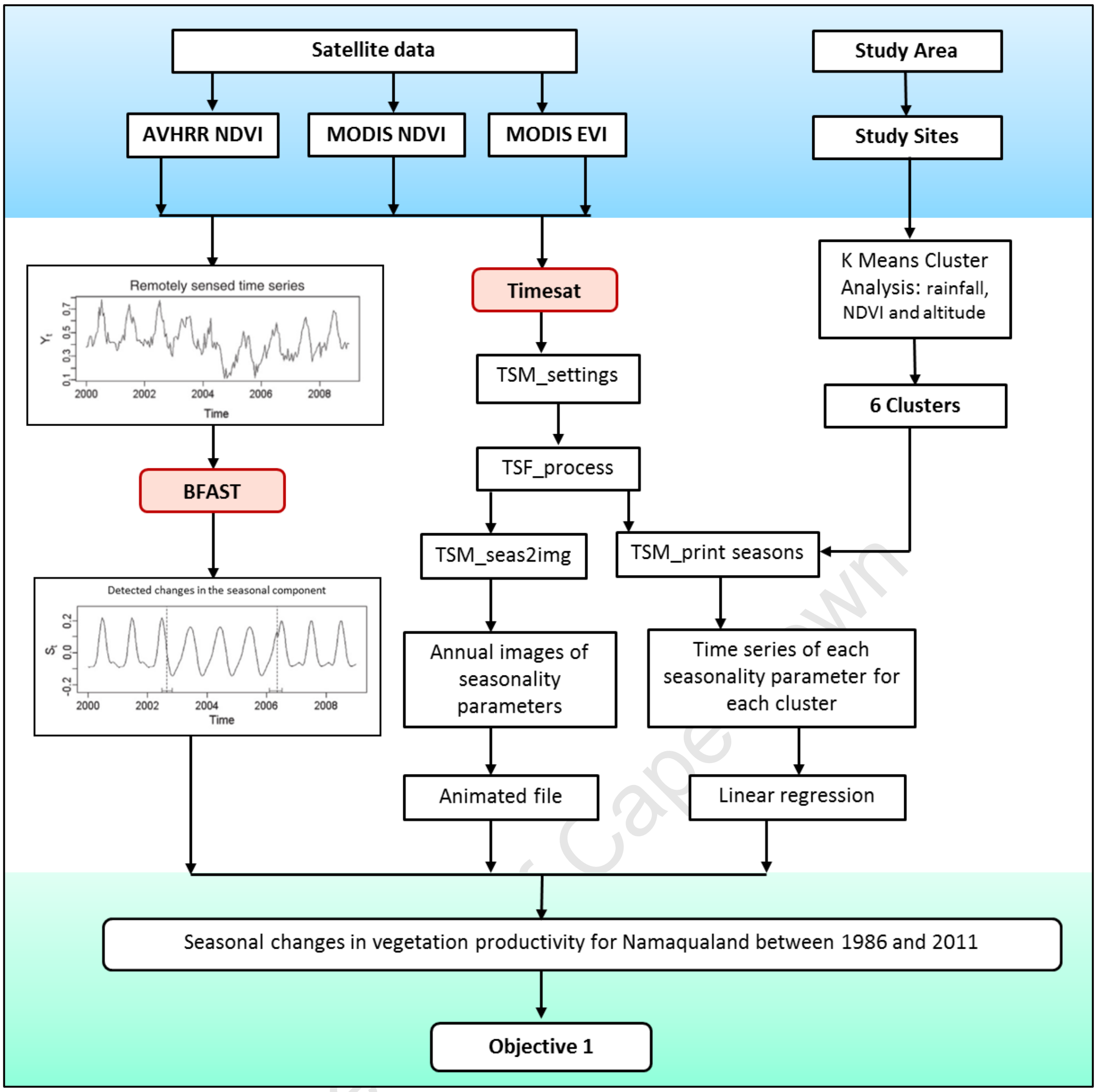


Figure 6.1: Flow diagram illustrating the methodological approach taken to determine the seasonal trends in NDVI and EVI. BFAST images taken from Verbesselt et al (2010a; 2010b).

6.2.1. Detecting seasonal breakpoints using Breaks for Additive Seasonal and Trend (BFAST)

The same method for detecting Breaks For Additive Seasonal and Trend (BFAST) as Chapter 5 (refer to section 5.2.2) is utilised here except that the seasonal component of the AVHRR NDVI, MODIS NDVI and MODIS EVI time series were calculated. Each time series was generated by extracting data from all three sensor data sets for each study site using a 2 km^2 grid (refer to Figure C.1 in Appendix C) and then averaging all the study site data. The data was run using the harmonic seasonal model, the maximum number of breaks was set at default and the maximum number of iterations was 1.

6.2.2. Extracting vegetation phenology from satellite data using TIMESAT

The time-series analysis program TIMESAT version 3.11 was used to calculate phenology metrics from the AVHRR NDVI, MODIS NDVI and MODIS EVI data sets. The adaptive Savitsky-Golay filter was used as it closely modelled the raw time series data while capturing the sudden rises in the data values (Wessels et al. 2010). A window width of 4 data points was used in the successive curve fitting steps. Vegetation in Namaqualand has one growing season per year and thus the number of growth seasons was assumed to be 1 and the 'season cut-off value' was set to 1 in TIMESAT.

From the fitted model functions a number of seasonality parameters (Figure 6.2) were extracted. The start, end, length and mid position of the growing season are referred to as 'phenology metrics' while the small integral, large integral, seasonal amplitude and base level are referred to as 'productivity metrics' (Wessels et al. 2010 and Jönsson & Eklundh 2004 ; refer to Table 6.1 for details). A user defined threshold of 20% of the seasonal amplitude, as measured from the left minima of the seasonal curve, was set as the start of the growing season (Figure 6.2). The growth season was therefore not fixed but variable in timing and length. The end of the growing season was defined as the date at which the right edge has decreased to 20% as measured from the right minima. The large integral is an estimate of the total vegetation production from the zero level whereas the small integral is a measure of vegetation production within the season calculated above the base level from the start of the season start to the end of the season (Jönsson & Eklundh 2004; Eklundh & Jönsson 2012).

6.2.3. Identifying long-term trends in vegetation phenology

Using TIMESAT, the long-term mean was calculated for all metrics and average maps were produced. The relationship between climate (rainfall and temperature) and each of the phenology and productivity metrics derived from each dataset was calculated using the Pearson's correlation coefficient. Annual maps of each phenology and productivity metric were produced using the TSM_seas2img function in TIMESAT. Seasonal information was therefore extracted for six clusters, identified by the K-means cluster analysis (Figure 6.3), using the TSM_printseasons function in TIMESAT. Linear regressions were then performed on each of the metrics to determine the changes over time.

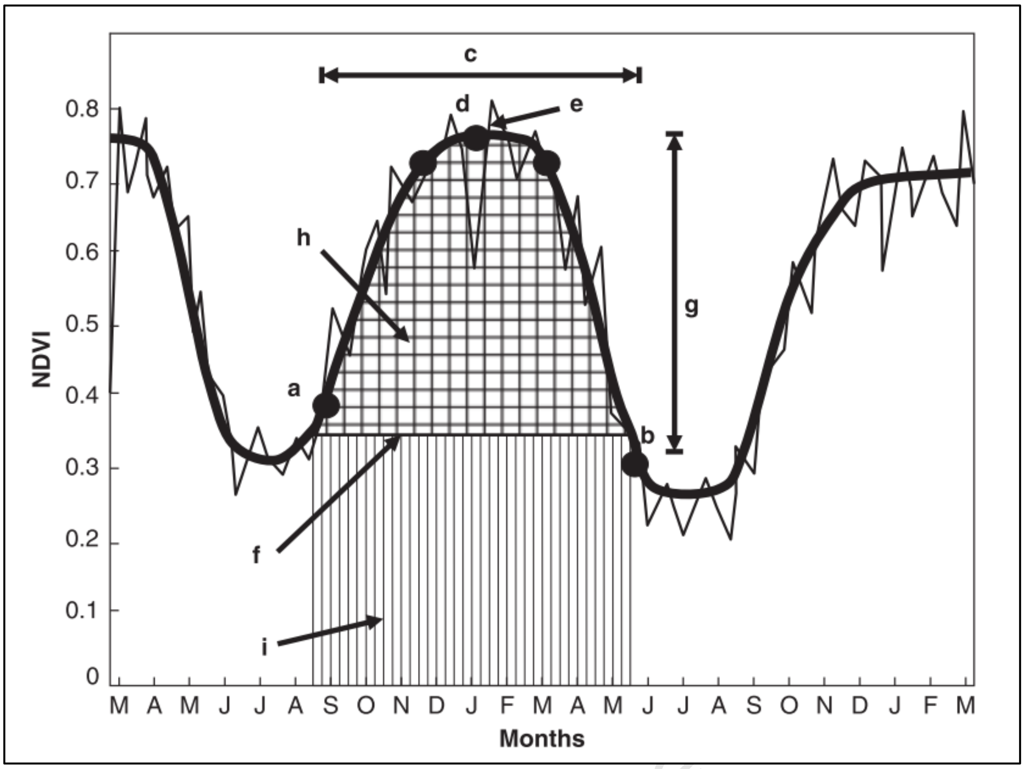


Figure 6.2: Phenology metrics extracted from the seasonal AVHRR NDVI, MODIS NDVI and MODIS EVI curves, as defined in TIMESAT (after Jönsson & Eklundh 2004) where (a) Start of season, (b) End of season, (c) Length of season, (d) Mid position of season, (e) Maximum NDVI, (f) Base level, (g) Seasonal amplitude, (h) Small seasonal integral, and (i) Large seasonal integral.

Table 6.1: Definitions of metrics shown in Figure 6.2, after (Jönsson & Eklundh 2004; Wessels et al. 2010).

Phenology metrics	Productivity metrics
a. Start of growing season: increase to 20% of seasonal amplitude as measured from the left minima of curve b. End of growing season: decrease to 20% of seasonal amplitude as measured from the right minima of curve c. Length of growing season: length of time from start to end of season d. Mid position of season: mean value of dates for which left edge increased to 80% and right edge decreased to 80%	e. Maximum NDVI: largest data value for the fitted function during the season f. Base level: average between left and right minima of curve g. Seasonal amplitude: difference between the maximum and base level h. Small seasonal integral: integral of growing season calculated between the fitted function and the base level i. Large seasonal integral: integral of growing season calculated between the fitted function and the zero level

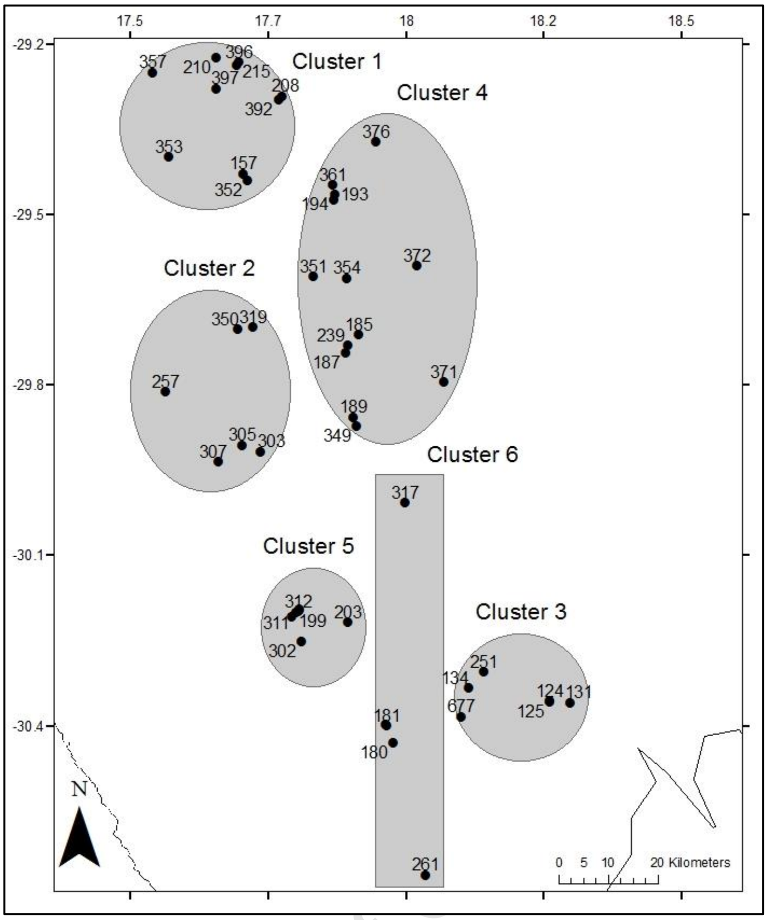


Figure 6.3: Location of the 6 clusters identified through K-Means cluster analysis and the study sites making up each cluster. The repeat photography sites are indicated by the black dots.

6.3. Results

6.3.1. Detecting phenological change in the AVHRR and MODIS time series using BFAST

The application of Breaks For Additive Seasonal and Trend (BFAST) to the AVHRR and MODIS time series produced estimates of the time and magnitude of major seasonal changes in vegetation production for the study area from 1986 to 2011. Figure 6.4 illustrates the detected phenological changes within the AVHRR NDVI (1986-2006), MODIS NDVI (2001-2009), and MODIS EVI (2000-2011) time series. The estimated average seasonal amplitude of the seasonal component is 0.2, 0.15 and 0.08 VI units for the AVHRR NDVI, MODIS NDVI and EVI time series respectively.

A major phenological change is identified in 1995 in the AVHRR NDVI time series which coincides with the launch of NOAA-14 sensor. Two seasonal breakpoints were detected in the MODIS NDVI time series whereas three were identified in the MODIS EVI time series. Both MODIS seasonal components demonstrate a decline in seasonal amplitude between

2000 and 2005, which is likely a response to the low rainfall totals recorded in 2003 and 2004 for the region (refer to Chapter 3). The increase in seasonal amplitude after 2005 implies that there is a slight lag between rainfall and vegetation recovery after a drought. A slight decrease in seasonal amplitude is observed after 2008 in the MODIS EVI time series.

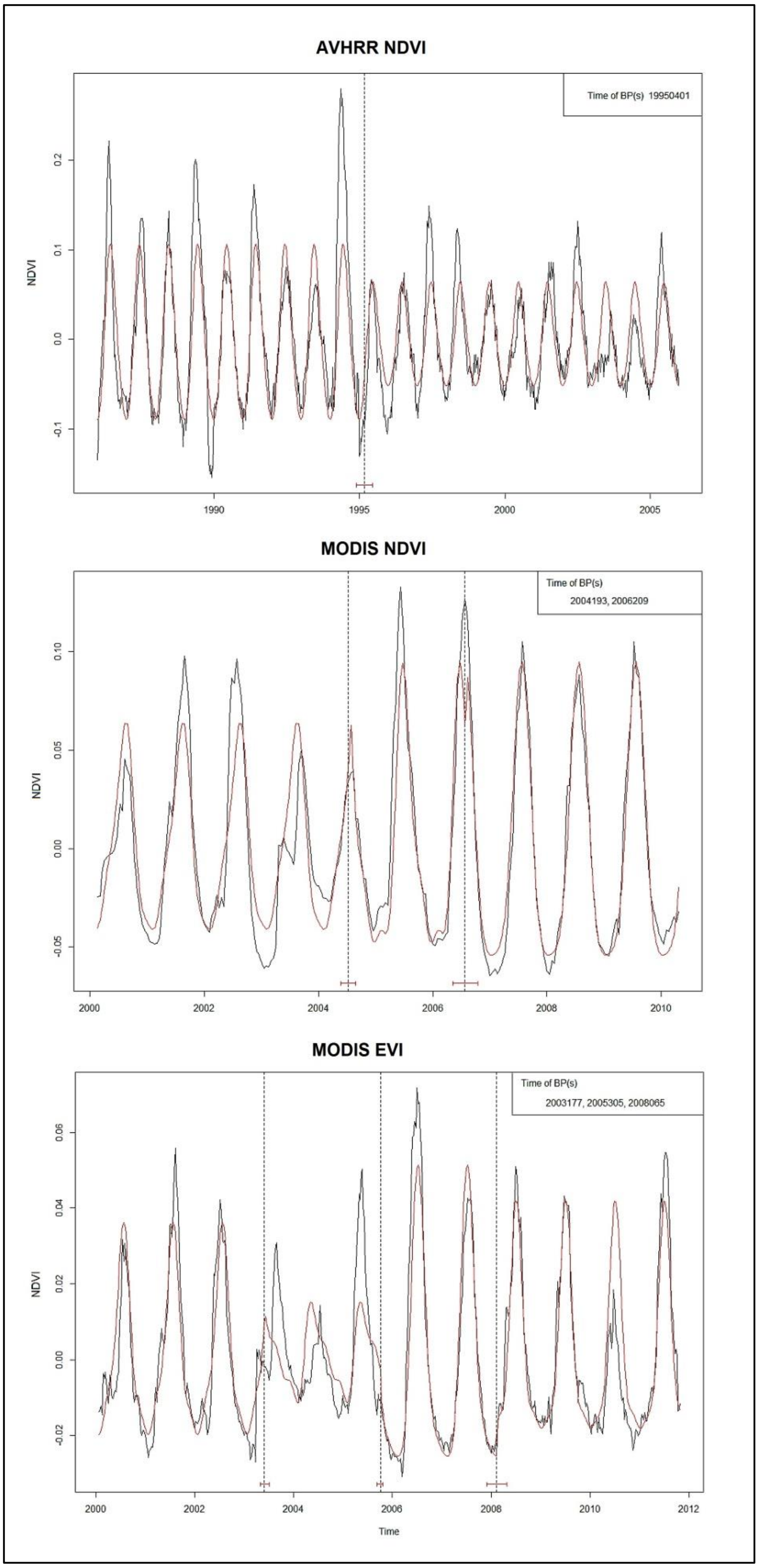


Figure 6.4: Detected changes in the seasonal component (red) of 16-day AVHRR NDVI data series between 1986 and 2006, 10 day MODIS NDVI data series between 2000 and 2010, and 8 day MODIS EVI data series between 2000 and 2011. Each data series (black) has been averaged across the study sites (n=46). The time of the change (---) together with its confidence intervals are also shown (|-|). The date of the breakpoints (BPs) is given in the top left corner of the graph.

6.3.2. Spatial patterns of phenology and productivity metrics

The maps of the average productivity and phenology metrics derived from AVHRR NDVI, MODIS NDVI and MODIS EVI datasets are given in Figure 6.5, Figure 6.6 and Figure 6.7 respectively. The sensor datasets compare fairly well where similar spatial patterns are observed. For the majority of the study area, the growing season starts in autumn (April and May). Later start dates (July to August) are observed in the ecotone between the winter and summer rainfall regions of the study area. The season peaks between August and September for the AVHRR NDVI dataset, June and July for the MODIS NDVI dataset, and July and August for the MODIS EVI dataset. The end of the season dates for the two MODIS datasets are very similar with the season ending in October and November for the majority of the study area whereas for the AVHRR NDVI dataset the season ends between January and February of the following calendar year. Consequently, a longer growing season of between 250 and 350 days (8 to 11 months) is identified from the AVHRR NDVI dataset. The length of the growing season derived from MODIS datasets is between 192 and 240 days (6 to 8 months).

The productivity metrics demonstrate clear altitudinal and rainfall gradients (Figure 6.7, 6.8 and 6.9), similar to those observed in Chapter 5. The areas along the escarpment and Kamiesberg mountain range demonstrate high seasonal amplitude, base level, maximum NDVI and EVI and small and large integral values.

Compared with the other two datasets, the MODIS EVI dataset was able to detect phenology and productivity patterns (Figure 6.7) for different land-use types (refer to Chapter 2 Figure 2.6 and Figure 2.7). Mining areas along the coastline and patches of cultivated land along the escarpment have later start and end dates of the growing season as well as a larger seasonal amplitude and a smaller integral.

Relationship of phenology and productivity metrics with climate

Correlations between metrics derived from TIMESAT and climatic variables are shown in Table 6.2 and Table 6.3. The phenology and productivity metrics derived from the AVHRR NDVI and MODIS NDVI datasets are generally most significantly correlated with mean annual rainfall and the coefficient of variation of annual rainfall. As demonstrated in Chapter 5, the MODIS EVI time series is not significantly correlated with annual rainfall or the coefficient of variation of annual rainfall. Maximum, EVI, base level and seasonal amplitude derived from the MODIS EVI time series are, however, significantly correlated with maximum temperature. This positive correlation differs from that of the correlation obtained for productivity metrics derived from the AVHRR NDVI time series, which demonstrate a significant negative correlation with maximum temperature. This difference could be attributed to the different start and end dates as well as to the small sample size of the MODIS datasets, which influences the relationship.

The length of the season derived from the AVHRR NDVI and MODIS NDVI datasets is negatively correlated with both temperature variables (Table 6.2). Minimum and maximum temperatures are also negatively corrected with the start, middle and end of season derived from the AVHRR NDVI dataset. The start and the middle of the season derived from the MODIS NDVI dataset are however, positively correlated with maximum temperature. Again, the small sample size of the MODIS NDVI dataset and later time period could account for these differences.

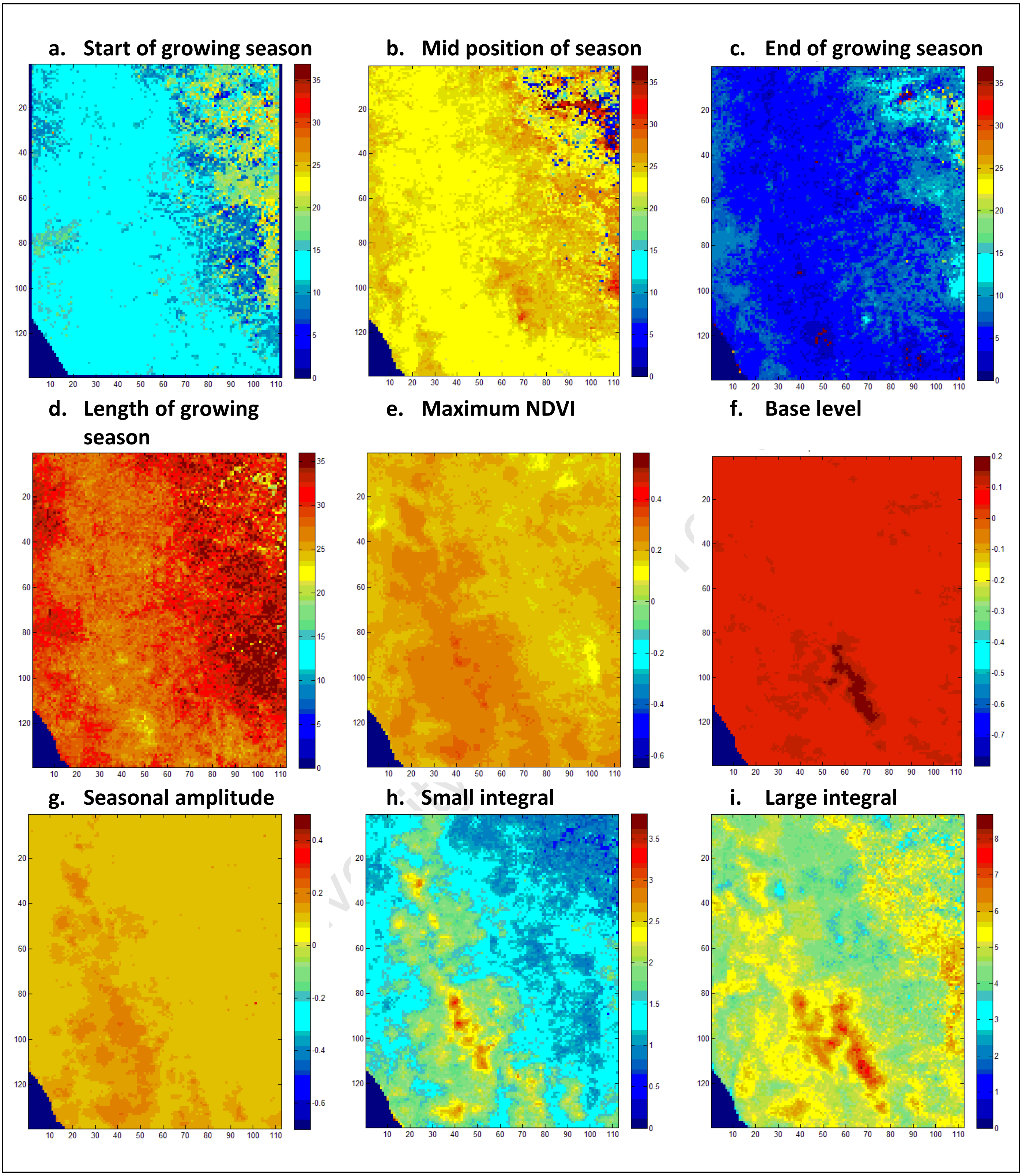


Figure 6.5: Mean of (a) start date of the growing season, (b) its peak, (c) its end date and (d) growing season length, (e) maximum NDVI, (f) base level, (g) seasonal amplitude, (h) small integral and (i) large integral as derived from 1 km^2 AVHRR NDVI time series from 1986-2006 for the study area. The values for (a)-(d) are expressed as decads (10 day periods) starting on 1 January of each year (value 1) to 21 December (value 36).

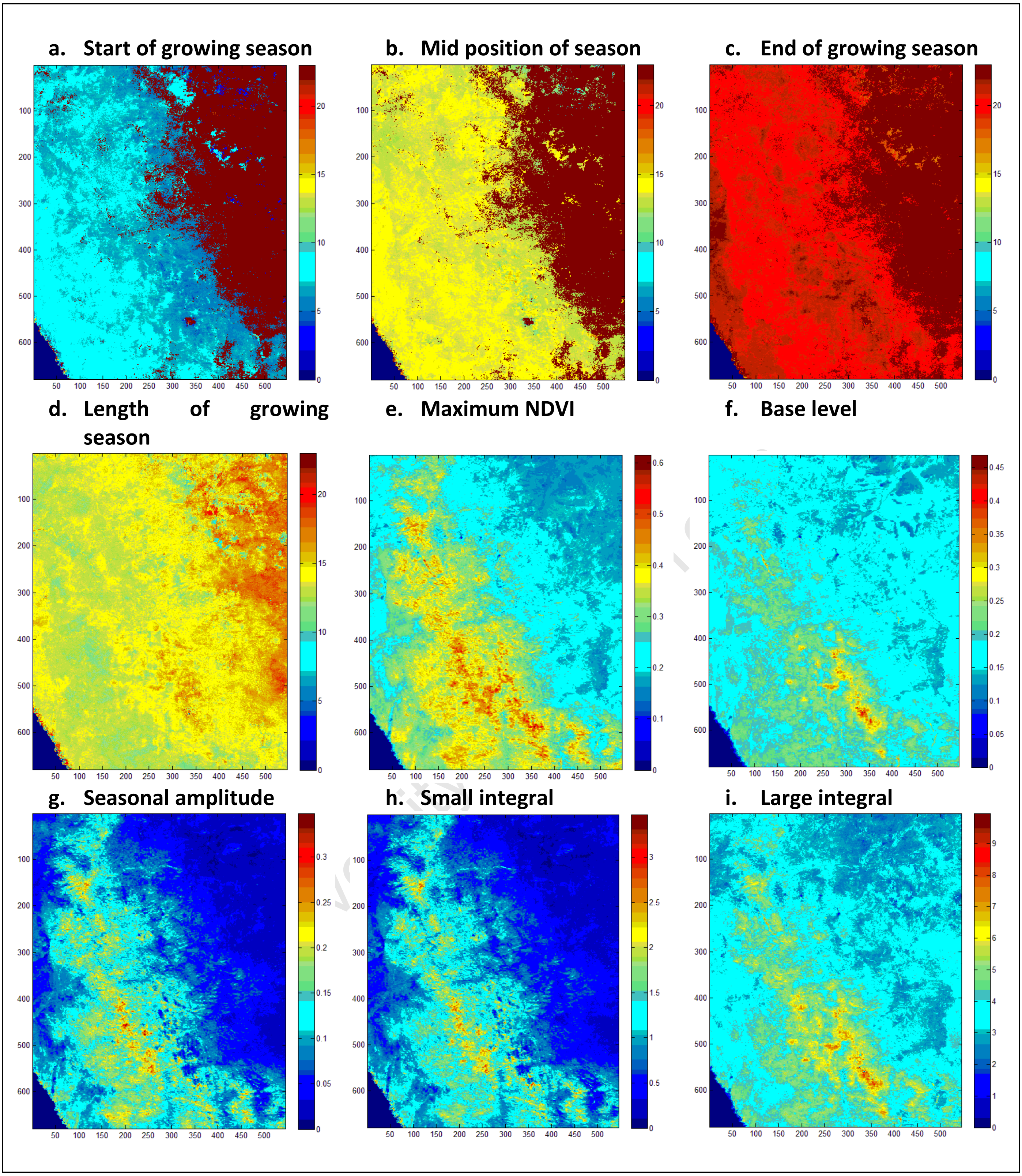


Figure 6.6: Mean of (a) start date of the growing season, (b) its peak, (c) its end date and (d) growing season length, (e) maximum NDVI, (f) base level, (g) seasonal amplitude, (h) small integral and (i) large integral as derived from 500 m^2 MODIS NDVI time series from 2001-2009 for the study area. The values for (a)-(d) are expressed as 16 day periods starting on 1 January of each year (value 1) to 19 December (value 23).

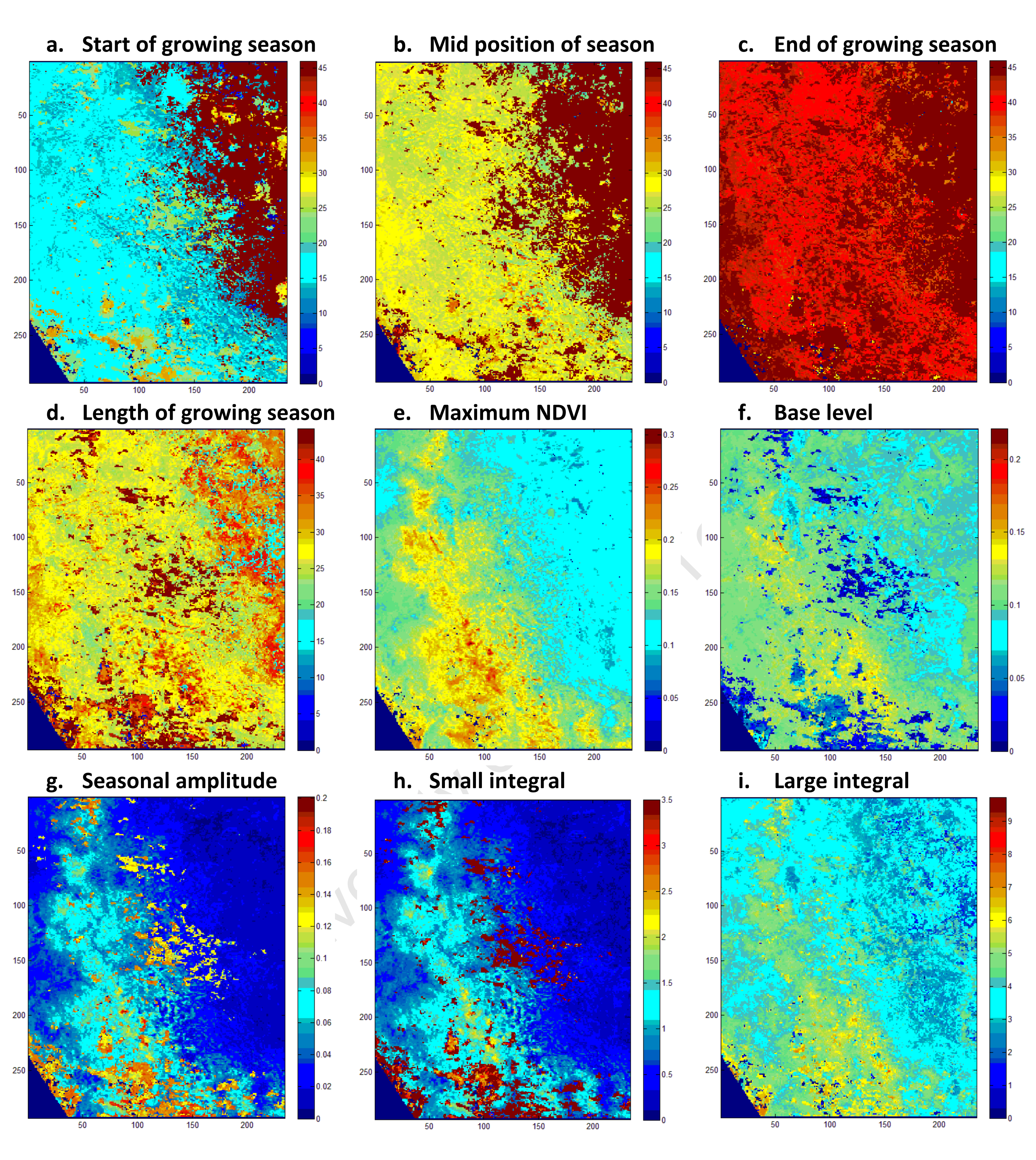


Figure 6.7: Mean of (a) start date of the growing season, (b) its peak, (c) its end date and (d) growing season length, (e) maximum EVI, (f) base level, (g) seasonal amplitude, (h) small integral and (i) large integral as derived from 500 m^2 MODIS EVI time series from 2001-2010 for the study area. The values for (a)-(d) are expressed as 8 day periods starting on 1 January of each year (value 1) to 27 December (value 46).

Table 6.2: Correlation matrix of phenology metrics derived from AVHRR NDVI, MODIS NDVI and MODIS EVI versus mean annual rainfall, the coefficient of variation in rainfall, and minimum and maximum temperature (n=47). Correlations are given as r values (Pearson's correlation). Significance values are given as: ***= p<0.001, **=p<0.01, *=p<0.05

Phenology metric	**Mean Annual Rainfall**			**Coefficient of Variation of Rainfall**			**Maximum temperature**			**Minimum temperature**		
	AVHRR NDVI	MODIS NDVI	MODIS EVI	AVHRR NDVI	MODIS NDVI	MODIS EVI	AVHRR NDVI	MODIS NDVI	MODIS EVI	AVHRR NDVI	MODIS NDVI	MODIS EVI
Start of season	0.38**	0.18	0.03	-0.18	-0.31*	-0.12	-0.28*	0.53***	0.07	-0.11	0.46***	-0.02
End of season	0.09	0.11	0.04	-0.03	-0.19	-0.10	-0.41**	-0.19	0	-0.50***	-0.17	-0.15
Length of season	0.02	0.21	0.02	0	-0.35*	0.02	-0.48***	-0.53***	-0.12	-0.59***	-0.46***	-0.21
Mid position of season	0.38**	0.35*	0.04	-0.30*	-0.46**	-0.14	-0.65***	0.41**	0	-0.61***	0.30	-0.17

Table 6.3: Correlation matrix of productivity metrics derived from AVHRR NDVI, MODIS NDVI and MODIS EVI versus mean annual, the coefficient of variation in rainfall, and minimum and maximum temperature (n=47). Correlations are given as r values (Pearson's correlation). Significance values are given as: ***= p<0.001, **=p<0.01, *=p<0.05

Productivity metric	**Mean Annual Rainfall**			**Coefficient of Variation of Rainfall**			**Maximum temperature**			**Minimum temperature**		
	AVHRR NDVI	MODIS NDVI	MODIS EVI	AVHRR NDVI	MODIS NDVI	MODIS EVI	AVHRR NDVI	MODIS NDVI	MODIS EVI	AVHRR NDVI	MODIS NDVI	MODIS EVI
Maximum NDVI	0.62***	0.29*	0.16	-0.73***	-0.52***	-0.22	-0.18	0.05	0.31*	-0.07	0.16	0.19
Base level	0.61***	0.40**	0.19	-0.74***	-0.48***	-0.25	-0.24	-0.18	0.27*	-0.13	-0.1	0.12
Seasonal amplitude	0.52***	0.25	0.10	-0.58***	-0.42**	-0.15	-0.10	0.12	0.30*	-0.01	0.22	0.25
Small seasonal integral	0.54***	0.12	0.12	-0.64***	-0.34*	-0.21	-0.15	0.15	0.22	-0.03	0.26	0.13
Large seasonal integral	0.59***	0.36*	0.19	-0.74***	-0.61***	-0.26	-0.24	-0.15	0.19	-0.20	-0.15	0.06

6.3.3. Trends in phenology and productivity metrics derived from TIMESAT

Phenology metrics

Over the last 25 years the start, middle and end of the growing season fluctuate by approximately 1.5 months (Figure 6.8). Over the analysis period, the start date of the growing season ranges from March to May, the peak date from June to August, and the end date from October to December. The growing season tends to come to an end before the following starts demonstrating that in the months between December and March there is limited vegetation growth. The inconsistent years are 1999, 2003 and 2004. The 1999 growing season starts in February which is earlier than any of the other years suggesting that there could have been late summer rains in that year. No growing season was identified for 2003 and 2004 based on the AVHRR NDVI and MODIS EVI datasets respectively. In addition, the 2003 growing season based on the MODIS NDVI dataset is shorter than any of the other seasons. The Standardised Precipitation Index (SPI) presented in Chapter 3 (Figure 2.6) identified below average annual rainfall for both 2003 and 2004.

In terms of the length of the growing season, there was no significant trend over the 25 year analysis period (Figure 6.9). The length of the growing season derived MODIS EVI dataset for cluster 3 did however, show a significant decline of 5.7 days ($p<0.01$), (refer to Appendix D for the individual cluster graphs).

Productivity metrics

In this section, the average time series of each of the 6 clusters are presented (refer to Appendix D for the individual cluster graphs). Figures 6.10 presents the trends in the productivity metrics obtained from the analysis in TIMESAT. Maximum NDVI derived from the AVHRR time-series demonstrates a significant decrease of 0.005 per year ($p<0.01$) whereas the maximum NDVI and EVI derived from the MODIS time-series remain fairly constant. The base level derived from both the AVHRR and MODIS NDVI datasets demonstrates a significant increase over the analysis period of 0.003 ($p<0.001$) and 0.002 ($p<0.01$) respectively. The time series of seasonal amplitude derived from the AVHRR NDVI data set demonstrates a significant decline of 0.008 ($p<0.0001$) whereas the MODIS NDVI and EVI time series show no change in the seasonal amplitude. A significant decline of 0.121 ($p<0.0001$) and 0.078 ($p<0.01$) is observed in the small and large integrals derived from the AVHRR NDVI time series. There are no statistically significant trends in the small and large integrals derived from the MODIS datasets.

In terms of the trends for individual clusters, cluster 3 demonstrates a consistently declining trend in all of the productivity metrics, except for the base level. Specifically, a decline of 0.008 per year ($p<0.001$) in maximum AVHRR NDVI, 0.01 per year ($p<0.0001$) in seasonal amplitude, 0.15 per year ($p<0.0001$) in small integral and 0.1 per year ($p<0.01$) in large integral are observed (refer to Appendix D for the individual cluster graphs).

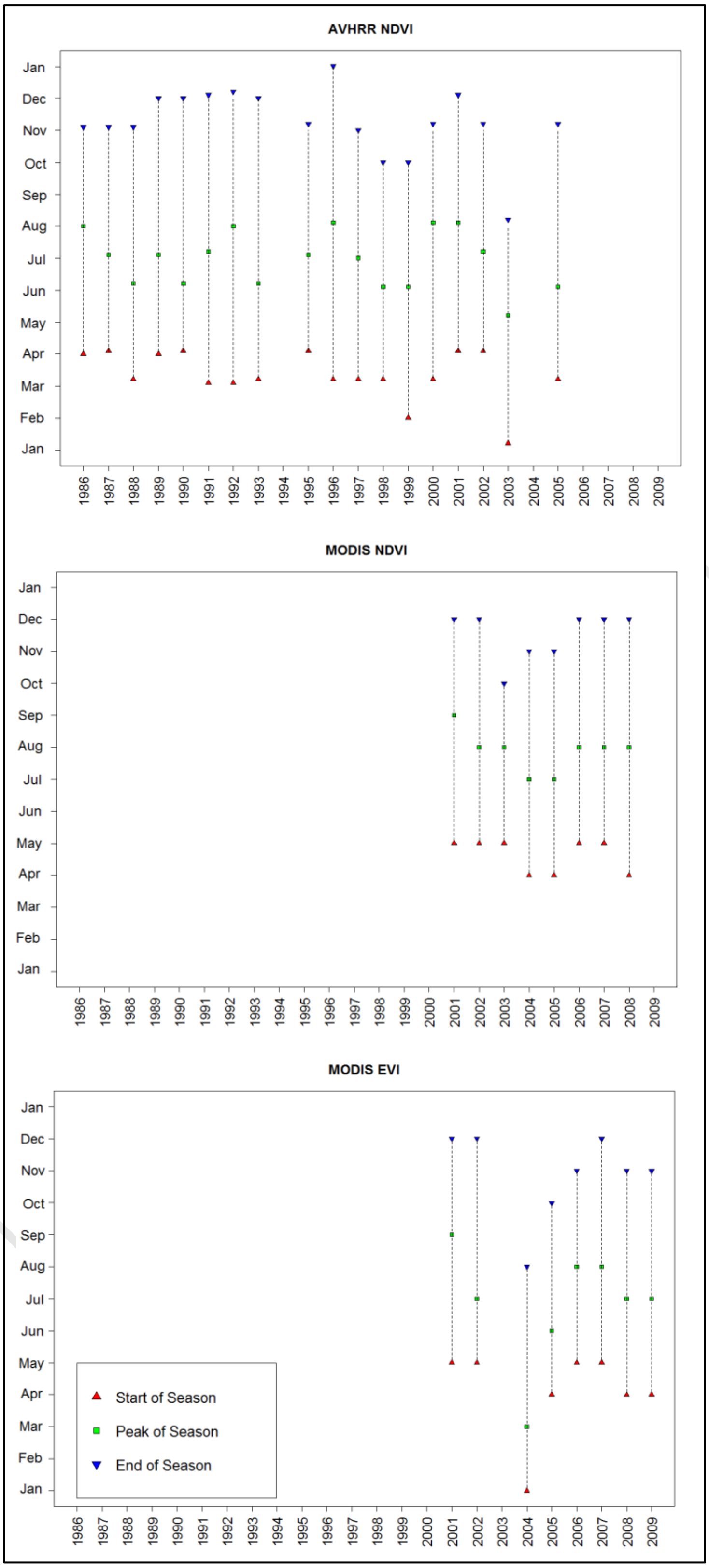


Figure 6.8: Phenology metrics averaged across the clusters (n=6) for the AVHRR NDVI, MODIS NDVI and MODIS EVI datasets for the 1986-2006, 2001-2009 and 2000-2009 periods respectively. The upward red arrow indicates the start of the season, the green square the middle of the season, and the downward blue arrow the end of the season.

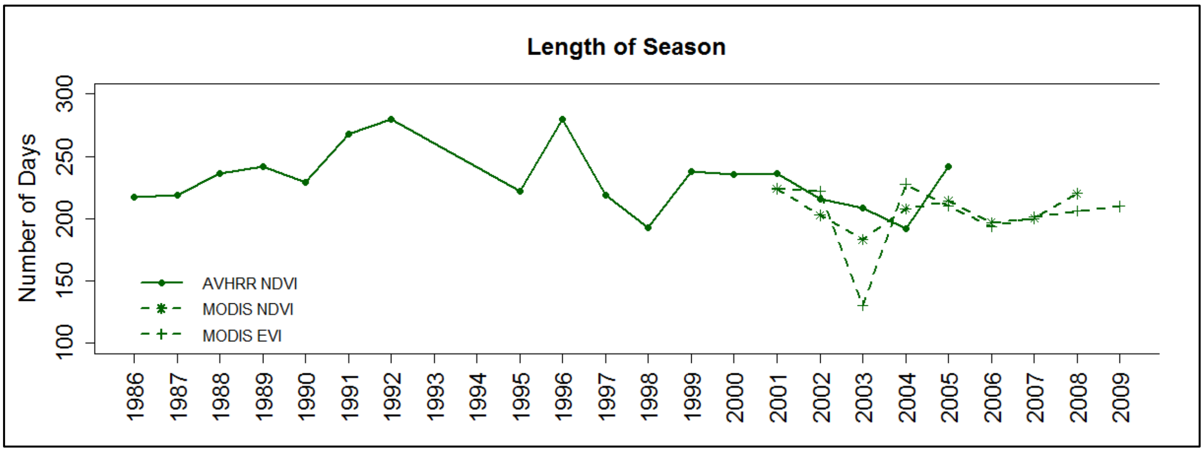


Figure 6.9: Time series of the length of the growing season averaged across the clusters (n=6) for the AVHRR NDVI, MODIS NDVI and MODIS EVI datasets for the 1986-2006, 2001-2009 and 2000-2009 periods respectively.

Figure 6.10: Time series of maximum vegetation productivity, base level, seasonal amplitude, small integral and large integral averaged across the clusters (n=6) for the AVHRR NDVI, MODIS NDVI and MODIS EVI datasets for the 1986-2006, 2001-2009 and 2000-2009 periods respectively.

6.4. Discussion

There have been very few phenological studies undertaken in the Succulent Karoo biome and even fewer which have assessed trends in phenology over time (Van Rooyen et al. 1979; Struck 1992; Struck 1994). In one of the few studies for Namaqualand, Fox et al. (2005) utilised AVHRR NDVI data to map the average phenological patterns of vegetation in Namaqualand. The results presented in this chapter build on the findings of Fox et al. (2005) by providing valuable information on the trajectory of phenology metrics for the region. Furthermore, this study improves on that of Fox et al. (2005) as it employs mathematical approaches, namely TIMESAT, which are specifically designed to detect and extract phenological information from remotely sensed data.

The phenology metrics presented in this chapter, show a very clearly defined spatial pattern in the growing season which is consistent with known plant phenological patterns and regional rainfall patterns for Namaqualand. The main vegetation growth season is confined to a 6 month period (May to October), from early winter to mid spring. Unlike other winter rainfall deserts the temperatures in Namaqualand are not low enough to suppress vegetation growth during the winter months (Cowling et al. 1999). The longer growing season identified by the AVHRR NDVI time series compared to the MODIS datasets could be a result of AVHRR overestimating NDVI. Nevertheless, the growing season identified here is consistent with that of Fox et al. (2005) but inconsistent with that of van Rooyen et al (1979) who found that the growing season of perennial shrubs occurred from late summer to early spring. This difference could be attributed to the relatively small spatial and temporal scale of the van Rooyen et al (1979) study compared to the study presented here which employs remotely sensed data at the landscape scale.

On average, the peak of the growing season occurs between July and August, which is consistent with the findings of Fox et al. (2005) who found that the maximum AVHRR NDVI peaked in August. Unpublished data for Paulshoek (Hoffman 2012) (near site 131 in cluster 3) demonstrate that peak shoot growth in 70 species monitored monthly since 1999 usually occurs in September and that flowering peaks in October after the temperature has risen (Van Rooyen et al. 1979). The autumn/summer rainfall section of the study area is clearly distinguished from the remainder of the study area with the start of the growing season occurring in July. The peak in vegetation production for this north-eastern region of the study area occurs in September-October.

This study found a high correlation between vegetation phenology and annual rainfall amounts as well as the coefficient of variation in rainfall. Since vegetation growth is driven primarily by rainfall (Van Rooyen et al. 1979; Struck 1994) the inter-annual variability in the growth season for the study area could be attributed to differences in the timing and amount of rainfall between years. BFAST and the phenological metrics extracted from TIMESAT were able to clearly detect the vegetation response to the severe drought which occurred in 2003 and 2004 and the recovery of vegetation post 2005. The ability of the vegetation to respond to rainfall whenever it may occur might increase the resilience of the region to future reductions in rainfall as outlined by the latest climate change projections (Tadross et al. 2011). No relationship between rainfall and EVI was found in this study suggesting that land-use patterns may play a more important role in the vegetation response measured by EVI. Furthermore, the MODIS EVI time series was also able to detect distinct patterns in phenology metrics which corresponded to the land-use patterns of the region, specifically agricultural activities. This suggests that EVI is less sensitive to rainfall versus land-use.

Although climatic controls on vegetation productivity are notoriously complex, this chapter found that both maximum and minimum temperatures are negatively correlated with the length of the growing season derived from AVHRR NDVI and MODIS NDVI and appear to limit the length of the growing season. This finding is cause for concern when considering the projected future increases in temperature for the region which could result in the temperature thresholds of certain species being exceeded (Archer & Tadross 2009).

6.4.1. Overall trends in productivity derived from TIMESAT

The spatial patterns in the productivity metrics reflect the physical characteristics of the study area where higher vegetation productivity is observed over the escarpment and Kamiesberg regions. Similar spatial patterns in NDVI and EVI were presented in Chapter 5. The trends in productivity metrics derived from TIMESAT suggested a decrease in the maximum, seasonal amplitude, large and small integral. Wessels et al. (2007) state that negative trends in the large integral through time can be used to identify areas experiencing land degradation whilst taking account of the natural inter-annual variability. The trends for cluster 3 as well as the evidence from the repeat photographs highlight that this region has undergone a significant decline in vegetation productivity as a result of livestock grazing (for example refer to site 131 in Chapter 4). The spatial trends presented in Chapter 5 support this finding for cluster 3 and demonstrate that in general the north-eastern region of the study area has experienced a decline in productivity. For the other clusters, evidence from the repeat photographs suggest that these negative trends in the productivity metrics may not indicate degradation but rather a change in the composition of the vegetation of the region.

6.4.2. Evidence for a shift in seasonality

Studies, mostly in the northern hemisphere, have shown that temperature changes have had a large impact on the start and end of the growing season (Tucker et al. 2001; Linderholm 2006; Jeong et al. 2011). Based on the data extracted from TIMESAT there is little evidence to suggest distinct long-term changes in the start, end or peak of the growing season. Both minimum and maximum temperatures are negatively correlated with the start and end dates of the growing season suggesting that even though recent increases in temperature have not yet affected the timing of vegetation growth in the study area they could result in shifts in the future. Currently, the start, end and peak of the growing season did, however, demonstrate considerable inter-annual variability of approximately 1 and half months.

The declining seasonal amplitude and the repeat photographs (refer to Chapter 4) support the hypothesis presented in the introduction that there has been a shift in dominance of annual and perennial plants and that vegetation dominated primarily with perennial plants produces an NDVI or EVI curve showing stable year-round growth (Thompson et al. 2009). In addition, a significant increase in the base level was detected suggesting that vegetation growth is occurring more consistently throughout the year, which is consistent with the characteristics of vegetation dominated by perennial plants. Warmer winters as a result of recent increases in minimum temperature demonstrated in Chapter 3 could be facilitating the increase in base level. The shifting vegetation composition in the study area as identified by these productivity metrics may point towards an improvement of vegetation composition in the study area.

BFAST was able to detect the time at which seasonal changes, expressed as seasonal breakpoints, occurred in the study area. Considering the average data for the study area, no seasonal change was detected by the BFAST method for the AVHRR NDVI time series. A breakpoint was identified in 1995 which is related to the launch of a new satellite rather than changes in vegetation seasonality. The NOAA-14 sensor aboard the AVHRR was launched in December 1994. For the MODIS NDVI and EVI time series BFAST detected a decline in seasonal amplitude between 2003 and 2005 which is likely a response to the low rainfall totals recorded in 2003 and 2004 for the region (see Chapter 3). The increase in seasonal amplitude in 2006 implies that there is a lag between rainfall and vegetation recovery after a drought. The lag between rainfall and vegetation response could be due to vegetation responding to soil moisture rather than directly to rainfall (Cowling & Hilton-Taylor 1999). It is important to note that the outcome of the BFAST method is very sensitive to the seasonality model (dummy or harmonic) being applied and the parameters used where slight modifications result in a different number of breakpoints being identified.

There is a considerable level of confidence in the results presented in this chapter since they have replicated a considerable number of key findings presented in Chapter 5. The phenological information derived for the study area provide an important baseline or reference for assessing future changes in land-use and climate change. In the next chapter, the trends in vegetation productivity and seasonality derived from the remotely sensed data will be compared to the repeat photographs in order to determine whether these two methods could be successfully combined in future studies assessing vegetation change in semi-arid regions.

Chapter 7: Comparison of historical repeat photographs and satellite derived vegetation indices to assess vegetation change in Namaqualand

7.1. Introduction

Validation is a key component of remote sensing studies since time series alone are insufficient to successfully indicate vegetation change (Zhang et al. 2003). A key aspect of validating vegetation indices concerns their ability to capture essential biophysical phenomena, such as vegetation, with minimal interference from non-green components of the pixels, such as bare soil (Huete et al. 2011). Many studies utilise field data, aerial photography or a combination of both to validate vegetation indices derived from remote sensed imagery. For example Rasmussen et al. (2001) used a combination of aerial photography and SPOT imagery to assess vegetation cover change for northern Burkina Faso and Fensholt et al. (2009) validated NDVI outputs against ground data collected between 2002 and 2007 for a single pixel in Senegal, West Africa.

There are however, several limits to the quantitative evaluation of time series trends in vegetation indices. Firstly, there is a general lack of suitable field data spanning the full duration of the satellite time series (1980 to present) and secondly, old aerial photographs often still require ground truthing themselves (Wessels et al. 2012). Most studies have resorted to using regional expert option and related publications to validate trend analyses (Wessels et al. 2007; Wessels et al. 2007; Bai et al. 2008) but these have methods proved to be insufficient and alternative forms of validation are being sought (Wessels et al. 2012). A few studies have utilised repeat photography in conjunction with detailed analysis of satellite imagery to provide a more robust measure of landscape change (McClaran et al. 2010; de Mûelenaere et al. 2010; de Mûelenaere et al. 2012). These studies demonstrate that repeat photographs do provide sufficient information which can be compared to observations from remote sensing. The study presented here is the first of its kind to do so in Namaqualand as well as in South Africa.

This chapter explores the possibility of using historical repeat photography as an alternative tool to validate trends in NDVI and EVI in Namaqualand. Repeat photographs were used in this study instead of aerial photographs or field based measurements since firstly, there is a lack of long-term, scientific records for Namaqualand from which to verify vegetation change (Hoffman & Rohde 2010) and secondly, a greater level of detail, such as the change in annual and perennial species, was required for this study. In this chapter, the analysis of the remotely-sensed vegetation indices (Chapter 5 and 6) was compared with the assessment of historical repeat photographs (Chapter 4) in order to determine whether repeat photography can be used in future studies to as a viable methodology to validate or ground-truth trends in NDVI and EVI. This chapter addresses the second research question of objective 1: how do the patterns of vegetation change derived from remotely sensed techniques differ from the assessment of the repeat photographs?

7.2. Methodology

Figure 7.1 outlines the approach taken to compare the trends in vegetation change derived from the remotely sensed vegetation indices and from the assessment of the repeat photographs. Linear regressions were conducted for each study site (n=46) utilising key productivity and phenology metrics derived from the AVHRR time series data. The AVHRR NDVI time series (1986-2006) was used in this chapter as it is the longest of the remotely sensed datasets utilised in this study. The metrics investigated include the cumulative sum of annual NDVI and the standardised residuals of NDVI presented in Chapter 5 of this thesis as well as the length of season, maximum NDVI, base level, seasonal amplitude, and small and large integrals obtained from the TIMESAT analysis presented in Chapter 6. The slope of the linear regression, expressed as the change per year, was noted for each study site.

The photograph pairs were then compared with the trends in AVHRR NDVI for the corresponding study site by creating scatterplots of the value of the slope of the linear regression and the qualitative assessment of the repeat photograph (-2 to +2). Only the change in perennial cover as observed in the repeat photographs was compared with the trends derived from the AVHRR NDVI time series as this is often used as the baseline for evaluating degradation in the region (Thompson et al. 2009; Todd & Hoffman 2009). This comparison was done to check if changes indicated by the repeat photographs were also detected by the trend analysis. A t-test was also conducted in order to see if the trends differed significantly from the assessment of the repeat photographs.

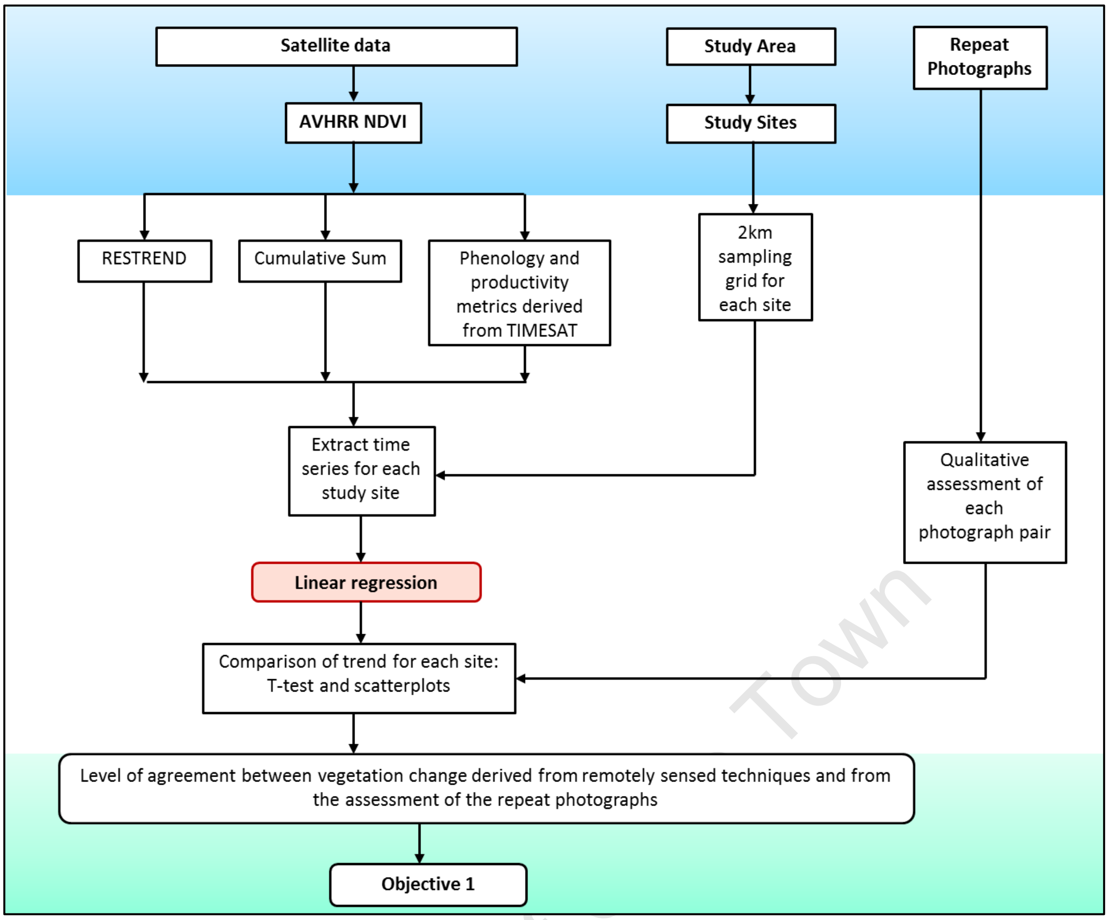
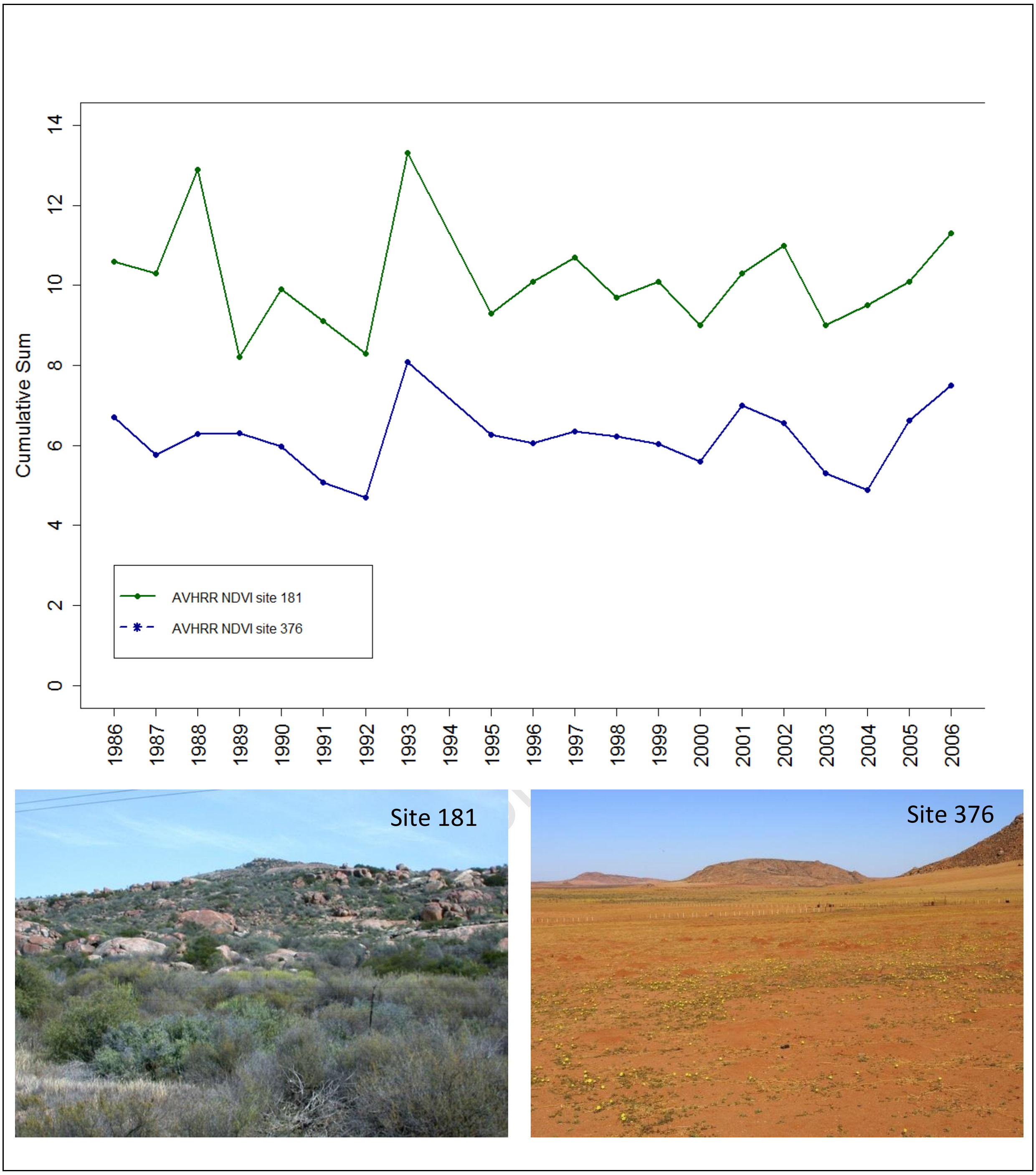


Figure 7.1: Flow diagram illustrating the methodological approach taken to determine the level of agreement between the trends in vegetation change derived from the remotely sensed vegetation indices and from the assessment of the repeat photographs.

7.3. Results

7.3.1. Spatial patterns of vegetation productivity

The georeferenced photographs confirm the observation that Kamiesberg and high rainfall regions of the study area have higher vegetation productivity than the surrounding areas. For example, the repeat photograph and trend in cumulative sum AVHRR NDVI for site 180 (Figure 7.2) which is located north of Garies along the escarpment demonstrates higher vegetation productivity than site 376 which is located in the northern, lower rainfall region of the study area.



<u>Figure 7.2:</u> Time series of cumulative sum AVHRR NDVI for site 181 and site 376 as well as the matched photographs for each site taken in 2003 and 2005 respectively. Photographs courtesy of Hoffman and Rohde.

7.3.2. Inter-annual trends in satellite derived vegetation indices

This section compares the assessment of repeat site photographs presented in Chapter 4 and the trends in AVHRR NDVI presented in Chapter 5. The matched repeat photographs and the corresponding AVHRR NDVI temporal profile for each study site (n=46) is provided in Appendix E Table E.1. There is very little agreement between the trends in cumulative sum and standardised residuals derived from the AVHRR NDVI dataset and the assessment of perennial cover from the repeat photographs for each study site (Figure 7.3). Furthermore, the t-test revealed that the two datasets were very different (n=47, t= -3.54, p=0.0003). It was expected that there would be a positive (negative) trend in AVHRR NDVI at sites where an increase (decrease) in perennial cover was observed but for the majority of sites this was not the case.

For example, the trend in the standardised residuals derived from the AVHRR NDVI dataset as well as the cumulative sum of AVHRR NDVI for site 302 showed a decline in vegetation productivity between 1986 and 2006 (Figure 7.4). The repeat photograph pair however, provides evidence for an increase in vegetation cover in the foreground of the image where perennial plants have colonised abandoned fields. The cultivation in the background remains unchanged. This highlights the smaller scale patch dynamics of the land-use and vegetation cover in Namaqualand, which are often difficult to detect using coarse resolution satellite imagery. Similar small scale patterns are observed in the repeat photographs for site 397 where vegetation cover has increased the slopes in the background of the re-photographed image but decreased in the valley as a result of heavy grazing around the water point (Figure 7.5). The trends in cumulative sum standardised residuals derived from the AVHRR NDVI dataset this site detected an overall increase in vegetation productivity (Figure 7.5). This demonstrates the importance of scale of the two approaches since the remotely sensed images cover large areas whereas the repeat photographs cover a narrow field of view.

There were however exceptions where the assessment of repeat photographs matched the trends in AVHRR NDVI. For example, the increase in vegetation productivity for site 350 demonstrated by the repeat photographs was positively identified by the trends in standardised residuals derived from the AVHRR NDVI dataset (Figure 7.6). The abandonment of cultivation at this site resulted in the re-colonisation of *Elytropappus rhinocerotis*, perennial plant species, at this site.

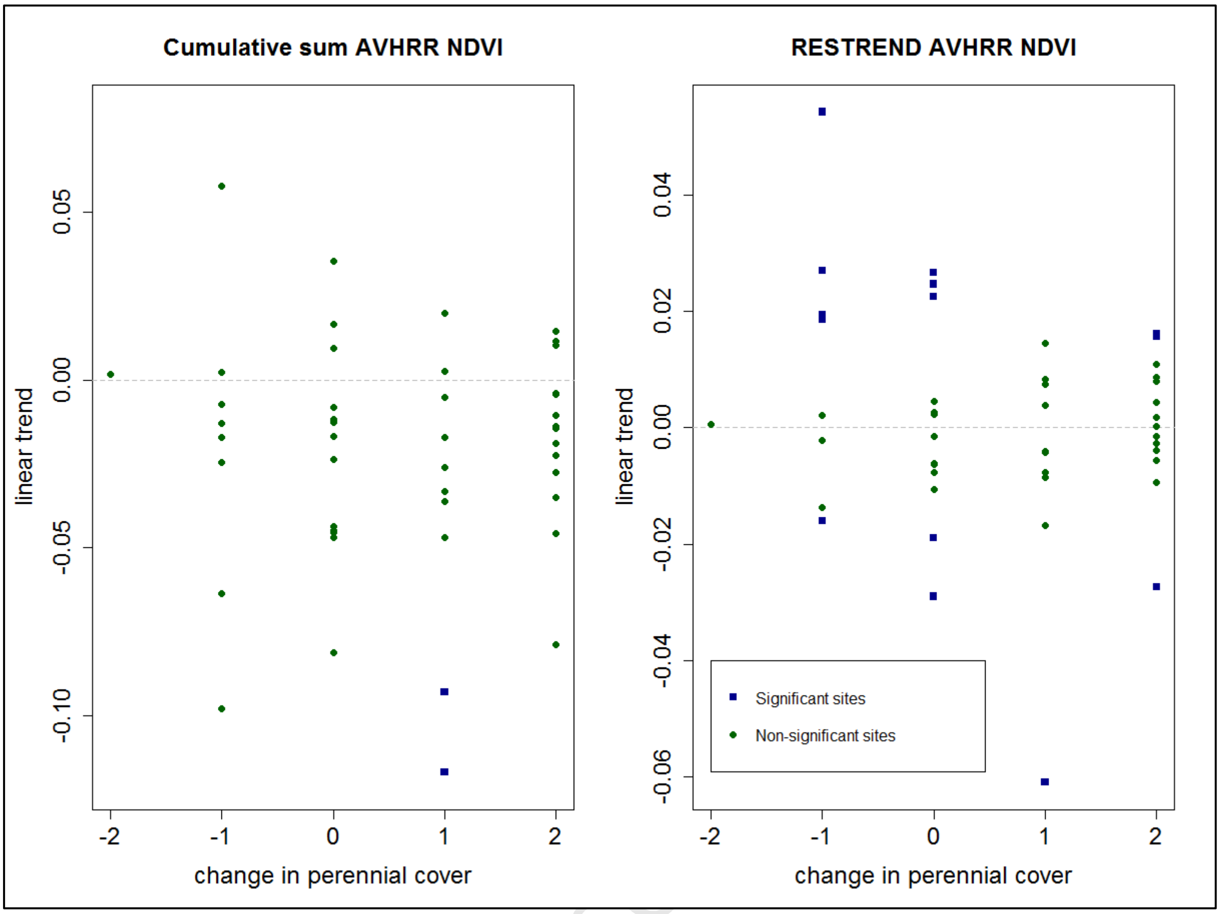


Figure 7.3: Scatterplot of the trend in the cumulative sum of AVHRR NDVI (left) and the trend in the standardised residuals derived from AVHRR NDVI (right) with the change in perennial cover observed in the repeat photographs. Each data point represents a study site (n=46). Statistically significant sites ($p<0.05$) are indicated by the blue squares.

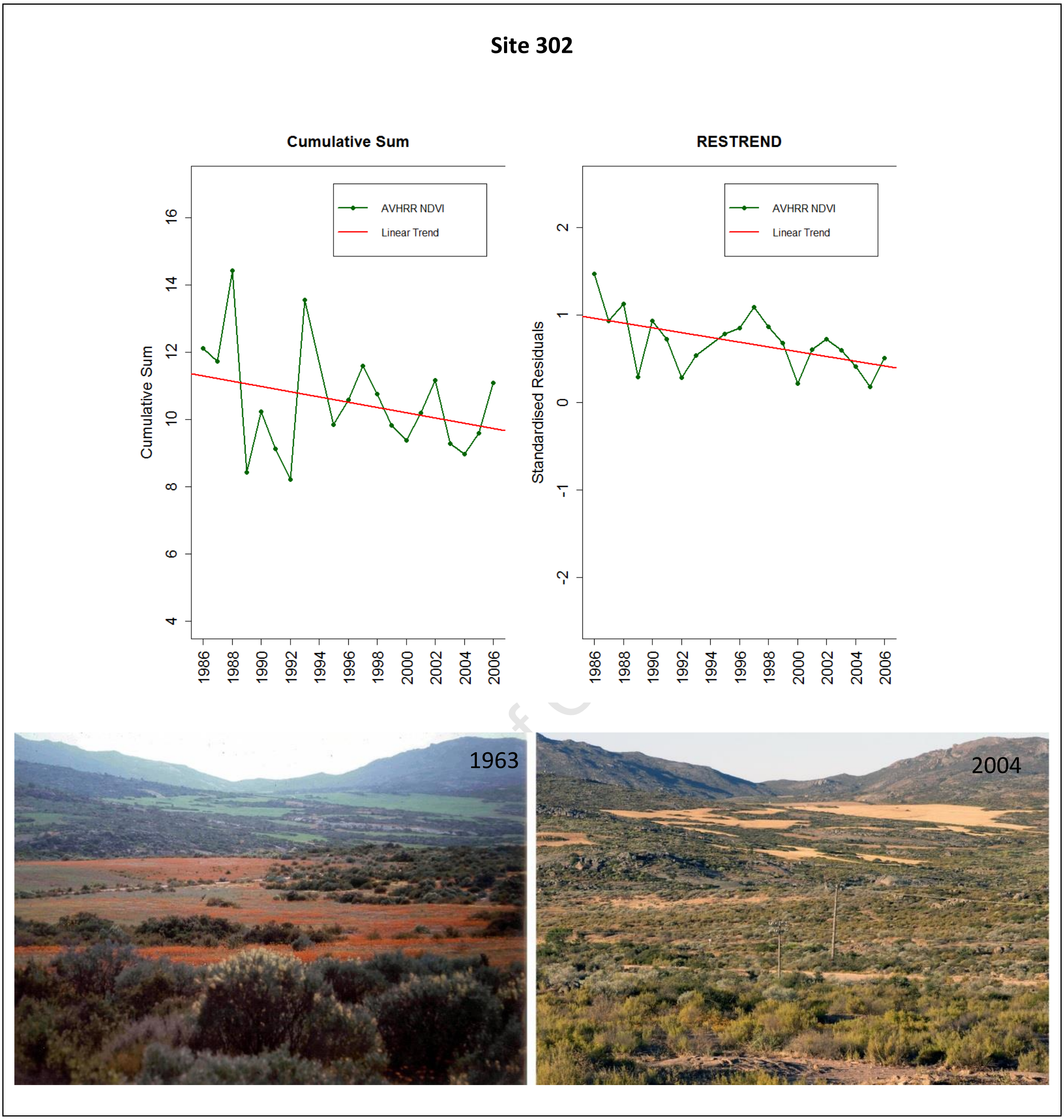


Figure 7.4: Time series of cumulative sum and RESTREND derived from AVHRR NDVI dataset for 1986-2006 for site 302. The site is located north of Garies on commercial land and was first photographed by Frank Steiner in August 1963. The repeat photograph was taken by Rick Rohde on 24 November 2004. In the foreground of the re-photographed image perennial plants have colonised abandoned fields. The cultivation in the background remains unchanged. Photograph on the left courtesy of the South African National Biodiversity Institute and the photograph on the right courtesy of Hoffman and Rohde.

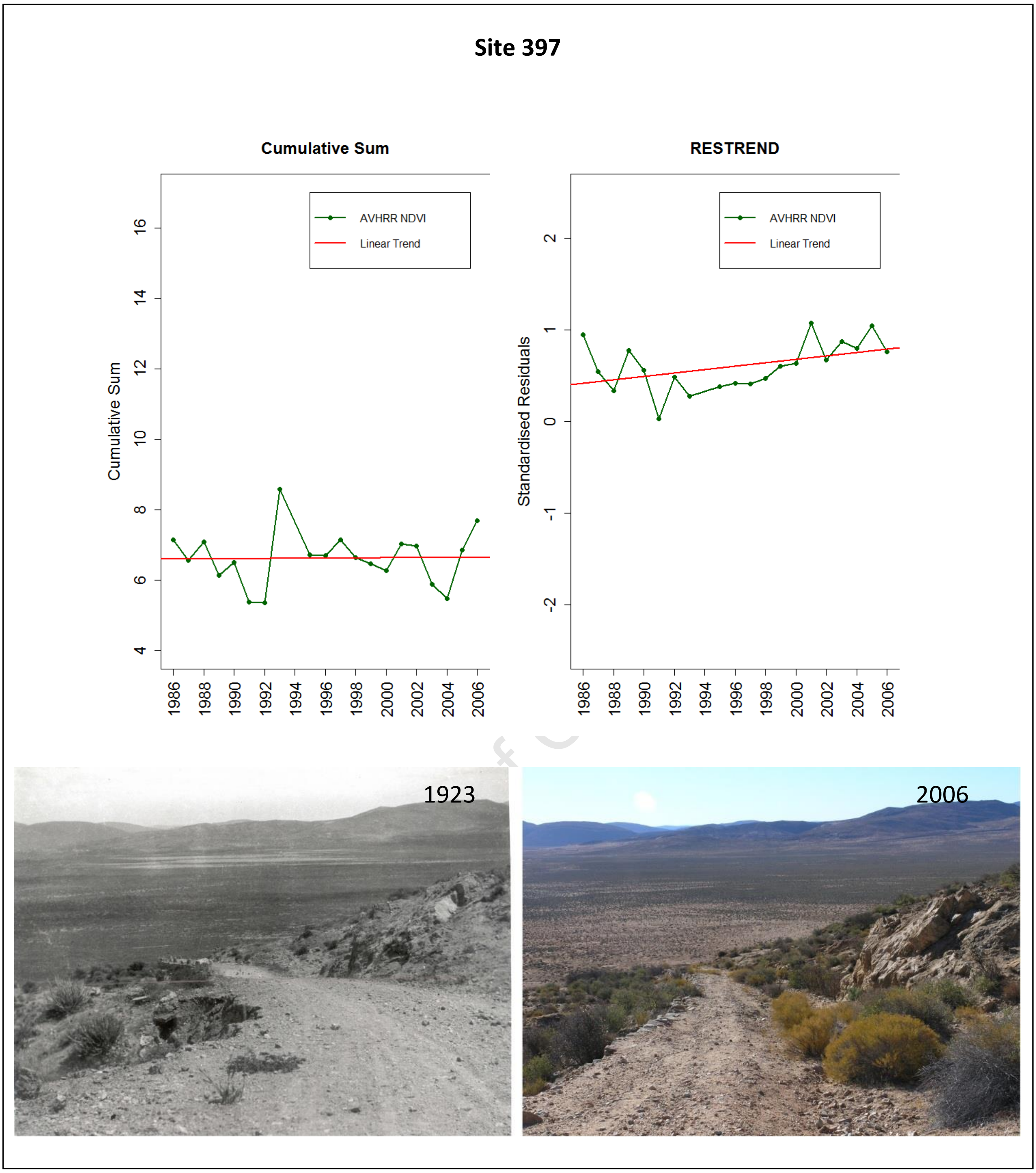


Figure 7.5: Time series of cumulative sum and RESTREND derived from AVHRR NDVI dataset for 1986-2006 for site 397. Site 397 located in the Steinkopf communal area along the old Anenous Pass road was first photographed by an unknown photographer in 1923. The re-photographed image illustrates heavily grazed areas around a water point at the bottom of the pass and was taken by Rick Rohde on 23 March 2006. Photograph on the left courtesy of the South African Library and photograph on the right courtesy of Hoffman and Rohde.

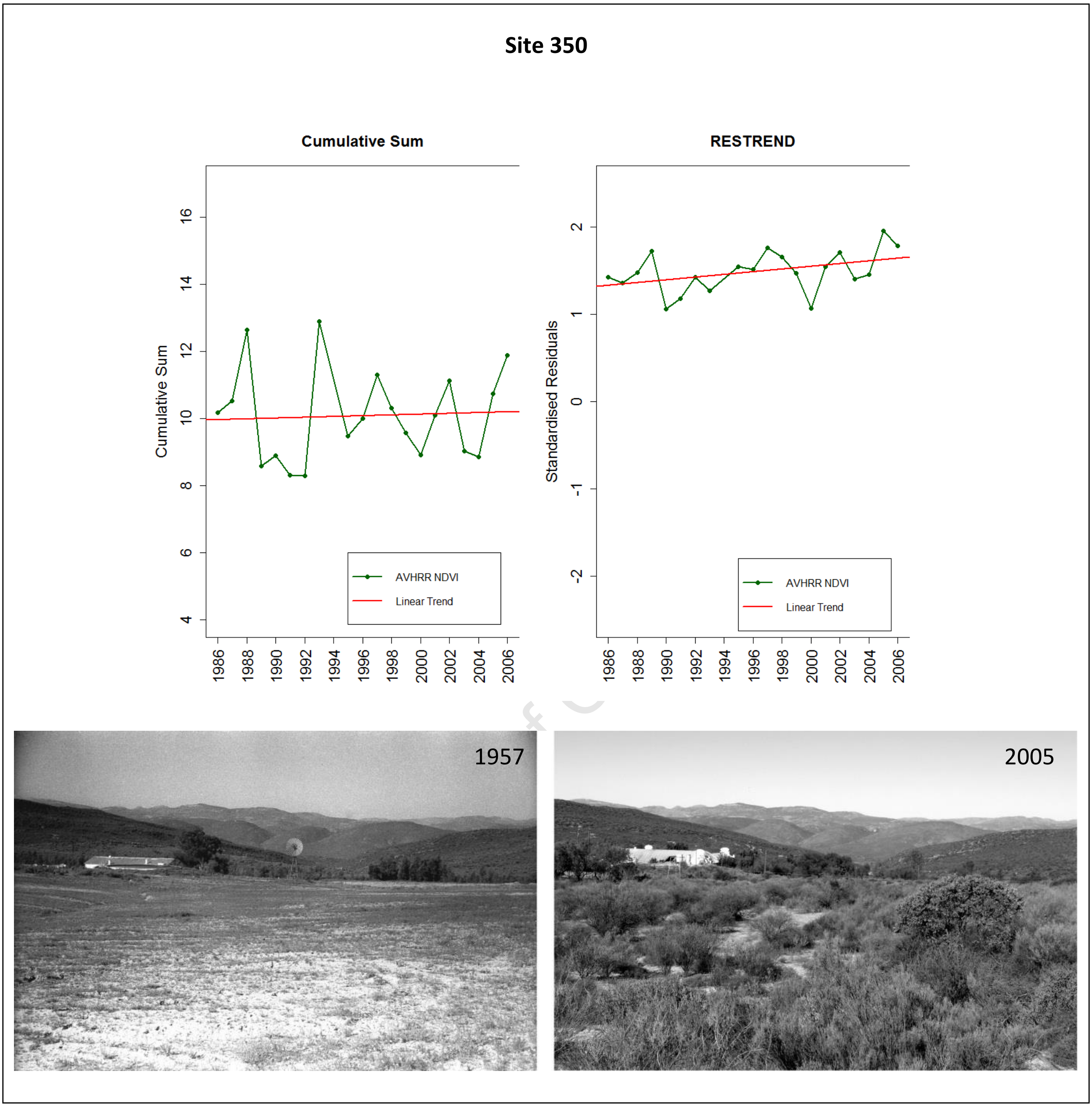


Figure 7.6: Time series of cumulative sum and RESTREND derived from AVHRR NDVI dataset for 1986-2006 for site 350. The site is located on a privately owned farm located approximately 27 km west of Sprinkbok and was first photographed by John Acocks on 24 September 1957. When it was re-photographed by Rick Rohde on 27 January 2005 the old field had been lying fallow for several decades and was dominated by *Elytropapus rhinocerotis* and *Galenia africana*, which are both early successional shrubs. Photograph on the left courtesy of the South African National Biodiversity Institute and photograph on the right courtesy of Hoffman and Rohde.

7.3.3. Satellite derived vegetation phenology

This section specifically addresses the observation that there is a shift in dominance from annuals to perennials at sites where cultivation has been abandoned. In general the trends in phenology and productivity metrics derived from TIMESAT for all the study sites suggested a decrease in all the productivity metrics (maximum, seasonal amplitude, large and small integral) except for the base level, which increased steadily over the period of analysis. The decline in seasonal amplitude supports the hypothesis that there has been a shift in dominance of annual and perennial plants and that vegetation dominated primarily with perennial plants produces an NDVI or EVI curve showing stable year-round growth.

In general, there is a better agreement between the metrics derived from TIMESAT and the assessment of the repeat photographs than the trends in AVHRR NDVI presented previously (Figure 7.7). An increase in the length of the season, reduction in maximum and increase in base level correspond to sites that have experienced an increase in perennial cover, for example site 372 in Figure 7.8.

The sites where the repeat photographs disagreed with the trends in productivity and phenology metrics tended to have historical images that were of poor quality (for example site 311), or were affected by disturbances such as floods (for example site 353) or the dumping of waste (for example site 208).

The seasonal trend component of the BFAST analysis was able to detect changes in seasonality at study sites that had experienced a shift from annual to perennial cover. For example, one seasonal change was detected for site 181 (Figure 7.9) in 1998 after which the seasonal amplitude declined. This date could highlight the point at which the vegetation has started to recover from the impact of cultivation practises.

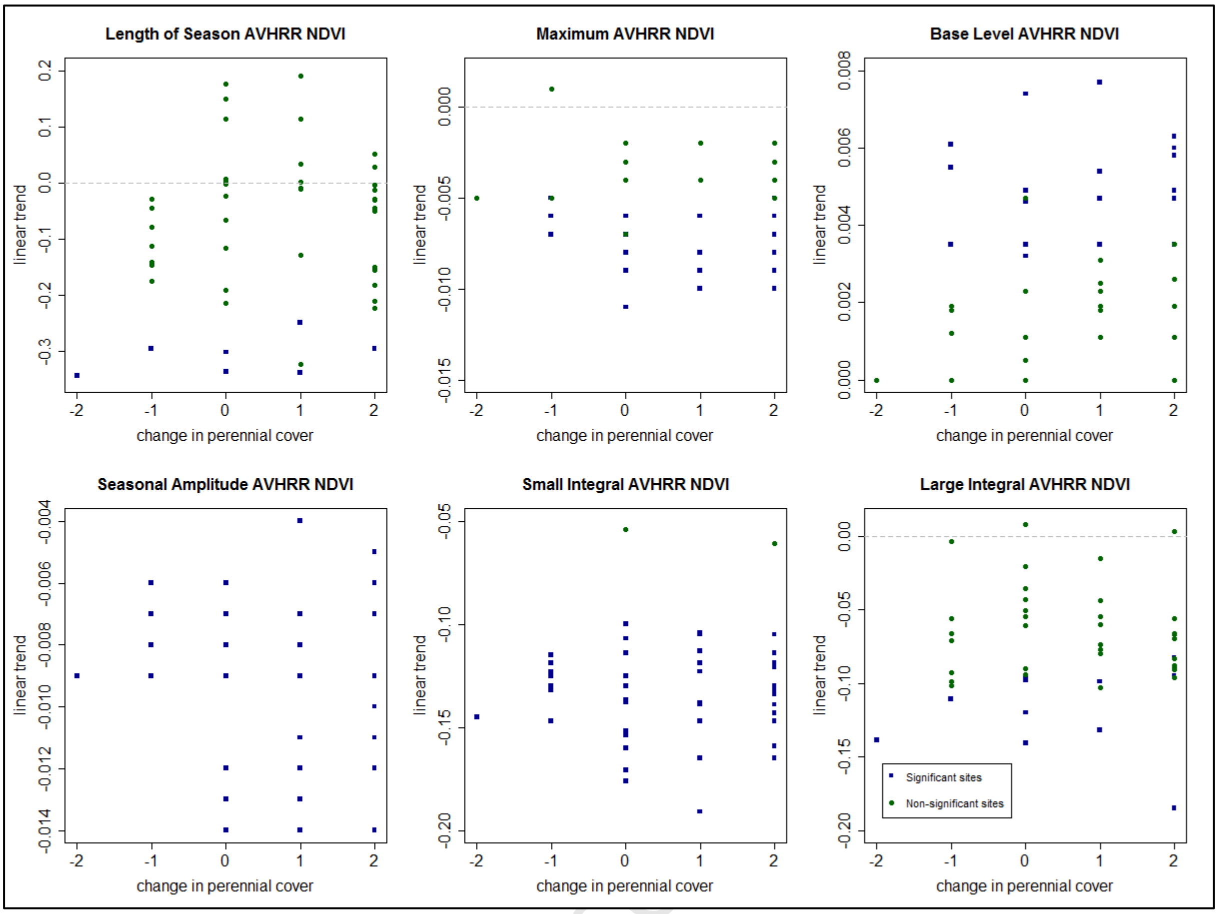


Figure 7.7: Scatterplot of the trends of phenology and productivity metrics (length of season, maximum, base level, seasonal amplitude, and small and large integrals) derived from AVHRR with the change in perennial cover observed in the repeat photographs. Each data point represents a study site (n=46). Statistically significant sites ($p<0.05$) are indicated by the blue squares.

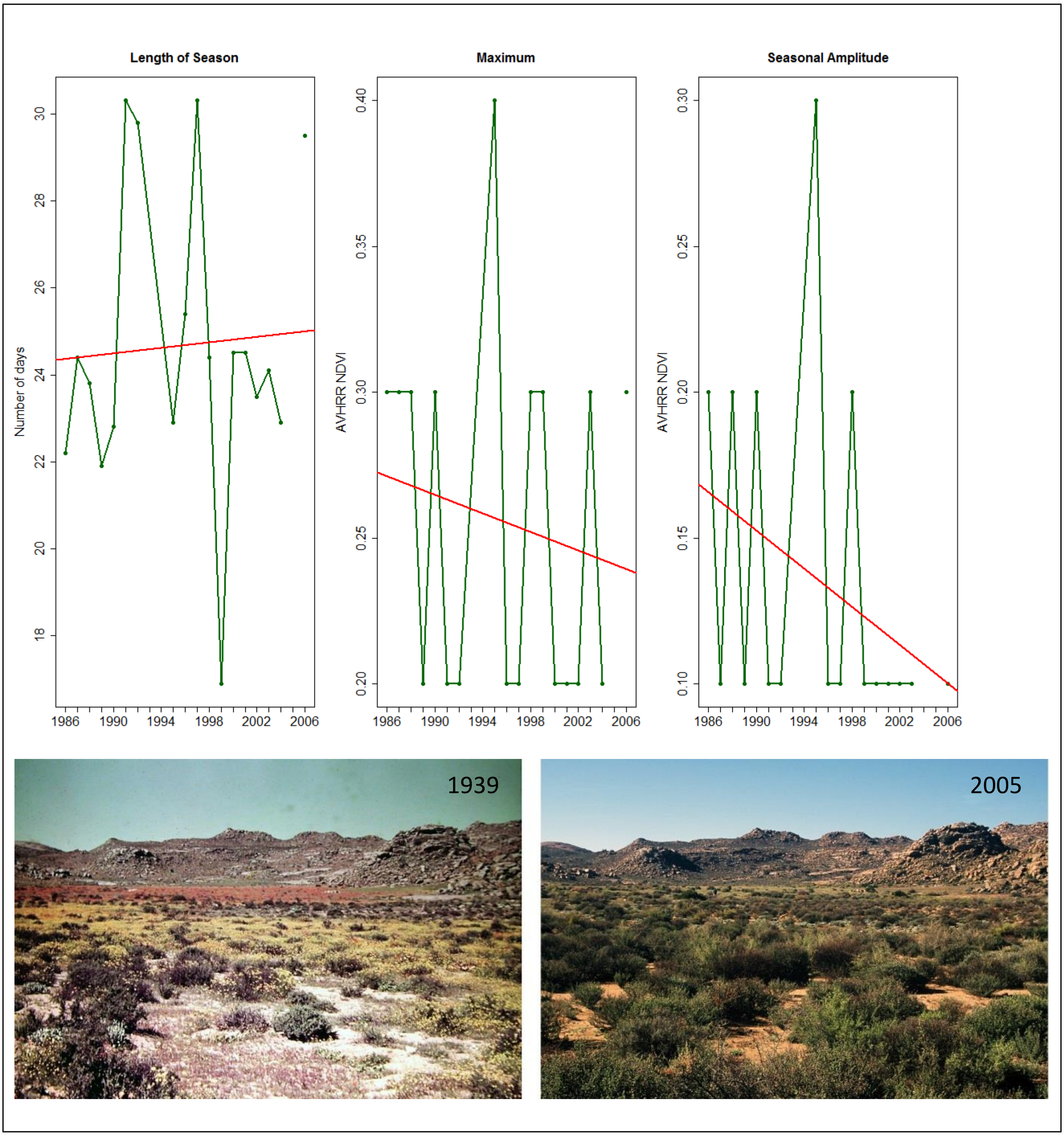


Figure 7.8: Time series of cumulative sum and RESTREND derived from AVHRR NDVI dataset for 1986-2006 for site 372.There was no data in 2004 and 2005 as a result of the drought during that time. Site 372 is located in the Geogap National Park and has been protected for 35 years. It is the only site included in this study that has been formally protected. When the site was re-photographed in 2005 it was dominated by *Drosanthemum hispidum* and *Ruschia robusta* was larger and more abundant than in 1939. Photograph on the left courtesy of H. Herre and photograph on the right courtesy of Hoffman and Rohde.

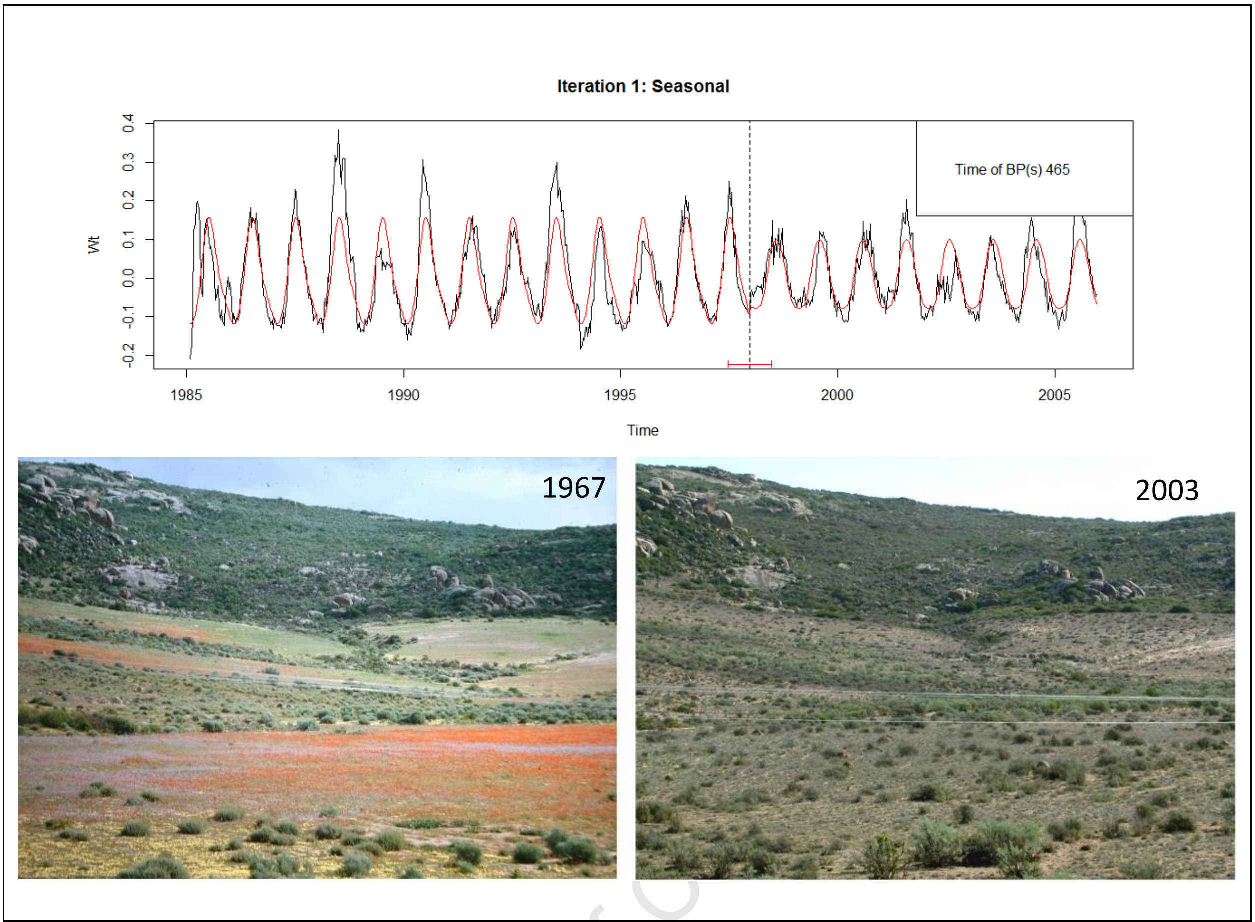


Figure 7.9: Detected changes in the seasonal component (red) of 16-day AVHRR NDVI data series between 1986 and 2006 for site 181. Site 181 is located on the Brakdam farm and was first photographed by Frank Steiner in August 1963. It was re-photographed by Rick Rohde on 7 August 2003 and the dominance of short lived shrubs has been replaced by perennial shrubs. The orange and purple colour in the 1967 is caused by an abundance of flowering *Drosanthemum hispidum* individuals. Photograph on the left courtesy of the South African National Biodiversity Institute and the photograph on the right courtesy of Hoffman and Rohde.

7.4. Discussion

Trends in remotely sensed vegetation indices need to be sufficiently validated or evaluated before they guide important land management decision (Wessels et al. 2012). This chapter aimed to determine whether repeat photography could be successfully used as an ancillary data set for remote sensing studies in Namaqualand. This chapter combined the changes in vegetation productivity and composition obtained from the repeat photographs with the trends derived from the remotely sensed vegetation indices in order to determine if repeat photograph could successfully be used as an ancillary data set for remote sensing studies in Namaqualand. A comparative analysis between the assessment of repeat photographs and the trends derived from AVHRR NDVI time series was conducted at the scale of the study sites.

A key strength of repeat photography lies with the relatively long time period covered by the images as well as the level of detail provided in each image. The repeat photographs have proved to be useful in understanding and documenting long-term vegetation change in the study area. The photographs also provided information of species composition changes as well as changes in land-use practices for the study area. Overall the repeat photographs demonstrate an improvement in the vegetation composition of the study area with a clear shift in dominance from annuals to perennial (Hoffman and Rohde 2007; 2011; Rohde and Hoffman 2008). There is very little agreement between the assessment of vegetation cover and the trends in cumulative sum of NDVI and RESTREND derived from AVHRR NDVI dataset. There was better agreement between the photographs and the phenology and productivity metrics derived from TIMESAT since these metrics more closely matched the change in species composition being measured in the repeat photographs.

The weak agreement can be attributed to key limitations of the repeat photography approach utilised in this study. Firstly, the AVHRR NDVI dataset provides a continuous measure of vegetation growth whereas the photograph pairs only represent two, sometimes 3, snapshots in time and are thus not likely to be representative of the average vegetation dynamics at a particular site. For example, the trends detected by AVHRR NDVI indicated considerable variability at some sites whereas the photographs showed fairly stable vegetation conditions. Furthermore, the start and end dates of the repeat photographs do not match those of the satellite time series and in most cases only the re-photographed image overlaps with the satellite time-series.

It is also important to note the limitations of the subjective nature of the assessment of the repeat photographs. The field of view of some of the repeat photographs covered large areas which complicated the assignment of one index of change since more than one land-use was often present and the direction of change for each was generally not the same. This suggests that photographs with a more narrow-field of view may be more appropriate for remote sensing studies. The selection of repeat photography sites is, however, limited by the availability of historical material and the primary purpose of such photographs were not necessarily to monitor vegetation.

In the cases where the assessment of change based on the repeat photographs differed with the phenology and productivity metrics derived from TIMESAT, the photographs were of poor quality and a few were affected by disturbances such as flash floods and urbanisation. The assignment of change for each of these photographs was unlikely to correctly represent the changes in vegetation at a particular site. Consequently, these sites should not have been included in this study. This highlights the importance of the selection of repeat photography sites for a remote sensing study.

Despite these limitations, this study has shown that combining information from both repeat photography and remote sensing provides the best description and interpretation of landscape vegetation change. By utilising both approaches some of the limitations could be offset. Remotely sensed vegetation indices cover a large spatial area which overcomes the problem of the bias of the repeat photographs to certain regions of a landscape. The remote sensing information provides important large-scale spatial information on how vegetation changes along rainfall and altitudinal gradient in Namaqualand and is also more recent than the photographs. The coarse resolution of the AVHRR NDVI dataset, however, limits the ability to detect small scale changes in vegetation productivity and composition that are observed in the repeat photographs. The TIMESAT and BFAST techniques were able to detect changes in seasonality to some extent but the repeat photographs were required in order to interpret this change in terms of changes in land-use practises, such as the abandonment of cultivation. In terms of climate change, the impacts are likely to occur at the local scale (Qin et al. 2007) and future studies of vegetation change in Namaqualand should make use of higher resolution satellite data, such as SPOT (Brown et al. 2006). These higher resolution data sets are, however, limited by the shorter time period covered compared to AVHRR NDVI. The trend of vegetation indices can only detect changes that occurred within the time series and thus ignore the land-use history of the area. There is a long history of vegetation change in Namaqualand where the majority of change is likely to have occurred before the start of the satellite record and may have not changed significantly since. Namaqualand was considerably impacted by subsistence agriculture during the middle of the century when the number of domestic livestock in the region reached a peak (Hoffman & Rohde 2007).

There are several improvements which could be made to this study to facilitate the use of repeat photography with remotely sensed vegetation indices. Firstly, more recent photographs need to be taken for each study site in order to consider the trends derived from the MODIS NDVI and EVI datasets. Secondly, site visits should have been undertaken in order to compare recent field based measurements with the remotely sensed information. Lastly, photographs need to be obtained for the regions of the study area which are not currently included in the network of study sites, for example, Bushmanland in the north east.

Chapter 8: Synthesis and Conclusions

8.1. Introduction

This research project was prompted by a number of interrelated lines of concerns encompassing both physical and ecological components. These included the dynamics of Succulent Karoo vegetation, the perceived and predicted impacts of climate change on the region, and the perception that livestock grazing (the main land use type in the area) has impacted significantly on the vegetation of the region. In the Succulent Karoo, one of the key debates is the relative contribution of human-induced land degradation and climate change to vegetation change. Initial studies based on bioclimatic envelop models suggested that the an increase in temperature and more arid conditions projected for the future could result in the vegetation cover of the Succulent Karoo being significant reduced by up to 40% (Rutherford et al. 1999). More recently, however, less extreme changes in rainfall have been indicated which would result in the vegetation of the biome remaining fairly stable with possible increases in the spatial extent of this biome by 2050 (Driver et al.2012). Evidence from field data in Namaqualand over the last decade has indicated that vegetation dynamics respond to climate signals but that vegetation has experienced an unexpected positive trend in terms of both cover and species richness (Schmiedel et al. 2012; Hoffman & Rohde 2007; 2010). These studies suggest that the majority of the changes can be interpreted in terms of the changes in land-use in the area over time.

Detecting and characterising vegetation change over time is the natural first step toward identifying the drivers of change and understanding the change mechanism. Such an understanding is required for effectively predicting the future trajectory of vegetation change, long-term land management plans and the improvement of strategic adaptation responses to climate change (Verbesselt et al. 2010a).

In this study vegetation change within the semi-arid and arid winter rainfall region of Namaqualand, South Africa was investigated at a landscape scale. By combining repeat photography (Hoffman & Rohde 2010) and satellite data from NOAA-AVHRR and TERRA-MODIS sensors as well as baseline climatology data from the CRU TS 3.2 data set, this study aimed firstly, to determine the critical pathways of inter-annual (Chapter 5) and intra-seasonal (Chapter 6) vegetation change in the Namaqualand region of the Succulent Karoo biome in South Africa. Secondly, this study aimed to investigate the role of land-use (Chapter 4) and climate variability (Chapter 3) as key drivers of vegetation change in Namaqualand. A key focus of this research was to identify where land use and climate may impact vegetation productivity with a view to identify areas of critical change.

This study presents a unique approach in the sense that it employs multi-source and multi-temporal data to assess vegetation change over time. Vegetation cover change was defined in this study as changes in the vegetation indices (NDVI and EVI), and is considered to be the most direct response of vegetation to climate changes and human activity (Zhao et al. 2012). The foundation for using vegetation indices in monitoring arid and semi-arid areas is based on a large body of research since the 1980's presented in the literature review component of this chapter (see Chapter 1). The study presented here is the first of its kind to investigate recent changes in both vegetation productivity and phenology at a landscape scale in Namaqualand using remotely sensed vegetation indices.

Few international studies have utilised repeat photography in conjunction with detailed analysis of satellite imagery to provide a more robust measure of landscape change (de Mûelenaere et al. 2010; 2012; McClaren et al. 2000). The study presented here is the first of its kind to do so in Namaqualand as well as South Africa. Remote sensing technology is regarded as a valuable tool for monitoring vegetation in arid and semi-arid environments at broad spatial and temporal scales. However, satellite time series alone are insufficient to successfully indicate vegetation change and require validation processes which are normally conducted using field-based measurements. In Namaqualand there is a lack of long-term, scientific records from which to verify remotely sensed vegetation change and the option of utilising repeat photography was investigated in this study.

The objective of this chapter is to provide a synthesis of the main findings that emerged from the various approaches, and to discuss the implications of these findings with a special focus on the role of climate and land use as drivers of vegetation change. Limitations of the research are outlined and recommendations for future studies are noted.

8.2. Key Findings

Figure 8.1 and 8.2 provide a summary of the data used, the methodology employed and the key results for each research objective and research question. To address objective 1 (Figure 8.1), remotely sensed vegetation indices derived from Advanced Very High Resolution Radiometer (AVHRR) and from Moderate-resolution Imaging Spectroradiometer (MODIS) data sets were used to detect firstly, long-term trends in vegetation productivity (Chapter 5) and secondly, seasonal or phenological changes in vegetation cover (Chapter 6). The repeat site photographs were qualitatively assessed (Chapter 4) in order to detect changes in vegetation cover within the different land tenure systems and in response to different land-use practices. The repeat photograph pairs were compared with the trends in NDVI and EVI for the corresponding study site and the level of agreement was qualitatively determined (Chapters 5 and 6). This processes contributed in part to addressing objective 2 (Figure 8.2) where trends in NDVI and EVI for sites with different land-uses and tenure systems were investigated. The analysis of the remotely-sensed vegetation indices was compared with the assessment of historical repeat photographs in order to determine whether repeat photography can be used in future studies to as a viable methodology to validate or ground-truth trends in NDVI and EVI (Chapter 7). Recent trends in climate for Namaqualand (Chapter 3) were investigated in order to provide a basis for the interpretation of the trends in vegetation productivity derived from the remotely sensed information as well as the repeat site photographs. In addition, the statistical relationship between climate and NDVI and EVI productivity and phenology metrics was also determined (Chapters 5 and 6).

8.2.1. Recent trends in local climate in Namaqualand between 1901 and 2009

There is good evidence to suggest that temperatures in the study area have been increasing over the last century, and that the rate of warming has been increasing – most notably in the last two decades. Minimum temperatures are increasing at a faster rate than the maximum temperatures and the rate of warming in minimum temperature has increased since 1970. Temperature trends were found to be inconsistent across seasons where the highest temperature trends were observed in summer and autumn and the lowest in spring.

There was no clear evidence for a significant change in mean annual rainfall, and the rainfall time series remain dominated by oscillating wet and dry conditions. The spatial pattern of change for evaporation is characterised by a steepening inland-coastal gradient where areas along the coast show a significant increase in evapotranspiration whereas areas towards the north-east of the study area have experienced a decline in evapotranspiration. A true indication of the changes in water availability was not able to be determined for this study as data on coastal fog for the region is lacking.

8.2.2. Spatial patterns of vegetation productivity and seasonality in Namaqualand

A key finding of this study was the distinct spatial differences in vegetation productivity. Vegetation productivity reflected by the magnitude of the NDVI and EVI values is strongly associated with altitudinal and rainfall gradients. Over the study area, high NDVI and EVI signals were detected over the escarpment and Kamiesberg regions whereas low NDVI and EVI signals were detected in the north-eastern region of the study area encompassing parts of Bushmanland. The georeferenced photographs confirmed this observation where sites along the escarpment (for example site 181) had higher vegetation cover than sites further inland (for example site 376). For Namaqualand, Fox et al. (2005) found similar spatial patterns in AVHRR NDVI and Anderson et al. (2010) found plant biomass to vary significantly in relation to the altitudinal and rainfall gradients. The significant positive correlation between rainfall and cumulative sum NDVI derived from AVHRR and MODIS indicated a close relationship between rainfall and vegetation growth in the region, which was comparable to those reported elsewhere (Wessels et al. 2007; Fox et al. 2005). In general, there is a strong relationship between rainfall and vegetation production in arid and semi-arid environments (Prince et al. 1998, Evans & Geerken 2004, Ayamba & Tucker 2005, Olsson et al. 2005).

In terms of phenology, the results showed a clearly defined spatial pattern at the start of the growing season which is consistent with known plant phenological patterns and regional rainfall patterns for Namaqualand (Fox et al. 2005). The main vegetation growth season is confined to a 6 month period (May to October), from early winter to mid spring. The growing season identified here is consistent with that of Fox et al. (2005) but inconsistent with that of van Rooyen et al (1979) who found that the growing season of perennial shrubs occurred from late summer to early spring. This difference could be attributed to the spatial and temporal scale of the van Rooyen et al (1979) study compared to the study presented here which employs remotely sensed data at the landscape scale. On average, the peak of the growing season occurs between July and August. The autumn/summer rainfall section of the study area is clearly distinguished from the remainder of the study area with the start of the growing season occurring in July. The peak in vegetation production for this north-eastern region of the study area occurs in September-October.

Although climatic controls on vegetation productivity are notoriously complex, both maximum and minimum temperatures were shown to be negatively correlated with the length of the growing season derived from AVHRR NDVI and MODIS NDVI and appear to limit the length of the growing season. This finding is cause for concern when considering the projected future increases in temperature for the region which could result in the temperature thresholds of certain species being exceeded. Furthermore, there was high correlation between vegetation phenology and annual rainfall amounts as well as the coefficient of variation in rainfall. Since vegetation growth in the region is driven primarily by rainfall (Van Rooyen et al. 1979; Struck 1994) the inter-annual variability in the growth season for the study area could be attributed to differences in the timing and amount of rainfall between years. BFAST and the phenological metrics extracted from TIMESAT were able to clearly detect the vegetation response to the severe drought which occurred in 2003 and 2004 and the recovery of vegetation post 2005. The ability of the vegetation to respond to rainfall whenever it may occur might increase the resilience of the region to future reductions in rainfall as outlined by the latest climate change projections.

8.2.3. Evidence for changes in vegetation productivity in Namaqualand

Remotely sensed vegetation indices derived from AVHRR NDVI and from MODIS NDVI and EVI data sets were able to detect trends in vegetation productivity over the last 25 years. The trend in rainfall provided a physical basis for the trends observed in NDVI and EVI where low NDVI and EVI years are associated with low rainfall years (e.g. 1992 and 2003). In general, NDVI and EVI trends over the analysis period suggested an improvement in vegetation productivity. The trends were, however, not unidirectional and demonstrated considerable variability. The spatial trend analysis of key productivity metrics (maximum and cumulative sum) derived from the AVHRR NDVI time series demonstrated a decline in vegetation productivity for the period 1986-2006 over the higher altitude regions. Between 2000 and 2011, however, the trends in MODIS NDVI and EVI reflected an improvement in vegetation conditions with the most pronounced increases occurring over the Kamiesberg.

Recent increase in vegetation productivity is unlikely to be a result of changes in rainfall since no significant trends in mean annual rainfall were observed. The repeat photographs were able to add information to suggest that land-use may be important in determining these spatial differences in vegetation change. The assessment of repeat photographs at these sites suggest that the increase in vegetation production at sites located along the escarpment and Kamiesberg regions is a result of the abandonment of cultivation on commercial and communal land (Rohde et al. 2003; Hoffman & Rohde 2007). Indigenous perennial species have been able to recolonize these abandoned fields resulting in an improvement in vegetation cover and composition of the sites.

A key limitation of spatial trend analysis conducted using the Earths Trends Modeler was that it assumed monotonic trends throughout the time series and thus an alternate method was used to detect the timing of vegetation changes in the AVHRR and MODIS time series. The piecewise linear trends (Verbesselt et al. 2010a; Verbesselt et al. 2010b) technique, BFAST, was more applicable in this case since it does not assume monotonic trends throughout the time-series but instead decomposes the time-series into gradual trends and abrupt changes at breakpoints (Wessels et al. 2012). Considering the full AVHRR NDVI and MODIS NDVI and EVI time series, the BFAST results highlighted three periods of change in the vegetation productivity of the region. A decreasing trend was observed between 1985 and 1997, followed by an increasing trend between 1997 and 2006 and then a decreasing trend between 2006 and 2011. The recent declining trend in NDVI and EVI highlights the importance of continued monitoring.

There were considerable spatial differences in the magnitude and direction of vegetation trends. There was evidence from both the repeat photographs and the MODIS NDVI and EVI images to suggest that vegetation in riverine habitats and drainage lines have experienced a significant increase in cover, particularly of the dominant tree species (*Acacia karroo*) in the region. The most pronounced increases in vegetation occurred over the higher altitude regions of the study area. The north-eastern region of the study area encompassing parts of Bushmanland demonstrated clear declines in vegetation productivity over the analysis period. The repeat photographs have shown that vegetation cover at sites located in this area has been significantly impacted by both cultivation and grazing practises over long periods of time. In Namaqualand, the loss of plant biomass in the low-lying communal areas is principally a result of heavy grazing practices (Anderson et al. 2010; Todd and Hoffman 2009).

8.2.4. Evidence for changes in seasonality of vegetation in Namaqualand

The changes in the coefficient of variation of annual NDVI and EVI could imply that changes in vegetation productivity are occurring at a seasonal time scale. This is especially the case over the escarpment region of the study area, which demonstrated changes in the amount of inter-annual variation in vegetation production. Based on the data extracted from TIMESAT there is little evidence to suggest distinct changes in the start, end or peak of the growing season. The start, end and peak of the growing season did however demonstrate considerable inter-annual variability of approximately 1 and half months. Gaps between rainfall events during the growing season can have a significant impact on the vegetation productivity even when the same total seasonal rainfall is recorded (Prince et al. 1998). The timestep of the rainfall data used in this study was one month, which is too low a frequency to detect the effects of rainfall on seasonal vegetation productivity.

Studies, mostly in the northern hemisphere, have shown that temperature changes have had a large impact on the start and end of the growing season (Tucker et al. 2001; Linderholm 2006; Jeong et al. 2011). Both minimum and maximum temperatures are negatively correlated with the start and end dates of the growing season suggesting that even though recent increases in temperature have not yet affected the timing of vegetation growth or the length of the growing season in the study area they could result in shifts in the future. This could be because the temperature thresholds of vegetation may have not been crossed yet and are still within the range of tolerance at +1.5°C.

The assessment of the repeat photographs suggests that there has been a shift in dominance from annual to perennial plant species on previously cultivated fields, under both commercial and communal management. The declining trend in seasonal amplitude supports the hypothesis presented in the introduction that there has been a shift in dominance of annual and perennial plants and that vegetation dominated primarily with perennial plants produces an NDVI or EVI curve showing stable year-round growth (Thompson et al. 2009). In addition, a significant increase in the base level was detected suggesting that vegetation growth is occurring more consistently throughout the year, which is consistent with the characteristics of vegetation dominated by perennial plants. Warmer winters as a result of recent increases in minimum temperature could be facilitating the increase in base level. The shifting vegetation composition in the study area as identified by these productivity metrics may point towards an improvement of vegetation composition in the study area. This improvement, however, is limited in the communal areas where sites continue to be heavily grazed. . Furthermore, successional processes remain slow in these semi-arid and arid environments and even after decades of rest from grazing or cultivation sites are often dominated by only one or two disturbance-tolerant species such as *Elytroppaus rhinocerotis* and *Galenia africana.*

The Breaks For Additive Seasonal and Trend (BFAST) was able to detect the time at which seasonal changes, expressed as seasonal breakpoints, occurred in the study area. No seasonal change was detected by the BFAST method for the AVHRR NDVI time series. For MODIS NDVI and EVI time series BFAST detected a decline in seasonal amplitude between 2003 and 2005 which is likely a response to the low rainfall totals recorded in 2003 and 2004 for the region. The increase in seasonal amplitude in 2006 implies that there is a lag between rainfall and vegetation recovery after a drought. The lag between rainfall and vegetation response could be due to vegetation responding to soil moisture rather than directly to rainfall (Cowling & Hilton-Taylor 1999).

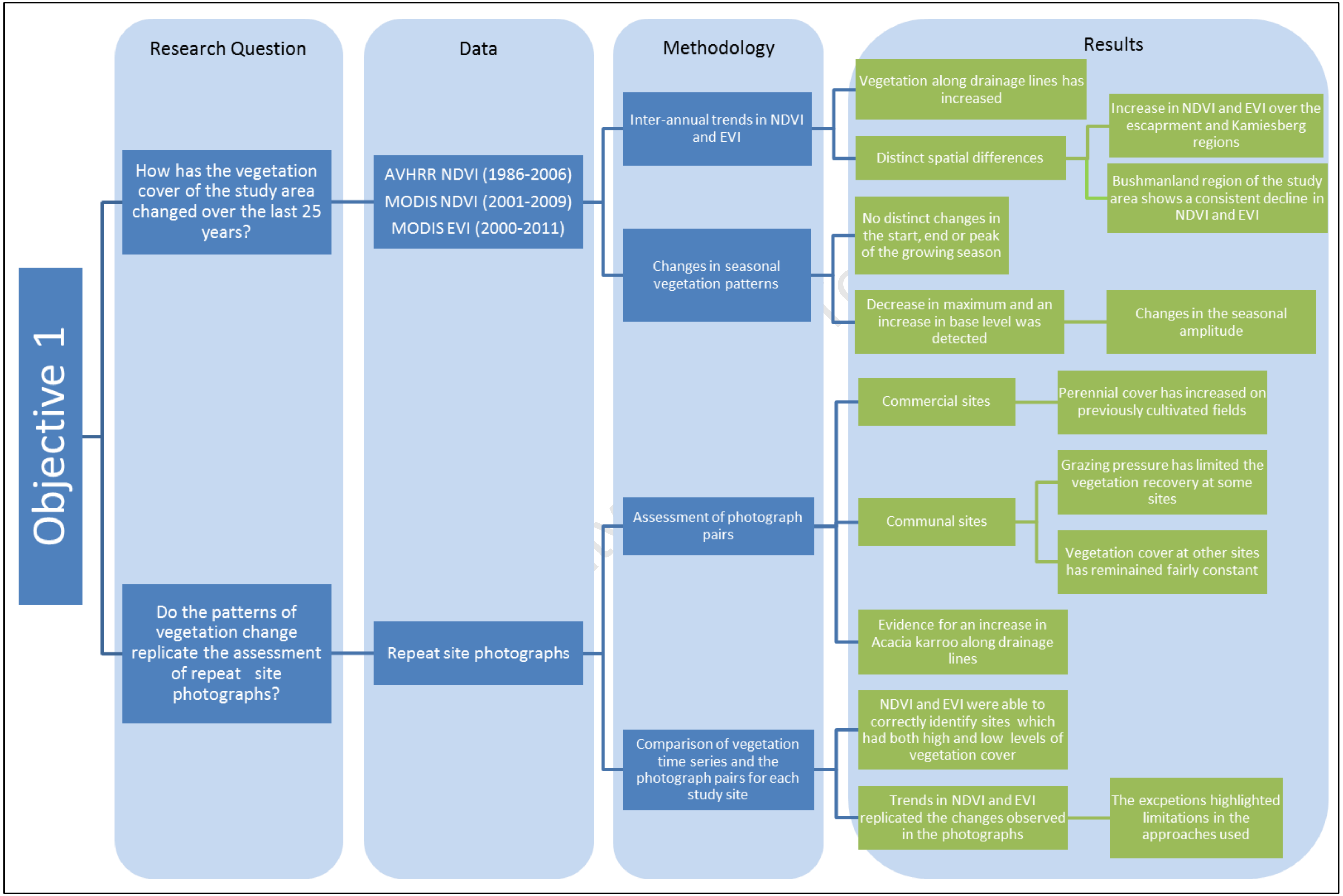


Figure 8.1: Flow chart of key research questions, data used, methodology employed and key outcomes to address research objective 1.

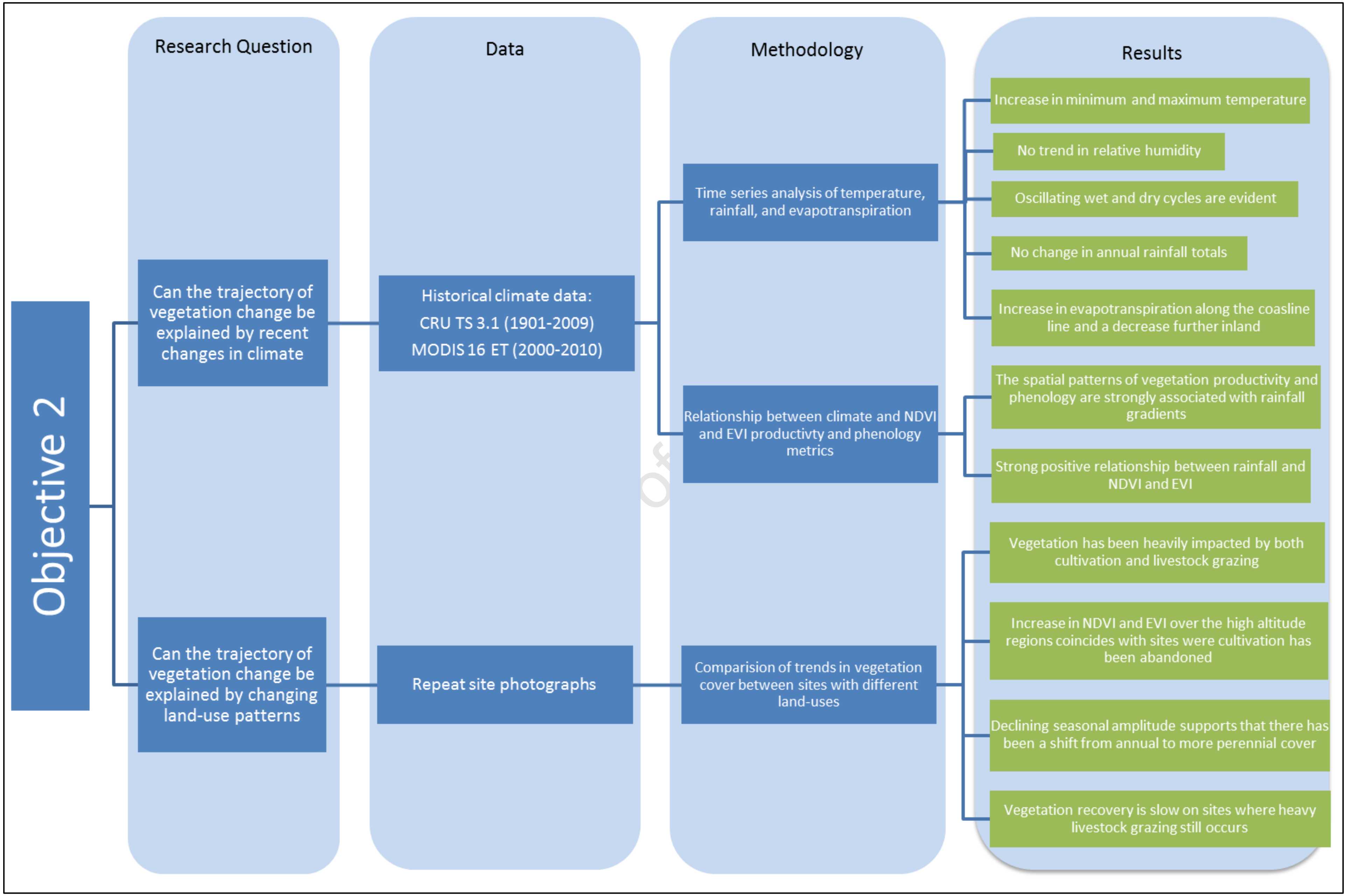


Figure 8.2: Flow chart of key research questions, data used, methodology employed and key outcomes to address research objective 2.

8.3. Evaluation of the data and methods used in this study

8.3.1. Repeat photography as a useful tool for validating trends in remotely sensed vegetation indices

The repeat photographs used in this study have been useful in understanding and documenting past changes and in validating trends detected by the remotely sensed vegetation indices. The repeat photographs were able to add value to the time series analysis of NDVI and EVI by providing information of species composition changes as well as changes in land-use practices for the study area. The combined use of repeat photography together with remotely sensed vegetation indices is a unique approach. A key strength of repeat photography lies with the relatively long time period covered by the images as well as the level of detail provided in each image. The photographs pairs however only represent two, sometimes 3, snapshots in time and are thus not likely to be representative of the average vegetation cover experienced at a particular site. Furthermore, the start and end dates of the repeat photographs do not match those of the satellite time series and in most cases only the re-photographed image overlaps with the satellite time-series. In addition, the location of the photography sites are based on the available historical material and the primary purpose of such photographs were not necessarily to monitor vegetation.

Despite these limitations, this study has shown that combining information from both repeat photography and remote sensing provides the best description and interpretation of landscape vegetation change. By utilising both approaches some of the limitations of each could be offset. For example, the trend of vegetation indices can only detect changes that occurred within the time series and thus ignore the land-use history of the area, which can more effectively be provided by historical repeat photographs. Overall, repeat photographs could be a promising alternative ancillary data source to bridge the gap between detailed monitoring of change and environmental reconstruction.

8.3.2. The combined use of AVHRR and MODIS vegetation indices to detect vegetation change

It is clear that there is potential for using remotely sensed vegetation indices to assess vegetation productivity in Namaqualand. The AVHRR NDVI data set has the advantage of a long-term data record (the early 1980s to the present) while the more recent MODIS data sets have greater spectral and spatial resolution as well as other technical improvements (Huete et al. 2002). Both the AVHRR NDVI and MODIS NDVI and EVI data sets are used in this study to provide a longer data record. The two sensor datasets compared well where similar trends in vegetation productivity were observed during overlapping years. The MODIS EVI values were generally lower than the NDVI values. Fensholt and Sandholt (2005) found that MODIS EVU was approximately 0.04 NDVI units below MODIS NDVI. The AVHRR dataset however, tended to overestimate very low productivities due to technical problems with the use of satellite observations of NDVI. Given the low rainfall (133 mm/pa) much of the region has fairly sparse canopy cover resulting in a certain proportion of NDVI values representing the background soil brightness (Sebego et al., 2008). The MODIS EVI dataset was useful in overcoming this problem as this index reduces the sensitivity to atmospheric and soil effects (Zhang et al. 2005). Furthermore, no relationship between rainfall and EVI was found suggesting that land-use patterns may play a more important role in the vegetation response measured by EVI. The MODIS EVI time series was also able to detect distinct patterns in phenology metrics which corresponded to the land-use patterns of the region. This study demonstrated that these two VIs complement each other and improve the detection of vegetation changes and extraction of phenology metrics.

From the results presented no one method appeared better than another in investigating the trends on NDVI and EVI over time but rather that a range of methods is required to detect vegetation change. The Earth Trend Modeler in Idrisi Taiga (Eastman 2009) was successfully used to determine the spatial-temporal trends of the AVHRR NDVI and MODIS NDVI and EVI datasets. These tools, namely the ordinary least squares (OLS) regression and Mann-Kendall non-parametric trend analysis are unaffected by the presence of outliers and provide more information than traditional (non-spatial) techniques (Fischer & Getis 2009).The trends produced by the Earth Trends Modeller were able to provide valuable insight into the spatial differences in vegetation change. A key limitation of these trend analyses is that they are based on a limited time-series where vegetation change occurring within the first or last two years of the time series is very difficult to detect (Wessels et al. 2007). The period of assessment also has a large influence on the detection of linear trends. Thus the results from the trend analyses are only applicable to a certain period and trends may change following the addition of years to the time series. Piecewise linear trends (Verbesselt et al. 2010a; Verbesselt et al. 2010b) proved to be more applicable in this case since they did not assume monotonic trends throughout the time-series but instead decomposed the time-series into seasonal variations, gradual trends and abrupt changes at breakpoints (Wessels et al. 2012). The TIMESAT program was useful at detecting seasonal changes by extracting key phenological metrics from the AVHRR and MODIS time series. A key limitation of this approach was that spatial trends were not able to be produced due to technical difficulties in the program that did not allow for the data to be exported in a format that could be analysed further with the Earth Trend Modeler in Idrisi Taiga.

Overall, there can be a high confidence in the trends derived from the AVHRR and MODIS time series. Firstly, the same results were replicated with a number of different approaches and secondly, to some extent the trends in NDVI and EVI were able to replicate the trajectory of vegetation change observed in the repeat photographs as well as sites negatively impacted by cultivation and grazing were positively identified.

8.4. Main conclusions and future directions

Using a range of combined techniques, this study was able to quantify the rate, nature and direction of vegetation change for the region at a range of spatial and temporal scales and relate these to changes in climate and land use patterns. The main conclusions that are pertinent to the objectives of the thesis are:

1. Vegetation in Namaqualand is considerably variable over space and time.
2. A trend towards an improved vegetation cover and composition is evident in the study area, which is line with the projections by Driver et al. (2012).
3. Climate variability and changing land-use patterns, such as increases in grazing pressure and the abandonment of cultivation, have a considerable influence on vegetation change and disentangling these two remains a challenge.
4. Recent changes in climate, especially temperature, have not had a discernible negative effect on the measure of vegetation productivity used in this study.
5. Land-use practises and land tenure are important filters through which to interpret vegetation change in Namaqualand.
6. A combined set of techniques, including remote sensing and repeat photography, is required for detecting the full range of landscape vegetation change over time including long-term productivity and seasonality.

This research offers new insights into the spatial patterns and inter-annual variability of vegetation productivity and seasonality of Namaqualand that could not be mapped without the use of long-term satellite time series data. The results could indicate an increase in the resilience of the vegetation in Namaqualand, which is an important consideration in the face of climate change. While acknowledging the limitations, remotely sensed information on vegetation can play an indispensable role in characterising the functional dynamics of vegetation in the Namaqualand. Several improvements could be made in this study which includes the addition of more recent photographs, study site visits in order to compare recent field based measurements with the remotely sensed information, and the use of higher resolution satellite data such as SPOT. It is important to note that spatial and temporal scales should be taken into consideration since the time scale over which measurements are made is critical for detecting long-term trends of vegetation change. The interpretation of the observed change in vegetation, in terms of climate and land-use remains a complex issue. Gathering further data such as a detailed land use change map and more recent site photographs are important. Overall, the findings of this study have created a baseline or reference conditions for Namaqualand against which future change can be assessed. The approach taken in this study can guide future studies on the vegetation dynamics in Namaqualand.

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