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Understanding the past to conserve the future: Long-term Environmental and Vegetation Change in the Karoo Midlands, South Africa over the 20th Century

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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.

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Signature Date

Dedication

To the Plant Conservation Unit as we strive towards understanding the nature & extent of land cover change in South Africa at various spatial and temporal scales, as well as highlight trajectories of climate, land use and vegetation change; and emphasize the value of long-term monitoring from decades, centuries to millennia

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Professors Timm Hoffman and William Bond were supportive since the time I got my six-month contract to complete a PhD proposal in order to get further financial support from South African National Parks (SANParks). They really provided supervision and guidance during the exploration and discovery phases of the whole thesis since day one and accepted the challenge of mentoring me during the three years of the PhD. I am especially indebted to Timm for his patience, guidance and making himself available at all times either for discussion or checking up on my progress and in that sense is the best supervisor I have ever had throughout my career. When the months were lean, Timm and William always supported me with funding either through bursary top ups or a salary when my contract with SANParks expired in April 2012. I am grateful to our co-author in Chapter 4, Dr. James Gambiza who provided valuable comments on the chapter and was also encouraging at the start of my PhD during the fieldtrip around the Eastern Karoo. I must thank Peter Burdett (Park Manager-Camdeboo National Park (CNP)) for setting up the photo-monitoring at Camdeboo National Park and allowing me access to the data and in chapter three. I am also grateful to the rangers and other CNP staff members who assisted me with many logistics during my visits in the park. All the farmers and private reserves owners in the Eastern Cape who welcomed us when we showed up unannounced at their doorstep or found us look through their fences while locating the photographs. Thank you so much for granting us permission to work on your properties. In terms of photographs used for the ecotone (chapter 4) and regional (chapter 5), I must thank Timm and Lauren Davids who set me up in terms of archiving and analysis of the images in Adobe Photoshop CS4. I must also acknowledge the foundation of the work laid out by Dr Piet Roux in his 1961/2 study as well as Timm’s work in 1989 for the ecotone study. It was so fascinating and humbling to listen and discuss issues with Dr Roux on his observation of climate, land use and vegetation changes in the karoo in the last 60 years. His wealth of knowledge and opinions were really interesting and inspiring. The late John Acocks and other photographers as well as the Cory Library in Grahamstown provided their collection and have contributed immensely to understanding the extent of change in the vegetation in the central interior of South Africa. Grootfontein Agricultural College (Pasture Research Section) especially Lorraine van den Berg and their technicians (Mr Maseti and others) assisted in the field with species identification during field work in Middelburg and Cypress Grove. Department of Water Affairs and Forestry (DWAF) and South African

Weather Service (SAWS) supplied the long term climate data while the Plant Conservation Unit at the University of Cape Town supplied historical photographs and long-term vegetation survey data. I am very grateful to SANParks and Andrew Mellon Foundation for financial support as well as the Mazda Wildlife for transportation. SANParks and UCT have afforded me an opportunity to do my PhD studies. PCU colleagues are acknowledged for discussions around theory and literature on environmental change in the past 2000 years in various ecosystems in the world but more specifically in various well researched biomes in the southern Africa region. SANParks Junior Scientist Programme funded by the Andrew Mellon Foundation was responsible for my PhD registration fees and for fieldwork and conference fees. I must acknowledge Sandy Smuts, Tamara Nozewu and Anthea Stain for assistance with administration issues in the Botany Department. The various scientific services contributed immensely in sourcing funds and data during my PhD, specifically Prof Melodie McGeoch (Head-Scientific Services-Cape Node), Dr Stefanie Freitag-Ronaldson (Science Operations Manager) and Danie Pienaar (Head-Scientific Services-Savanna Node) for their approval of contracts and expenditure during the 3 years. Patricia Khoza and Jolene Waller are thanked for the administration duties performed and always helping when I called and stepped into their offices for assistance. The following people whom I met during my PhD in Cape Town are warmly acknowledged for the love, support and friendship Nonkonzo Thando Bangiso, Matome Rammutla, Pheeha Machaka, Nokuzola Valencia Mnguni, Michael Tladi, Mbuyisile Sithole, Mpilo Sithole and Abraham Dabengwa. Suleimann Coenraad and family provided me accommodation for 3 years and were always supportive. Finally and most importantly, I cannot thank my family enough especially my baby boy Kgothatso Masubelele who this work is dedicated to, for their emotional support (bringing a smile watching you grow from pea size to a big talkative boy) and patience when daddy was never home for months. My mom, dad, younger brother and two sisters had always supported my decisions and took precious care of my son which allowed me time to be committed to obtaining my childhood dream of a doctorate. This PhD is for you all, and I am forever indebted to you for your patience, love and support and just knowing that I can always count on you for everything.

Abstract

This study investigated the nature, extent and rate vegetation change in the Karoo Midlands region of South Africa at multiple spatial and temporal scales in relation to local and global drivers. This is important because changes in land cover have major implications for the conservation and management of biodiversity in the region. The thesis is comprised of an historical analysis of climate as well as three cases studies which use repeat photography and long-term surveys to assess vegetation change in the region. In the first chapter the primary theoretical considerations addressed by the thesis are outlined and the climate change projections at a global and regional scale are presented. In chapter 2 changes in the historical record of several climate variables within the three main biomes (Grassland, Nama-karoo and Albany Thicket) of the region are analysed. A non-parametric Mann-Kendall test for trend is carried out on historical trajectories of change in time series of rainfall, temperature, pan evaporation and the incidence of drought in the region. Results showed that the trajectories of annual rainfall and drought incidence were not consistent with the aridification hypothesis which has been suggested by most global climate models. In fact, in the Nama-karoo biome there is evidence to suggest that the incidence of large wet events has increased over the course of the 20th century and that seasonal rainfall patterns have also changed. While there has been in increase in temperature this pattern was not consistent across all biomes. There also appeared to be no consistent pattern between climate stations in the trend for pan evaporation. In Chapter 3 vegetation change within the Camdeboo National Park (local scale) was investigated at 32 fixed-point photo monitoring sites for the period 1988-2010 and related to climate and herbivory. Results from the 1,150 images analysed showed that major growth forms within the four main vegetation types in the park responded differently over the study period. Sites within Grassy dwarf shrubland and Azonal vegetation were dynamic over time while sites within the Albany thicket and dwarf shrubland vegetation remained relatively unchanged over the roughly two decades of observation. Abiotic factors such as rainfall amount, changes in rainfall seasonality and the occurrence of drought and flooding events were more responsible for changes in the cover of grasses and tall shrubs than herbivory particularly since the density of animals were relatively low during the course of the study. In Chapter 4, changes over the period 1962-2009 in the abundances of grasses, dwarf shrubs and tall shrubs were investigated at eight localities within a broad 1,000 km ecotone between the Grassland and Nama-karoo biomes. Results showed that grass cover has increased significantly and that dwarf shrub cover has decreased over time. This contradicts earlier views which warned against the expansion of dwarf shrublands in response to over-grazing as well as more recent views which suggest that more mesic biomes in the Karoo Midlands will contract in response to climate-induced aridification. The decline in stocking densities and more conservation-friendly land management practices together with increased summer seasonal rainfall and large wet events are probably responsible for the increase in grass cover in the region. This pattern of vegetation change was also evident at a broader regional scale (Chapter 5). From an analysis of 65 repeat photograph pairs (some of which date to the late 19th century) grouped into 130 landform sub-units it is clear that grass cover has generally increased across the Karoo Midlands region and dwarf shrub cover has decreased over time. Tall shrubs have also increased particularly within ephemeral rivers but also on slopes of the more mesic Grassland biome. These trajectories support more recent model outputs which describe an increase in tall woody cover over much of southern Africa. While several components of climate (e.g. rising temperature) as well as elevated CO_2 concentrations may have played a role, the widespread decline in stocking rates can also not be dismissed as an influence on vegetation change in the region. The findings of this study have created benchmark conditions for the different biomes and have provided an understanding of land cover change in one part of southern Africa over the last 100 years. The broader management and policy implications of the study as well as the value of techniques used are discussed in the final chapter.

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Chapter 1: Introduction

1.1. Problem statement

Landscapes are dynamic in time and space. Substantial changes in vegetation cover and composition are expected at a range of spatial scales throughout the world due to climate and land use change as well as to rising concentrations of CO_2 in the atmosphere (de Baan *et al*. 2012; Ellis 2011; IPCC 2007; Leadley *et al*. 2011; Williams *et al*. 2007). This study takes place in the Karoo Midlands in the central interior region of South Africa. It is a dynamic region in which different biomes and vegetation types (Mucina & Rutherford 2006) (see Figure 1.1.), occurring on a range of land forms, interact along gradients in temperature and moisture and in response to different intensities of land use.

This region is also expected to undergo significant change in the future in response to changes in climate, land use and an increase in atmospheric CO_2 concentration. An increase in temperature and drought frequency associated with a decline in rainfall is predicted to increase aridification in the region resulting in a loss of cover and a deterioration of the vegetation (Ellery *et al*. 1991; Rutherford *et al*. 1996). Dominant plant growth forms, vegetation types and biome boundaries are expected to change accordingly depending on whether they occur on slopes, plains or along riverine habitats. The main growth forms in the region are grasses, dwarf shrubs and tall shrubs. The majority of grasses in the region possess a C_4 photosynthetic pathway. Because of increasing concentrations of CO_2 in the atmosphere they are expected to be replaced by both dwarf and tall shrubs, most of which have a C_3 photosynthetic pathway (Collatz *et al*. 1998).

In response to both aridification and rising CO_2 concentrations the Nama-karoo biome is predicted to contract from the west and shift north eastwards into the Grassland biome (Ellery *et al*. 1991; Rutherford *et al*. 1996; Midgley *et al*. 2002, 2008). The latter biome is expected to contract further as a result of the spread of savanna trees favoured by the projected increase in temperature and CO_2 concentration (Midgley & Thuiller 2011). For the Grassland and Nama-karoo biomes the projected direction of change in response to future changes in temperature and rainfall is very similar to that proposed by Acocks (1953) in response to overgrazing by domestic livestock. Although the Albany Thicket biome has not been modelled extensively, preliminary work suggests that several, but not all, species in the biome are vulnerable to the impact of climate change (Robertson & Palmer, 2002). Historical overstocking of the land by domestic livestock, however, has been shown to be the primary driver of change in this biome (Kerley *et al*. 1995; Sigwela *et al*. 2009).

Even though there is considerable uncertainty associated with global climate and regional models, historical trajectories of change in climate, land use and vegetation, derived from long-term data, provide useful benchmarks against which future changes and even future projections can be evaluated (Costanza *et al*. 2012). This thesis explores several long-term data sets for the Karoo Midlands region in the central interior of South Africa and compares these historical trajectories of change with future projections for climate, land use and vegetation. Historical changes in rainfall and temperature as well as evaporation and the incidence of drought are analysed. Since atmospheric CO_2 concentrations are relatively similar across the globe and values in the Karoo Midlands region will not differ greatly from those for southern Africa, historical trends for CO_2 concentration are derived from global analyses (Bond & Midgley 2012). The potential influence of this gas on the biomes and growth forms in the region is suggested based on its influence in similar environments and region within South Africa as supported by literature. No CO_2 fertilization experiments were done in this study but a historical account and potential influence is nevertheless valuable if interrogations are to be done to ascertain its role as a driver in the region. The influence of these drivers on the observed changes in historical vegetation patterns, based largely on repeat landscape photography at different temporal and spatial scales, is investigated in this study. The current and relevant land use and climate change debates are presented together with how policy and management is likely to be influenced.

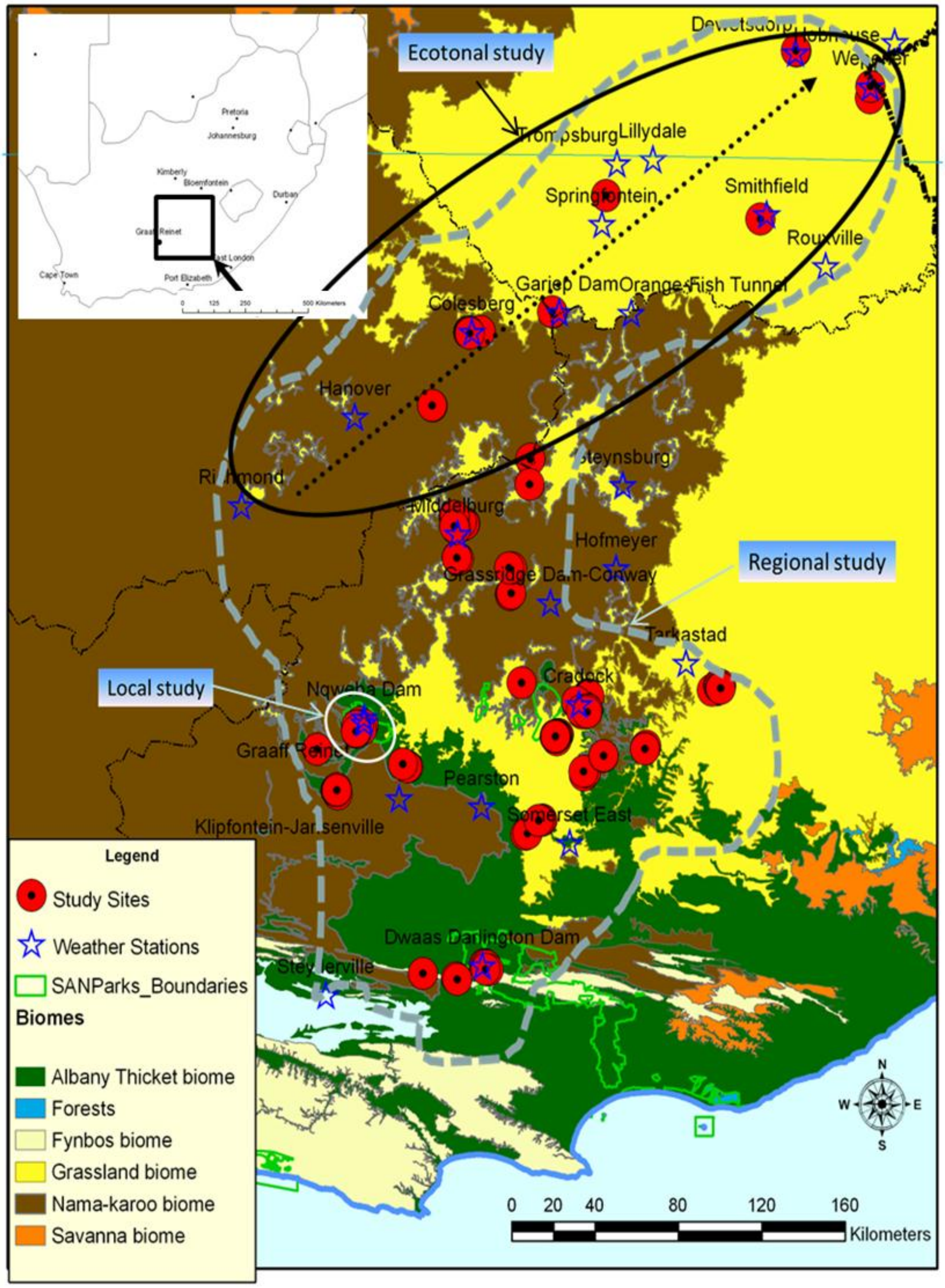


Figure 1.1: The location of the weather stations (used in chapter 2) and sites used in the Karoo Midlands regional study (area within the dashed line) (Chapter 5). The ecotonal study (black ellipse) (Chapter 4) has a decreasing rainfall gradient (black dotted line) from the northeast to the southwest across the Grassland and Nama-karoo biome boundary. The small circle indicates the site for the local study undertaken within the Camdeboo National Park (Chapter 3).

1.2. The impact of climate and land use change on vegetation

1.2.1. Future projections in key climate variables

Global climate change is likely to cause an increase in major climatic extremes such as drought and flooding (IPCC 2007). This is expected to pose a threat to water supplies, result in desertification and cause damage to the natural environment resulting in biodiversity losses. Projections for climate change are based on general circulation models (GCM's) of the atmosphere and oceans. Recently, in an effort to incorporate change at a regional level, GCM's have been downscaled to regional climate models (RCM's) especially for temperature and rainfall (Moise & Hudson 2008; Engelbrecht *et al*. 2009; Sanderson *et al*. 2011).

Global predictions for temperature suggest that there will be an increase of more than 2-3 ºC over the next century, with the northern latitudes expected to experience the greatest increase (Giorgi & Bi 2005) and that 4°C is a possibility (New *et al*. 2011). Models indicate that the large increase in higher northern latitudes will be caused by a loss of ice and reduced winter snow coverage that will eventually expose the land and oceans to most of the incoming solar radiation (Sanderson *et al.* 2011). When GCM's are downscaled to regional levels, results suggest that while temperatures will increase in all regions in the 21st century (Gao & Giorgi 2008) the rate of warming will not be uniform across the world (Sanderson *et al.* 2011). For example, small areas over South America, southern Africa and Australia are expected to experience greater regional warming due to increased poleward energy transport. There is also general agreement amongst most models that continental interiors will warm by as much as twice the global average. While temperatures are expected to increase significantly in both the wet and dry seasons, for southern Africa, modelled data suggest winter months will experience the largest warming trend. The central interior as well as the western parts of the region will be the most affected (Warburton *et al*. 2005; Engelbrecht *et al.* 2009).

For rainfall, future global projections suggest widespread decreases around the subtropical zones of the world due to the widening of the Hadley circulation and increased atmospheric stability (Lu *et al*. 2007). Projections for high latitude areas in the northern hemisphere, however, suggest that there will be a consistent increase in rainfall (IPCC 2007). While model projections for Africa appear strongly dependent on the particular GCM used (Joubert & Hewitson 1997; Penlap *et al.* 2004), results for eastern Africa indicate that there will be an increase in precipitation over the course of the 21st century. For southern Africa, however, there is considerable uncertainty in the output of both the global and regional models for the region (Engelbrecht *et al.* 2009; Shongwe *et al.* 2009; Sanderson *et al.* 2011; Haensler *et al*. 2011; Tadross *et al*. 2011)). The impact and feedback of anthropogenic activities on rainfall are also not captured in the GCMs (Hély *et al.* 2006).

The frequency of both drought and flooding which is linked to rainfall patterns is expected to increase in most parts of the world except perhaps in a few arid regions and over some areas of the ocean (Dai 2011a). For most parts of Africa, including southern Africa, projections indicate that there will be an increase in the frequency of drought as well as an increase in the intensity of flood events. Haensler *et al.* (2011) suggest that because of the projected increase in temperature as well as in the frequency of drought conditions, most of the continent will likely experience an increase in aridity in the 21st century.

While evaporation is expected to increase in response to global warming (Huntington 2006; Matsoukas *et al.* 2011), long-term historical evidence shows that pan evaporation has declined in many parts of the world. While there are exceptions to this general trend such as in China (Chu *et al.* 2010; Goyal & Ojha 2011) and Mexico (Blanco-macías *et al.* 2011) most analyses report a decline (McVicar *et al*. 2012). This so-called ‘evaporation paradox’ (Roderick *et al*. 2009) is explained primarily by the decline in wind run, vapour pressure deficit and solar irradiance measured in long-term climate records (Roderick *et al*. 2009; Fu *et al*. 2009; McVicar *et al*. 2012). In the Western Cape region of South Africa the reported decrease in pan evaporation from 1970-2005 has been explained primarily by the decline in wind (Hoffman *et al.* 2011). This reduction in pan evaporation has occurred despite the significant increase in temperature recorded for most climate stations over the same time period. Eamus and Palmer (2007) reported a similar decline in pan evaporation for two climate stations in the Karoo Midlands region in the latter part of the 20th century.

The concentration of CO_2 in the atmosphere has increased globally since industrialization occurred in the mid-19th century and is expected to more than double in the future (IPCC 2007). Although there is a lack of observation stations in southern Africa the region follows global CO_2 trends since this gas is well mixed in the atmosphere. In response to this increase in CO_2 concentration, it is expected that C_4-dominated grasslands will be replaced by C_3 grasses and shrubs (Collatz *et al*. 1998; Lattanzi 2011). Experimental work indicates that C_4 plants are photosynthetically more efficient at low CO_2 concentrations but that this is not the case as CO_2 concentrations increase (Osborne & Sack 2012). The expansion of forest and savanna trees observed in many of South Africa's grasslands is thought to be driven, at least in part, by an increase in CO_2 (Bond & Midgley 2012; Kgope *et al*. 2010; Midgley & Thuiller 2011; Wigley *et al*. 2010). The impact of elevated CO_2 levels on plant and ecosystem function is also influence by temperature and moisture (Leakey *et al.* 2012). Thus vegetation within more arid areas may not respond in the same way as the vegetation growing within more humid areas (Bond & Midgley 2012; Leakey *et al.* 2012; Rohde & Hoffman 2012). While the Karoo Midlands region contains several temperature and rainfall gradients within its boundaries and provides an ideal environment within which some of these predictions can be tested, experimental fertilization of the gas although was not within the scope of the thesis will have to be done to ascertain its role as a driver of vegetation change. We could only speculate its role based on findings in similar regions in the globe and areas where experimentation was done within the country.

1.2.2. The projected impact of climate change on vegetation

Climate change will affect the habitat of most terrestrial species (Thomas *et al.* 2008). Bioclimatic envelope models (BEM's) (Pearson & Dawson 2003), Dynamic Global Vegetation Models (DGVM's) (Bond *et al*. 2005; Higgins & Scheiter 2012) as well as species loss component models suggest significant effects of climate change on vegetation at multiple spatial scales (Bellard *et al*. 2012). A synthesis of information from a broad range of projections from such models (Leadley *et al*. 2010) suggests that climate change will increase species extinctions, accelerate the loss of natural habitat, and bring about a change in species abundance and distribution over the course of the 21st century. Their synthesis concludes that model projections are weakly supported by historical trajectories and current trends within some plants and insects.

The majority of studies suggest that there will be major shifts in the distribution of species, vegetation types and biomes the 21st century due to climate change at both regional and global scales (Alkemade *et al*. 2011; Breshears *et al*. 2005; Fischlin *et al*. 2007; Midgley *et al*. 2002; Midgley & Thuiller 2011; Stich *et al*. 2008). Species and vegetation types are projected to move poleward and higher in altitude in response to a warming climate (CBD 2006). Increases in temperature and CO_2 concentrations are also expected to result in an increase in woody plant cover especially in savannas and grasslands across the globe (Scheiter & Higgins 2009). Key landscape-level processes and interactions, however, have been poorly incorporated into models (Bellard *et al*. 2012). There is, therefore, an urgent need to understand change at this level. In South Africa, the expected changes in climate will alter the structure and distribution of biomes (Midgley & Thuiller 2011) as well as the population dynamics within a wide range of species, together with vegetation structure and species richness (Chown 2010). An understanding of the projected climate change impacts on species, vegetation types and biomes at multiple spatial and temporal scales is essential for better management and policy implementation in South Africa.

1.2.3. The projected impact of land use change on vegetation

Habitat loss is one of the largest causes of species extinctions. Projections for habitat loss show large declines in natural habitat over the course of the 21st century due to both climate change and land use change such as deforestation, agricultural expansion and development (Vuuren *et al*. 2006; Jetz *et al.* 2007). Those species and populations which are most dependent on natural habitat for their survival are expected to experience the greatest decline (ten Brink *et. al*., 2007). In models that account for both climate change and land use change it is frequently observed that land use impacts will remain the dominant driver of species loss at a range of scales from landscapes to regions (Alkamande *et al*. 2009; Ellis *et al.* 2010; Turner *et al*. 2009).

Scenarios for the Eastern Cape indicate that land use impacts will increase over the short- and medium-term (10-30 years). In many former livestock-producing regions of the Eastern Cape, rural development initiatives will expand in response to the strong infrastructural linkages that are envisaged between coastal and inland municipalities (Driver *et al*. 2012). As demands to feed a growing human population increase the Karoo Midlands will continue to be an important area for livestock production. Other land use practices such as game farming and ecotourism will continue to increase as well (Driver *et al*. 2012; Smith & Wilson 2002). Corridor networks to protect biodiversity in the region have already been tabled by nature conservation organisations such as the South African National Parks (SANParks) and provincial nature conservation institutions (Berliner & Desmet 2007). An account of how historical land use impacts have affected the vegetation of the Karoo Midlands is essential. The impacts of land use at local (e.g. stocking densities within a park) to regional scales (e.g. stocking densities within magisterial districts) will therefore be investigated.

1.3. Research objectives and key questions

There were three broad objectives of the study:

- To analyse long-term changes in climate and land use drivers in the Karoo Midlands region over the course of the 20th century;
- To document the nature, rate and extent of change in the vegetation of the Karoo Midlands region at different spatial and temporal scales;
- To relate the observed historical trajectories in climate, land use and vegetation change to future projections for the region and to discuss these findings in terms of important management issues faced by farmers, conservation managers and policy makers.

The main question addressed by the thesis was: How has the vegetation of the Karoo Midlands region changed over the course of the 20th century in response to climate and land use at different spatial and temporal scales? Additional specific questions included:

- How have climate and land use changed in the Karoo Midlands over the last 100 years? How do these findings relate to future climate and land use change scenarios for the region?
- How has the vegetation changed in the Camdeboo National Park (CNP) based on photographic evidence for the past 20 years? What have been the main

drivers of this change and which species and growth forms have changed most? Is repeat photography a beneficial technique and a necessary skill to acquire for South African National Parks (SANParks)?

- Has the broad ecotone between the Nama-karoo and Grassland biomes changed over the last 55 years or have the two biomes remained relatively distinct and separate along the rainfall gradient? Has there been an expansion of more arid-adapted Nama-karoo species into the more mesic Grassland biome areas of the eastern Karoo over the last 55 years? What is the impact of climate and land use on species composition and on biome shifts between Nama-karoo and Grassland biomes within the ecotone?
- What has been the extent of change in major growth forms in biomes of the Karoo Midlands region over the 20th century at a range of spatial and temporal scales? What factors (e.g. climate and/or land use) best explain these changes? Are some landforms more susceptible to change than others (e.g. slopes, plains, rivers)
- What are the implications of these changes at multiple spatial and temporal scales for Protected Area managers, farmers and policy makers?

1.4. Conceptual framework

An understanding of ecological systems has benefited from and been advanced by the development of conceptual frameworks (Pickett *et al*. 2003). A simplified model of how climate and land use drivers interact with major land forms to influence the vegetation of the Karoo Midlands Region is shown in Figure 1.2.

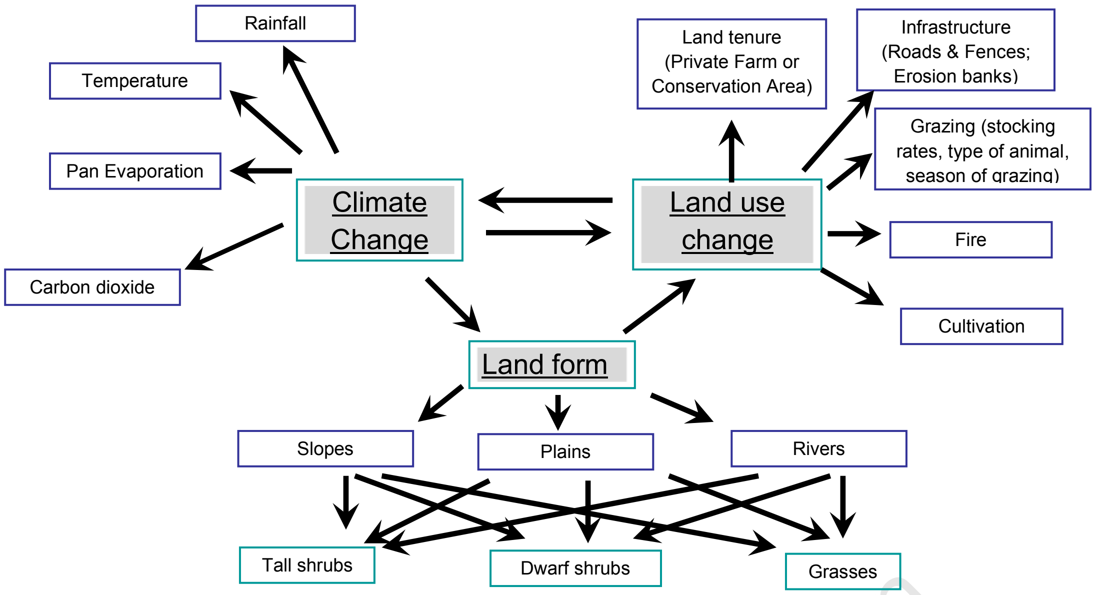


Figure 1.2: The important components influencing vegetation change in the Karoo Midlands region and which are investigated in this study.

Climate is the most important determinant of the distribution of biomes across the world (Adams 2010). Climate factors that are known to influence the distribution of biomes in southern Africa include rainfall, temperature, evaporation and the atmospheric concentration of CO_2 (Mucina & Rutherford 2006). These are the key climate variables investigated except atmospheric concentration of CO_2 which is interrogated in this study.

Land use also has an important impact on the vegetation and biomes of the Karoo Midlands and is comprised of several interrelated variables. Land tenure is an important lens through which to investigate vegetation change. Management objectives are often very different within privately-owned areas and conservation areas which are the two main forms of land tenure in the Karoo Midlands. The presence of infrastructure such as roads and fences also has an impact on the vegetation of an area since the extent and form of available infrastructure often determines the management approach adopted by the land owner. The type of animal and density of livestock are, in turn, often influenced by available infrastructure. While fire is relatively uncommon in the Karoo Midlands it does occur and can have important effects on the relative proportions of grasses and shrubs in an area. Fire is also used in the broader Eastern Cape landscape to control the spread of trees such as *Acacia karroo*. Finally, cultivation can have a large impact on the vegetation of semi-arid areas since most cultivation is marginal and is seldom maintained over any length of time. While cultivation is not an important land use practice in the Karoo Midlands it can occasionally have important consequences for the vegetation of an area and is often directed at more productive parts of the landscape such as along river banks.

The Karoo Midlands region is characterized by different major landforms such as slopes, plains and rivers. There is generally a lack of appreciation for how climate and land use change will affect major growth forms or biodiversity occurring within specific parts of the landscape (Dale *et al*. 2011; Verburg *et al*. 2012). This study should contribute to an understanding of how different landforms are affected by changes in land use and climate.

1.5. Research approach and thesis outline

The extent of change in vegetation in response to climate, land use and CO_2 drivers can be assessed through the use of repeat photographs which are used extensively in this study. Historical and recent evidence of change obtained from repeat photography and long-term vegetation surveys are important in bridging the gap between modellers and field ecologists. Historical trajectories also provide a basis for modelling and are essential for validating model predictions. Furthermore, coarse-scaled global models sometimes need more localised or regional accounts of landscape change particularly if the scenarios rely heavily on climate change projections alone. This is particularly important when the impact of some local drivers, such as heavy grazing or the expansion of cultivation, is able to overwhelm the influence of climate.

The thesis adopts a case study approach in dealing with vegetation change at different spatial and temporal scales. Case studies range from an analysis of vegetation change over about 20 years within communities of a protected area to an analysis of landscape scale changes in vegetation over 50 years along a 500 km ecotone between two major biomes as well as a regional analysis of vegetation change over 100 years or more within three major biomes of the Karoo Midlands region. The range of temporal and spatial scales used in this study assists in the generalization of key findings concerned with long-term environmental change in southern Africa. This analysis also shows whether the historical data supports the direction of change as projected by the climate change models for the 21st century. I used community, conservation and landscape ecological theory and principles including the use of community assembly theory (ordinations), alternative stable states and hierarchical spatial heterogeneity (Clements 1905; Holland 1988; Parmesan *et al*. 2003, Pickett *et al*. 2003; Gillson 2004) to understand the nature and extent of vegetation change in the Karoo Midlands region and to identify the major drivers of this change.

In Chapter 2 I analyse the historical trends in key climate variables in the Karoo Midlands region. I relate these to regional and global climate change projections and discuss the likely impact of these changes on the vegetation of the region. I then (Chapter 3) investigate the changes over two decades of major growth forms within four vegetation types in the Camdeboo National Park. Growth form dynamics over annual and decadal-scale time frames are related to changes in key climate and land use drivers in this detailed study of a relatively small area. In Chapter 4 I explore the key drivers of vegetation change along a 500 km ecotonal boundary between the Nama-karoo and Grassland biomes in the Karoo Midlands region. I analyse historical changes in key climate variables and stocking rates and relate that these to patterns observed in the vegetation over three time steps from 1962 to the present. Detailed vegetation surveys and repeat ground photographs are used to document the trajectories of change. In Chapter 5 I also use repeat photographs but document the extent, nature and rate of vegetation change at a regional scale over longer time scales of a century or more in some cases. Growth form changes within different landforms (slopes, plains and rivers) are compared in the three major biomes (Nama-karoo, Grassland and Albany Thicket) of the Karoo Midlands. The main findings from these studies are summarized in Chapter 6 and related to key management and policy debates in southern Africa.

Chapter 2: Twentieth century climate change in the Karoo Midlands Region, South Africa

Introduction

In most parts of the world, including southern Africa, it is predicted that increased temperature, flooding and extended droughts due to global warming will have a direct impact on millions of people and other living organisms. Key climatic variables that have changed globally include temperature, rainfall, evaporation, nitrogen deposition and the concentration of CO_2 (IPCC 2007; Williams *et al*. 2007). However, large internal climate variability and the confounding role of land-cover change are amongst the reasons climate change 'projections' (or scenarios) for Africa based on greenhouse gas warming remain at a low level of confidence (Hulme *et al*. 2001). Therefore, climate monitoring is vital to further advance our understanding of the complexity of the climate system and its predictability.

Rainfall over South Africa is markedly seasonal with more than 80% of the country receiving rain in summer (October to March). Winter season rainfall is experienced in the west of the country (Hobbs *et al.* 1998). The wide variety of South Africa's weather conditions (Davis 2010) are strongly influenced by several large-scale atmospheric weather systems. For example, the El Niño Southern Oscillation (ENSO) exerts a strong influence on the variability of precipitation in the Southern Hemisphere, including South Africa (Fauchereau *et al*. 2003; Jury *et al*. 1994; Lindesay 1988; Rouault & Richard 2003, 2005). Drought years in the summer rainfall region of South Africa are linked to El Niño events and are associated with a weakening or a regional shift of the Walker type circulation and the positioning of the subtropical jet stream (Ambrosino *et al*. 2011; Crétat *et al*. 2010; Mason 2001). Above normal rainfall in the region is linked to La Niña episodes (Rouault & Richard 2005). At a regional scale, inter-annual rainfall is regulated by sea surface temperature (SST) variations from the Atlantic and Indian Oceans with the latter ocean being the main source of moisture for summer rainfall in southern Africa (Hansingo & Reason 2009; Vigaud *et al.* 2007, 2009). Positive SST anomalies in the southwest Indian Ocean are associated with wetter conditions over the eastern and central interior of the country during summer (Reason 2002; Washington & Preston 2006). The variability in rainfall in the region is further influenced by tropical-temperate troughs (Hart *et al*.

2010) which produce a cloud band of NW-SE oriented convection with convergence at the surface and divergence aloft which sustains uplift and produces above-average rainfall. These troughs contribute most to rainfall in the central plateau of South Africa (Fauchereau *et al.* 2009; Pohl *et al.* 2009).

In the southern Africa context projections for 21st century changes in temperature suggest an increase of more than twice that of the global average (IPCC 2007; Shongwe *et al.* 2009; Tabor & Williams 2010) especially during the winter months (Engelbrecht *et al.* 2009). A smaller change is expected in the summer months especially in the central interior. Advances in regional climate models have increased the confidence in future temperature projections although confidence in projections for rainfall remain low (Moise & Hudson 2008). Recent rainfall projections for southern Africa suggest increases in summer rainfall for areas in the north and east while rainfall in the winter rainfall region in the west is expected to decrease. While global climate models suggest a general drying in the central interior of southern Africa (Dai 2011a; Hulme *et al.* 2001; Midgley *et al.* 2002; Shongwe *et al.* 2009), regional climate model projections suggest that the region will experience an increase in annual rainfall (Engelbrecht *et al.* 2009; Hewitson & Crane 2006; Moise & Hudson 2008). It is well recognized that the resolution for global climate models has not been adequate to meet the regional information needs and regional climate models have made significant advances in this regard. However, the effect of convective rainfall events and the influence of clouds, which are both primarily responsible for summer rainfall in South Africa, remains elusive to modelling (Moise & Hudson 2008). For example, it appears that for both southern Africa and Australia, model convergence in the simulation of future climate is greater than the ability of models to capture present-day climate (Moise & Hudson 2008).

Palaeo- and historical climate data provide a ‘base line’ against which to assess the direction and extent of future climate change (Nicholls 2010). The main aim of this chapter is to document the historical changes in climate for the Karoo Midlands of central South Africa and to discuss these historical trajectories in the context of future climate change projections. Projections, based on global climate models suggest that the Karoo Midlands will experience mostly drier conditions over the next 100 years (Haensler *et al*. 2011). However, evidence from regional climate models suggests that the region will experience a wetting trend with significant impacts on biodiversity (Tadross *et al*. 2011). It is therefore important to analyse the historical climate record (particularly long-term trends in rainfall, drought, temperature and pan evaporation) and to identify the direction and rate of change in these climatic parameters for different regions in the Karoo Midlands.

2.2 Study Area

This research is comprised of three studies ranging from local to regional scale. The local study took place within the Camdeboo National Park (CNP) which surrounds the town of Graaff-Reinet in the Camdeboo Municipality of the Eastern Cape Province (see Figure 3.1). The details of the local climate specific to the CNP are discussed in Chapter 3. At a slightly larger scale, the shrubland-grassland ecotone study was arranged along an aridity gradient from Richmond in the Northern Cape to Wepener in the Free State (see Figure 4.1). A detailed climate analysis for this study area is provided in Chapter 4. In this chapter (Chapter 2) I analyse historical climate records for sites within the central interior region of the Eastern Cape in an area broadly described as the Karoo Midlands region (Acocks 1953, Skead 1987). This analysis provides the climatic context for the analysis of vegetation change detailed in Chapter 5.

The Karoo Midlands region supports three of the nine major biomes of South Africa, namely the Nama-karoo, Grassland and Albany Thicket biomes (Fig. 2.1). The Nama-karoo biome is bordered by the Grassland biome to the northeast while the Albany Thicket biome occurs to the southeast. The central interior is considered either arid or semi-arid and consists of a range of landforms. These include the plains which in the Karoo Midlands region are occupied primarily by vegetation types with affinities to the Nama-karoo and Grassland biomes. The slopes or mountainous areas, however, are occupied by elements from the Grassland and Albany Thicket biomes. Rainfall is the fundamental driving force for primary production in the region and for most hydrological processes in the Karoo Midlands. It occurs as a pulsed input of moisture derived primarily from convective thunderstorms in summer. In this region, rainfall decreases uniformly westward from the eastern escarpment across the plateau.

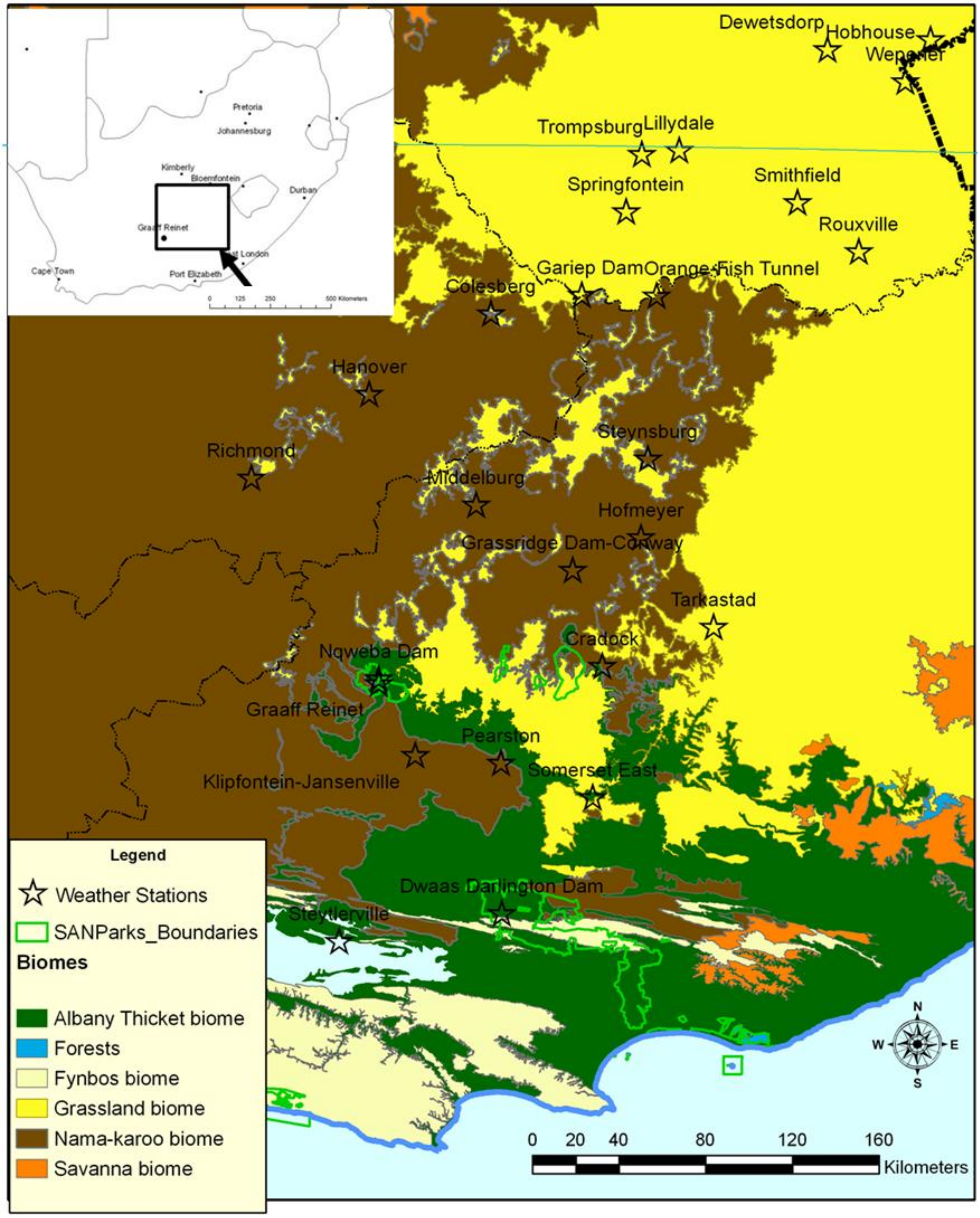


Figure 2.1: The location of the 27 weather stations used in this study of the Karoo Midlands grouped according to biome (Mucina and Rutherford 2006). Inset: Location of the study area in South Africa

The Karoo Midlands region experiences a broad range in annual rainfall of between 250 to over 600 mm. High temperatures, low relative humidity and relatively little cloud cover are characteristic of the region, especially within the Nama-karoo biome, thereby resulting in large annual and daily ranges in temperature (Desmet & Cowling 1999). Although temperature alone is not a significant factor in determining major regional vegetation patterns it has a direct influence on water availability and evapotranspiration (Schulze & McGee 1978). Sites within the Nama-karoo biome are associated with higher maximum temperatures, strongly seasonal rains and, for some regions, relatively high rainfall variability (Mucina *et al*. 2006a) than the other two biomes. The combination of low and unpredictable rainfall, and relatively high summer temperatures, makes the Nama-karoo biome one of the harshest environments in the Karoo Midlands.

The Grassland biome receives higher annual rainfall than the Nama-karoo and Albany Thicket biomes. It also receives more of its rain in summer with winter drought a common feature. The high elevation and inland continental aspect of the Grassland biome exert considerable influence on its climate (Mucina *et al.* 2006b). Rainfall generally increases with elevation while temperature decreases. Frost is common especially on the upper slopes of the Great Escarpment (Schulze 1984). Moisture availability and temperature range are generally used to differentiate between grassland communities. Grasses growing within high altitude, moist environments are usually different from those which dominate in low altitude, arid areas (Bond 1997; Ellery *et al*. 1991; Huntley 1994; Visser *et al*. 2012). In a recent analysis of the distribution of C_4 grasses, which are the dominant grasses in South Africa and the continent, they show that beside rainfall other factors strongly associated with the distribution include temperature, fire frequency and grazing pressure.

Unlike the Grassland and Nama-karoo biomes which receive rain primarily in the summer months (Mucina *et al*. 2006a, 2006b), the Albany Thicket biome experiences a bimodal summer-autumn rainfall regime (Hoare *et al*. 2006). In addition, high summer and low winter temperatures are common in arid thickets (Aucamp & Tainton 1984) while frost and fog may also occur (Vlok & Euston-Brown 2002).

2.3. Method and Materials

2.3.1. Climatic variables

2.3.1.1. Rainfall

Table 2.1: The name, years of data, geographical coordinates and altitude of the 27 climate stations used for rainfall analyses in the three biomes of the Karoo Midlands region.

Climate Station Name	No. of Years	Range of Years	Latitude (°S)	Longitude (°E)	Altitude (m)
Nama-karoo					
Middelburg	94	1915-2008	-31.494940	25.016936	1248
Richmond	107	1902-2008	-31.415334	23.945726	1419
Hanover	93	1916-2008	-31.065928	24.439683	1405
Colesberg	108	1901-2008	-30.727354	25.096599	1349
Gariep Dam	44	1965-2008	-30.625588	25.505849	1212
Hofmeyer	108	1901-2008	-31.649739	25.807998	1251
Orange-Fish River T	44	1965-2008	-30.692212	25.763778	1291
Grassridge Dam	86	1923-2008	-31.752971	25.454525	1063
Albany Thicket					
Cradock	108	1901-2008	-32.166469	25.625024	872
Graaff Reinet	108	1901-2008	-32.252347	24.540579	751
Nqweba Dam	82	1927-2008	-32.234969	24.528773	792
Roodeberg Farm	108	1901-2008	-32.519238	24.391054	858
Klipfontein-EC	108	1901-2008	-32.888028	24.702671	673
Steytlerville	108	1901-2008	-33.326811	24.343753	422
Darlington Dam	86	1923-2008	-33.206151	25.146423	232
Pearston	88	1918-2005	-32.580744	25.137404	710
Somerset East	108	1901-2008	-32.720193	25.583998	766
Grassland					
Tarkastad	103	1901-2003	-32.009619	26.256586	1394
Steynsburg	108	1901-2008	-31.293047	25.831734	1448
Smithfield	102	1907-2008	-30.212235	26.534446	1400
Rouxville	102	1907-2008	-30.418191	26.831279	1509
Springfontein	86	1923-2008	-30.265101	25.706306	1519
Trompsburg	95	1913-2008	-30.035846	25.784961	1416
Lillydale	102	1907-2008	-30.013745	25.957991	1476
Hobhouse	85	1920-2008	-29.526522	27.145686	1466
Dewetsdorp	104	1905-2008	-29.583116	26.659024	1542
Wepener	49	1960-2008	-29.727592	27.035359	1439

Long-term rainfall and temperature data was obtained from the South African Weather Service and from Lynch (2003). Annual and monthly trends in rainfall data were analysed from 27 weather stations in the region (Fig. 2.1; Table 2.1). The data was visually checked for errors and discontinuities and the empty cells replaced with long-term averages for a specific month. Patched data was largely removed from the analysis. Annual rainfall was measured as the sum of values from the month of October the previous year to September in the current year. This is largely due to the fact that rainfall starts around October in the region (Wessels *et al*. 2011). Trends in monthly rainfall totals for various weather stations grouped by biome were determined and statistically tested using a non-parametric Mann-Kendall test for trend (Modarres & da Silva 2007). For each month, the stations within the biome showing an increase were counted against those showing a decline and thereafter tested using a non-parametric Fisher exact test in Statistica 9. Seasonal rainfall differences between the 1930-1970 period and post-1970 values were compared. This is largely because the historical photographic images used in Chapter 5 go up to 1970. This period also allowed for a fair comparison of change between 40 versus 38 years.

The annual rainfall data were also used to determine the incidence of drought and flooding at three different time scales (6, 12 and 24 months) using a Standardised Precipitation Index (SPI)(McKee *et al*. 1993). The SPI is an index based on the probability of recording a given amount of precipitation. The probabilities are standardized so that an index of zero indicates the median precipitation amount (half of the historical precipitation amounts are below the median, and half are above the median). The index is negative for drought, and positive for wet conditions. The equation used in the analysis is described in detail in Edwards & McKee (1997). An analysis at 6, 12 and 24 months was carried out although only the 24 month time step is reported here since the focus of this chapter is on long-term trends.

2.3.1.2. Temperature

Long-term trends in temperature data were analysed from seven weather stations in the region (Table 2.2). Minimum and maximum temperature data were measured as the annual average from October the previous year to September in the current year. Similarly to annual rainfall when a new growing season for plants start.

Table 2.2: The name, years of data, geographical coordinates and altitude of the seven climate stations used for the calculation of temperature data in the three biomes of the Karoo Midlands region.

Biome and station	**No. of years**	**Range of years**	**Latitude (°S)**	**Longitude (°E)**	**Altitude (m)**
Nama-karoo					
Gariep Dam	45	1964-2008	-30.625588	25.505849	1212
Middelburg	40	1961-2000	-31.494940	25.016936	1248
Colesberg	19	1982-2000	-30.727354	25.096599	1349
Albany Thicket					
Graaff Reinet	49	1960-2008	-32.252347	24.540579	751
Cradock	24	1985-2008	-32.166469	25.625024	872
Somerset East	30	1979-2008	-32.720193	25.583998	766
Grassland					
Wepener	49	1960-2008	-29.727592	27.035359	1439

2.3.1.3. Pan evaporation

S-pan evaporation data was obtained for 7 stations in the study area from the Department of Water Affairs and Forestry website (http://www.dwaf.gov.za/Hydrology/FPMain.aspx) (Table 2.3). Annual pan evaporation totals were measured as the sum of values from the month of October the previous year to September in the current year. Trends for all climatic variables were analysed statistically using a non-parametric Mann-Kendall test for trend (Modarres & da Silva 2007).

Table 2.3: The name, years of data, geographical coordinates and altitude of the seven climate stations used for the derivation of S-pan evaporation data in the three biomes of the Karoo Midlands region.

Biome and station	No. of Years	Range of years	Latitude (°S)	Longitude (°E)	Altitude (m)
Nama-karoo					
Gariep Dam	47	1964-2010	-30.625588	25.505849	1212
Orange-Fish River T	47	1964-2010	-30.692212	25.763778	1291
Grassridge Dam	85	1926-2010	-31.752971	25.454525	1063
Albany Thicket					
Nqweba Dam	85	1926-2010	-32.234969	24.528773	792
Darlington Dam	85	1926-2010	-33.206151	25.146423	232
Grassland					
Egmont Dam	32	1978-2010	-30.052582	27.027107	1218
Weldebacht Dam	40	1971-2010	-29.876244	26.879870	1424

2.4. Results

2.4.1. Annual Rainfall

Mean annual rainfall for climate stations within the Karoo Midlands ranged from 241 mm at Steytlerville to 626 mm at Rouxville (Table 2.4). Average minimum, maximum and mean annual rainfall values were lowest for climate stations within the Albany Thicket biome and highest for those within the Grassland biome. However, rainfall variability, as measured by the coefficient of variation (CV) in annual rainfall was highest in the Nama-karoo biome (36%) followed by the Grassland and Albany Thicket biomes at 32% and 31% respectively. Annual rainfall changed significantly at eight of the 27 climate stations analysed in the Karoo Midlands region.

Table 2.4: Minimum (Rmin), maximum (Rmax), mean annual rainfall (MAR) (+SD), coefficient of variation (CV) and Z-scores (calculated using a Mann-Kendall test for trend) for MAR and the Standardised Precipitation Index (SPI) (24 months) for 27 stations in the Karoo Midlands. (*=p<0.05; **p<0.0l ***=p<0.001).

Biome and Station	**Rmin (mm)**	**Rmax (mm)**	**MAR (mm)**	**SD (mm)**	**CV (%)**	**MAR Z-score**	**SPI Z-score**
Nama-karoo							
Middelburg	138.9	766.4	325.9	121.9	37.4	**2.1***	**3.5*****
Richmond	110.0	600.9	320.3	104.3	32.6	0.6	1.7*
Hanover	128.1	729.1	326.3	117.5	36.0	0.8	2.1*
Colesberg	131.5	795.2	381.3	128.6	33.7	0.1	0.4
Gariep Dam	211.0	871.1	439.0	163.6	37.3	0.1	-0.7
Hofmeyer	69.9	742.5	323.7	135.2	41.8	1.2	0.8
Orange-Fish River T.	177.4	860.0	411.9	144.4	35.1	**2.6****	**2.4***
Grassridge Dam	133.3	573.9	300.8	93.8	31.2	**2.5***	**2.8*****
Total/Average	137.5	742.4	353.7	126.2	35.7	1.2	1.6
Stdev	42.2	108.5	50.4	22.2	3.3	1.0	1.4
Albany Thicket							
Cradock	126.1	596.2	316.7	99.7	31.5	1.6	**3.6*****
Graaff Reinet	125.2	646.2	332.7	94.6	28.4	0.0	0.4
Nqweba Dam	133.1	540.9	327.5	94.4	28.8	-0.2	0.2
Roodeberg Farm	160.5	622.6	355.4	105.6	29.7	-0.3	0.0
Klipfontein-EC	91.3	572.5	259.1	84.4	32.6	0.8	**1.8***
Steytlerville	74.2	413.8	241.0	90.5	37.6	0.1	0.6
Darlington Dam	116.7	466.5	255.8	82.6	32.3	0.9	**2.2***
Pearston	129.0	540.0	303.2	94.6	31.2	**-2.5***	**-3.0****
Somerset East	13.9	973.3	564.9	172.6	30.6	**-4.8*****	**-5.2*****
Total/Average	107.8	596.9	328.5	102.1	31.1	-0.4	0.1
Stdev	43.0	159.0	96.9	27.4	2.7	1.7	2.7
Grassland							
Steynsburg	143.0	899.5	424.0	131.6	31.0	**3.3****	**4.9*****
Tarkastad	95.7	786.0	416.0	128.0	30.8	-1.5	**-1.7***
Smithfield	193.5	925.3	505.8	151.4	29.9	-0.2	-0.2
Rouxville	223.5	1133.0	626.5	173.3	27.7	-1.1	-1.6
Springfontein	205.7	987.8	446.9	159.0	35.6	-0.9	-0.9
Trompsburg	152.1	989.8	419.9	156.1	37.2	**2.3***	**3.3****
Lillydale	141.1	849.7	420.1	130.8	31.1	**2.0***	**3.5*****
Hobhouse	101.4	1043.0	550.4	160.3	29.1	1.2	1.6
Dewetsdorp	271.0	1063.5	588.6	156.3	26.6	-0.1	-0.4
Wepener	81.5	1151.6	517.0	207.9	40.2	-1.4	**-1.8***
Total/Average	162.8	992.2	499.0	158.1	31.7	0.0	0.2
Stdev	64.8	122.6	78.6	23.5	4.6	1.5	2.1

In the Nama-karoo biome the general trend was for an increase in annual rainfall with three of the eight stations returning a significant increase since 1901. For the Albany Thicket biome, five of the nine weather stations showed an increase in annual rainfall while four showed a decline with two of the four exhibiting a significant decrease. In the Grassland biome the results were also mixed as six of the 10 stations showed a decline while the remaining four showed an increase with three stations having increased significantly. In general, sites within the Nama-karoo biome have experienced the greatest increase in annual rainfall over the course of the 20th century (67 mm). Sites within the Grassland biome showed the least change (8 mm) while sites within the Albany Thicket biome declined on average by 14 mm over this period.

2.4.2. Monthly rainfall

Of the 27 weather stations in the Karoo Midlands, 22 had positive slope values for January and December rainfall amounts over the course of the 20th century (Table 2.5). Only one station (Rouxville) in the Grassland biome showed a significant decline in rainfall trend for January while two exhibited a significant decrease for December. Twenty three stations showed a consistent decline for the months of March and May while all the other months reflected variable results. At the biome level, climate stations within the Nama-karoo biome showed the greatest increase in monthly rainfall over the course of the 20th century for the months of December (38 mm) and January (34 mm) while March rainfall declined by 20 mm. In the Albany Thicket biome the greatest decrease in monthly rainfall (13 mm) was for September followed by March and May which both showed a decrease of 9 mm. Rainfall increased in most Albany Thicket biome climate stations in January. In the Grassland biome monthly patterns were different from those shown for the Nama-karoo and Albany Thicket biomes. The increase in rainfall in January was generally lower than for August and February. December rainfall generally increased although not significantly for six of the seven stations. The only significant increase in December was for Steynsburg which borders on the Nama-karoo biome.

Table 2.5: Slope values fitted to monthly and total rainfall time series data from 27 climate stations grouped within three biomes in the Karoo Midlands Region. Significant monthly trends ($p<0.05$) are shown in bold.

Biome and station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
Nama-karoo													
Middelburg	0.30	0.16	0.09	0.11	0.03	-0.01	-0.01	0.06	-0.05	0.19	0.04	0.15	1.06
Richmond	0.21	-0.05	-0.13	-0.01	-0.08	0.03	0.00	0.09	-0.09	-0.02	0.13	**0.18***	0.26
Hanover	0.26	0.23	-0.26	0.00	-0.06	0.09	0.00	0.09	-0.07	0.05	-0.05	0.22	0.50
Colesberg	0.08	0.01	-0.15	0.03	-0.04	0.02	0.01	0.09	-0.09	**-0.03***	0.07	0.06	0.06
Gariep Dam	0.49	-0.29	-0.75	-0.30	-0.34	0.17	-0.05	0.02	0.26	**-0.79***	-0.02	0.70	-0.90
Hofmeyer	**0.34***	0.02	-0.02	0.01	**-0.09***	0.02	-0.04	0.03	-0.11	0.04	0.13	0.20	0.53
Orange-Fish Tunnel	0.75	0.44	-0.25	-0.35	0.11	0.40	-0.16	0.18	0.43	-0.01	0.04	**1.44***	3.02
Grassridge Dam	**0.26***	**0.19***	-0.10	0.04	-0.12	0.13	-0.02	0.08	0.03	0.11	0.19	0.05	0.84
Ave	*0.34*	*0.09*	*-0.20*	*-0.06*	*-0.07*	*0.11*	*-0.03*	*0.08*	*0.04*	*-0.06*	*0.07*	*0.38*	***0.67***
SD	*0.20*	*0.22*	*0.25*	*0.17*	*0.13*	*0.13*	*0.06*	*0.05*	*0.20*	*0.31*	*0.08*	*0.48*	***1.12***
Albany Thicket													
Cradock	**0.18***	-0.05	-0.06	0.03	**-0.13***	-0.01	0.03	0.07	-0.06	0.09	**0.27***	0.18	0.54
Graaff-Reinet	0.16	-0.03	-0.03	0.00	-0.08	-0.02	0.00	0.12	**-0.17***	-0.02	0.12	0.01	0.06
Nqweba Dam	0.20	-0.14	-0.04	0.10	-0.09	0.09	-0.11	0.09	-0.07	0.03	0.04	0.03	0.13
Roodeberg Farm	0.18	-0.06	-0.09	-0.03	-0.06	0.00	0.00	0.10	-0.15	0.03	0.12	-0.04	0.00
Klipfontein-EC	**0.17***	0.00	-0.01	0.00	-0.05	-0.02	0.02	0.09	-0.07	0.01	0.13	0.03	0.29
Steytlerville	**0.13***	0.03	-0.03	0.03	**-0.04***	**-0.03***	0.01	0.03	-0.13	0.00	0.10	0.08	0.18
Darlington Dam	0.12	**0.11***	0.02	0.04	**-0.11***	**0.07**	-0.01	0.00	-0.07	-0.10	0.12	0.16	0.35
Pearston	0.08	-0.14	-0.18	-0.05	-0.03	0.00	-0.06	-0.02	-0.11	0.01	-0.09	-0.11	-0.70
Somerset East	-0.08	**-0.31***	**-0.43***	**-0.21***	**-0.24***	**-0.16***	-0.02	0.10	**-0.33***	**-0.27***	-0.04	**-0.26***	-2.25

Ave	*0.13*	*-0.07*	*-0.09*	*-0.01*	*-0.09*	*-0.01*	*-0.01*	*0.06*	*-0.13*	*-0.02*	*0.09*	*0.01*	*-0.15*
SD	*0.09*	*0.13*	*0.14*	*0.09*	*0.06*	*0.07*	*0.04*	*0.05*	*0.09*	*0.10*	*0.11*	*0.14*	*0.86*
Grassland													
Tarkastad	0.03	-0.18	**-0.18***	**-0.11***	**-0.16***	-0.06	0.05	0.06	**-0.25***	**-0.04***	0.00	0.01	-0.83
Steynsburg	0.15	0.16	0.07	0.15	0.00	0.05	0.03	0.11	-0.03	0.10	**0.23***	**0.25***	1.27
Smithfield	0.03	0.01	-0.29	0.05	-0.09	0.01	-0.06	0.11	0.07	0.09	-0.02	0.11	0.02
Rouxville	**-0.04***	**-0.05***	**-0.27***	0.16	**-0.12***	0.00	-0.07	0.11	-0.01	0.06	**0.03***	**-0.05***	-0.25
Springfontein	-0.02	0.21	-0.19	-0.11	-0.13	0.04	0.01	0.10	0.16	0.00	-0.01	**-0.30***	-0.24
Trompsburg	0.20	0.28	-0.18	-0.01	-0.05	0.09	-0.04	0.13	0.14	0.14	0.14	0.14	0.98
Lillydale	0.21	0.22	0.14	**0.04***	**0.01***	0.09	-0.04	0.10	0.03	0.00	0.07	0.13	1.00
Hobhouse	0.22	0.05	-0.18	-0.20	-0.03	-0.02	0.00	0.10	0.01	0.10	0.02	0.14	0.21
Dewetsdorp	-0.02	0.25	0.21	-0.01	-0.10	0.01	-0.06	0.09	-0.06	0.07	-0.06	0.05	0.37
Wepener	-0.02	-0.19	-0.55	**-0.60***	0.03	-0.19	-0.15	0.19	0.05	-0.29	0.22	-0.24	-1.74
Ave	*0.07*	*0.08*	*-0.14*	*-0.06*	*-0.06*	*0.00*	*-0.03*	*0.11*	*0.01*	*0.02*	*0.06*	*0.02*	*0.08*
SD	*0.11*	*0.17*	*0.23*	*0.22*	*0.07*	*0.08*	*0.06*	*0.03*	*0.12*	*0.12*	*0.10*	*0.18*	*0.91*

2.4.3. Seasonal rainfall

An analysis of seasonal rainfall suggests that the timing of summer rain has changed over the course of the study period (Figure 2.2). When the data were separated into two time periods (1930-1970 and 1971-2009) and averaged over five years, the results showed that early growing season (November-February) rainfall has increased while late season (March-May) rainfall has declined (Figure 2.2). This pattern is more apparent for Nama-karoo biome sites than for sites in the other biomes especially for the month of January which shows that rainfall has increased significantly over the period 1971 to 2009. For the Albany Thicket biome summer rainfall also increased over the 1971-2009 period and was less bi-modally distributed as it was in the period 1930-1970. In the Grassland biome, February rainfall has increased since 1971 and peak rainfall now occurs in February rather than in March which was the case prior to 1971. August rainfall has also increased slightly in the 1971-2009 period in the Grassland biome when compared to the earlier time period.

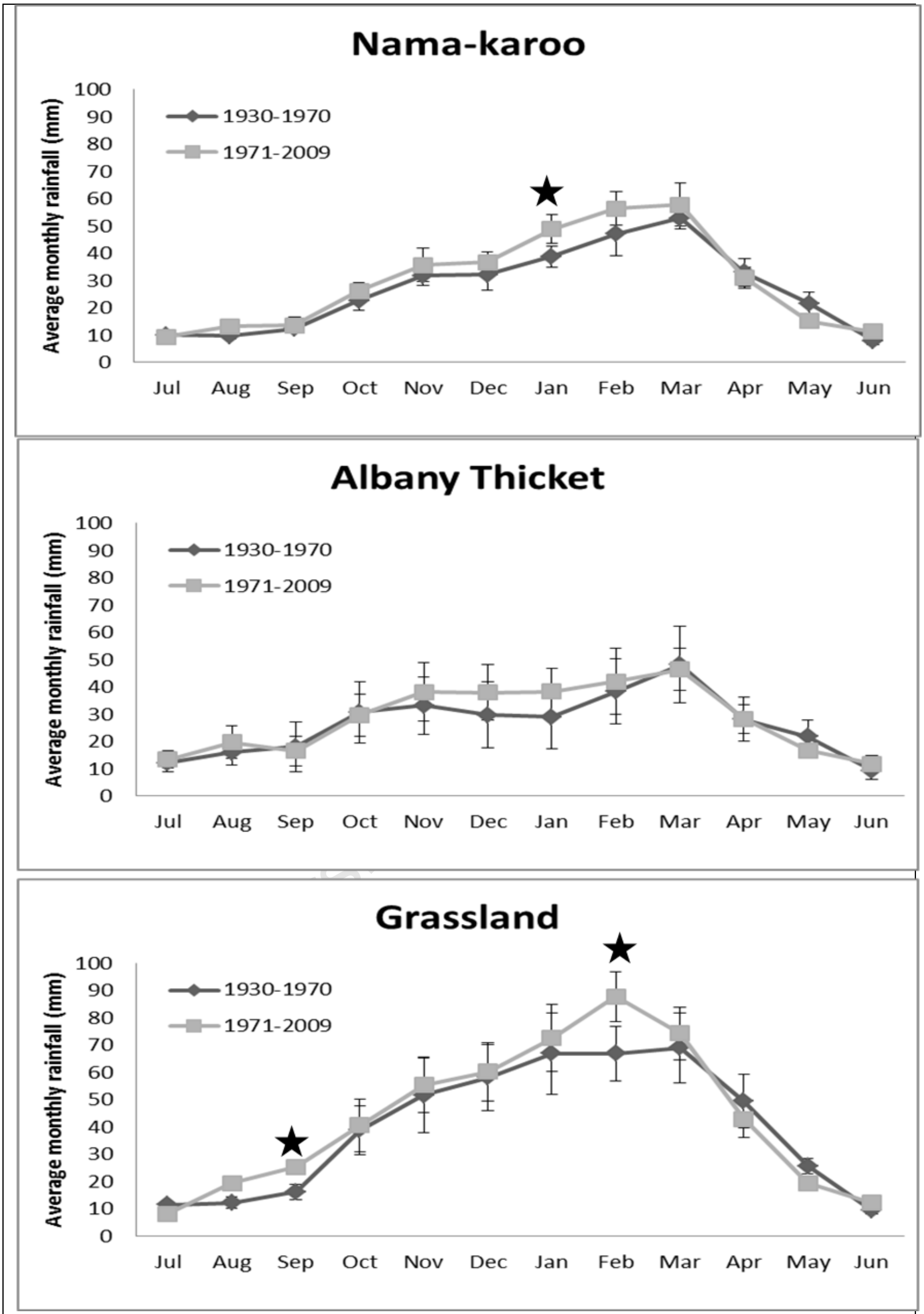


Figure 2.2: Average (±SD) seasonal rainfall for 27 stations in three Karoo Midlands biomes for the periods 1901-1970 and 1971-2009. ★ represent a significant month.

2.4.5. Standardised Precipitation Index

The Standardised Precipitation Index (SPI) is used to investigate long term trends in the incidence of drought and flooding. General patterns showed that SPI values in the Nama-karoo biome have increased significantly in the majority of stations investigated (Table 2.4; Figure 2.3). The three stations (Middelburg, Orange-Fish River Tunnel and Grassridge Dam) with significant positive trends in annual rainfall also exhibited a significant increase in SPI trend together with Richmond and Hanover. A significant wetting trend appears to have occurred in this biome. The two Albany Thicket biome climate stations (Pearston and Somerset East) with a significant decline in the trend for annual rainfall also exhibited a significant increase in the incidence of drought as shown by the trend in their SPI values. However, the remaining seven stations in this biome showed a wetting trend similar to that in the Nama-karoo biome with values for three stations significantly positive (Cradock, Klipfontein, Darlington Dam). There was no directional change in the average SPI values for the Grassland biome. Some stations exhibited a significant increase, some a decrease while for the majority of stations there was no significant trend in SPI values over time.

The SPI analysis (Figure 2.3) suggests that years of severe drought in the Nama-karoo biome were 1915-16, 1927-29, 1932-33, 1936-38, 1969-70, and 1998. Years of wet periods included 1910, 1917, 1939-40, 1974-77, 1986-89, and 2005. Drought years for the Albany Thicket biome included 1919-20, 1927-29, 1945-49, 1965-70 and 1992-93. The years of wet periods includes 1907, 1917, 1922-23, 1939-40, 1972, 1974-77, 1989, 1997, and 2001-02. Years of severe drought in the Grassland biome were 1913-15, 1919-20, 1932-33, 1945-49, 1969-1970, 1992-3 and 2004-05. The years of wet periods included 1924-25, 1943-44, 1974-77, 1988-89, and 2001. It appears the region in generally experienced the longest droughts for the biomes during the periods 1927-29 and 1936-38 for the Nama-karoo, 1945-49 and 1965-70 in the Albany Thicket as well as in the Grassland. The recent droughts of 1993, 1998 and 2003 were not long but left different signatures in the different biomes. The longest period with extremely wet events was 1974-77 and 1986-1989 in the region. A similar trend to that of recent droughts can be seen from recent extreme wet events in the different biomes.

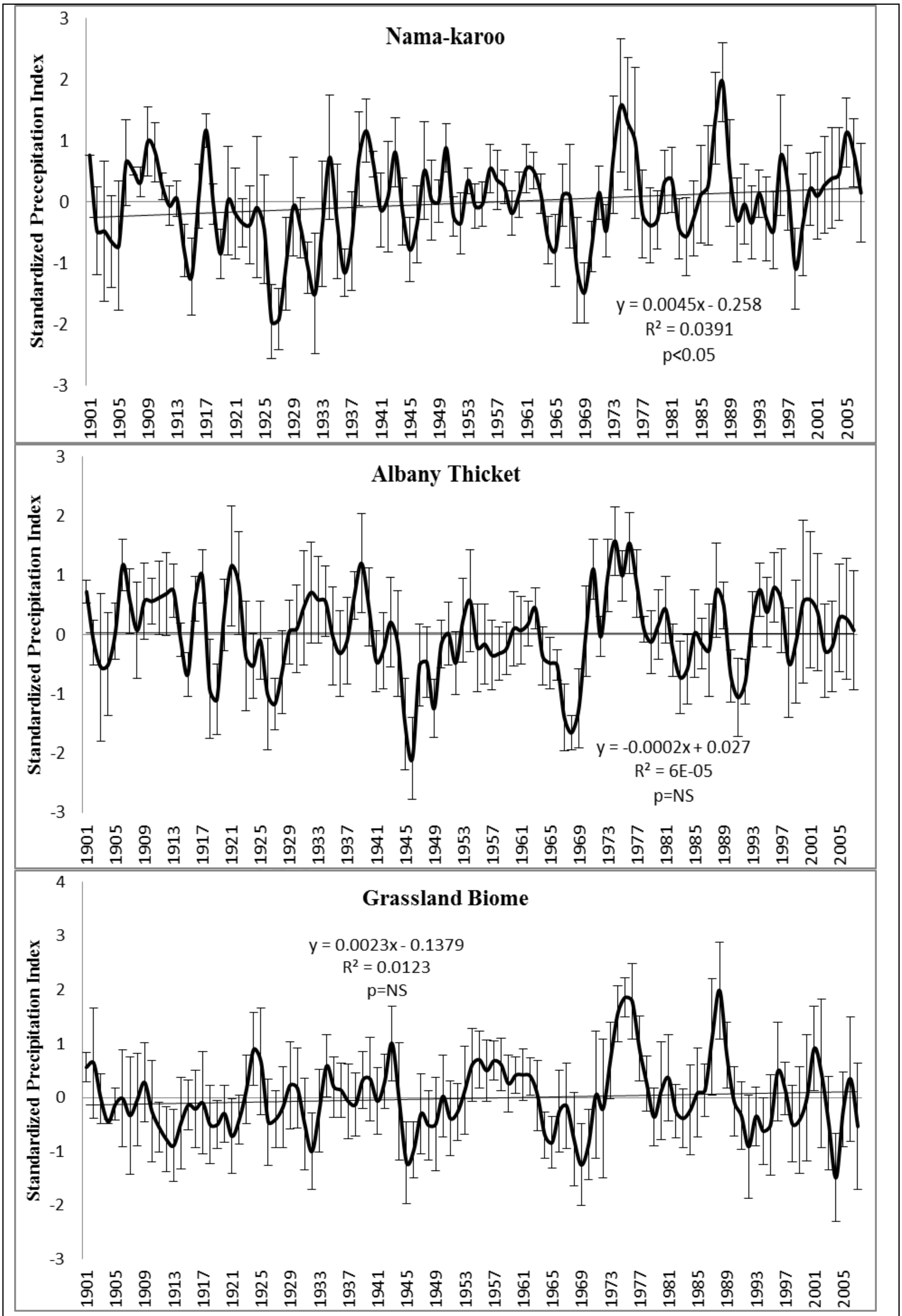


Figure 2.3: Average Standardized Precipitation Index values (±SD) for climate stations within the three biomes of the Karoo Midlands region.

2.4.6. Temperature

Temperature is the climate variable that has shown the most consistent trend over time (Table 2.6). The lowest minimum temperature (-4.7 ºC) was recorded in May 1980. The long-term trend for annual minimum temperature within Nama-karoo biome stations has not changed significantly except for Middleburg which has increased significantly by 0.02 ºC per year. In the Albany Thicket biome two of the three climate stations showed a significant decline in minimum temperature which averaged -0.04 ºC per year for the biome. Only one climate station with temperature data was available for the Grassland biome and it showed a significant increase in both minimum (0.014 ºC) and maximum (0.015 ºC) temperature.

Table 2.6: Mean annual minimum (Tmin) and maximum (Tmax) temperature values for seven weather stations in the Karoo Midlands for the period 1960-2008, as well as their slope values, Z-scores and significance levels (*=p<0.05; **p<0.00l ***=p<0.001).

Biome and station	Tmin (°C)	Slope (Tmin)	Trend (z-score)	Tmax (°C)	Slope (Tmax)	Trend (Z-score)
Nama-karoo						
Gariep Dam	10.9	0.016	1.49	24.1	0.007	1.05
Middelburg	7.5	0.048	**2.33***	23.5	0.016	**1.83***
Colesberg	8	-0.014	-0.45	24.1	-0.012	-0.23
Average	*8.8*	*0.017*	*1.12*	*23.9*	*0.004*	*0.83*
SD	*1.8*	*0.031*	*1.43*	*0.3*	*0.014*	*1.12*
Albany Thicket						
Graaff-Reinet	10.7	-0.043	**-4.44*****	25.6	0.037	**4.84*****
Cradock	10.1	-0.025	-1. 24	25.1	0.021	**1.74***
Somerset East	9.9	-0.044	**-3.03****	24.8	0.043	**2.94****
Average	*10.2*	*-0.037*	*-2.90*	*25.2*	*0.034*	*3.17*
SD	*0.4*	*0.011*	*1.51*	*0.4*	*0.011*	*1.56*
Grassland						
Wepener	7.7	0.014	**2.66****	24	0.015	**1.77***

The highest annual maximum temperature (34.6 ºC) was measured in Graaff-Reinet in the Albany Thicket biome during the month of January 2003. For the Nama-karoo biome only Middelburg showed a significant increase in mean annual maximum temperature. The long-term trend in annual maximum temperature was significantly greater in the Albany Thicket biome compared to the other biomes and has increased on average by 0.04 ºC per year.

2.4.7. S-pan Evaporation

The long-term trend in annual pan evaporation values varied considerably between the three sites in the Nama-karoo biome (Table 2.7).

Table 2.7: Minimum (Emin), maximum (Emax) and annual average (Eave) (±SD) S-pan evaporation values for seven weather stations in the Karoo Midlands, as well as their Z-scores and significance level (p<0.05; ***=p<0.001).

Biome and station	Emin (mm)	Emax (mm)	Eave (mm)	SD (mm)	Z-score
Nama-karoo					
Gariep Dam	1846.7	2620.7	2221.1	155.2	-0.51
Orange-Fish Tunnel	1669.2	2463.4	2124.1	193.7	**1.91***
Grassridge Dam	1602.6	2413.3	1926.2	177.7	**-4.44*****
Average	1706.2	2499.1	2090.5	175.5	-1.01
SD	126.2	108.2	150.3	19.3	3.21
Albany Thicket					
Nqweba Dam	1718	2324.7	1995	148.4	-0.51
Darlington Dam	1345.9	2057.8	1755.9	165	**3.51*****
Average	1532.0	2191.3	1875.5	156.7	1.5
SD	263.1	188.7	169.1	11.7	2.84
Grassland					
Egmont Dam	1738.4	2175	1935.4	129.8	0.08
Weldebacht Dam	1371.5	2198.2	1838.3	186.9	-0.8
Average	1555.0	2186.6	1886.9	158.4	-0.4
SD	259.4	16.4	68.7	40.4	0.6

For example, values from the Gariep Dam showed no significant change while data from the Orange-Fish River Tunnel showed a significant increase and data from Grassridge Dam a significant decrease over time. There was also no consistent pattern for climate stations within the Albany Thicket biome. For example, values for

Nqweba Dam did not change while values from Darlington Dam showed a significant increase in evaporation over time. The long-term trend in annual pan evaporation values was not significant for either of the two climate stations in the Grassland biome.

2.5. Discussion

The historical climate in the Karoo Midlands region in the central interior of South Africa was explored and data from weather stations within three different biomes in the region was analysed. Trends in the past 100 years in rainfall, temperature and pan evaporation measures were assessed. Historical trajectories of change are discussed in the context of 21st century climate change scenarios for the region which suggest both an increase in rainfall (Dai 2011a; Hewitson & Crane 2006; Moise & Hudson 2008) as well as a decrease over time (Hulme *et al.* 2001; Midgley *et al*. 2008; Shongwe *et al.* 2009); Midgley *et. al.* 2008; Shongwe *et. al.* 2009; Tabor & Williams 2010;).

2.5.1. Annual rainfall trends for the region

Annual variability in rainfall was relatively high for the Karoo Midlands region and CV values were similar to those for other semi-arid and arid environments across the globe (Lioubimtseva 2004; MacKellar *et al*. 2007; Modarres & da Silva 2007; Van Etten 2009). This high variability and the relatively short period over which rainfall figures have been recorded influences the identification of any trend in annual rainfall totals over time. While some weather stations showed an increase and others a decrease in rainfall over the course of the 20th century more than 70% of the stations in the region showed no significant change in annual rainfall. This pattern is consistent with most studies for southern Africa. For example, in the high lying areas of the Grassland biome in KwaZulu Natal, Nel (2009) found no significant change in annual rainfall.

In the Succulent Karoo biome west of the Karoo Midlands Hoffman *et al*. (2009a) also found no significant change in annual rainfall. There is general agreement in the literature that annual precipitation in southern Africa has not changed significantly over the past century (Kane 2009; Kruger 2006; Mason & Jury 1997). However, smaller, more localised areas have experienced significant changes in rainfall (Kruger 2006; Warburton *et al*. 2005) which can be attributed more to changes in local rainfall regimes than to large-scale changes in the patterns of atmospheric circulation.

2.5.2. Monthly and seasonal rainfall trends

Monthly rainfall showed both increasing and decreasing trends depending on the station. However, the trend in rainfall for March and May showed a consistent decline while the trend for January and December generally showed an increase, particularly in the Nama-karoo and Albany Thicket biomes. This supports the analysis of the trend in seasonal rainfall which suggests that there has been a shift in peak rainfall in the last four decades relative to the period 1901-1970. Since 1971 the peak rainfall period has occurred earlier in the summer growing season with an increase in rainfall between December and January in particular. Rainfall has also declined consistently between February and April in the last four decades relative to the period 1930-1970. Du Toit (2010) analysed a longer time series for Middleburg and found a similar trend with an increase in summer rain (December and January) and a decrease in autumn rain (March-May). This is in accordance with regional projections by Engelbrecht *et al.* (2009) which suggest a January increase in rainfall in the future. Such changes in rainfall seasonality have important implications for the vegetation of the region. A shift to more early season rainfall is likely to favour grasses at the expense of shrubs since the former utilize early season rains while the latter are able to utilize late season rains (Milton & Hoffman 1994).

2.5.3. Trends in drought and flooding for the region in relation to future projections

Most studies for southern Africa suggest that there has been no significant change in the incidence of drought although the incidence of wet periods appears to have increased since 1970 (Hoffman *et al*. 2009a; Roualt & Richard 2004; Warburton & Schulze 2005; Ujeneva 2011). For the Karoo Midlands changes in the Standardized Precipitation Index (SPI) over time suggest that localities within the Nama-karoo biome have experienced a significant increase in wet periods while Grassland biome sites have remained unchanged. This clearly supports the notion that South African droughts occur at different intensities, spatial extension and duration (Roualt &

Richard 2004). The most severe drought periods in the Karoo Midlands in terms of intensity and duration appear to have occurred around 1927, 1945 and 1969 and not in the last two decades as suggested by Roualt & Richard (2004). Drought severity has an important influence on plants which can be weakened through low soil water potential and become susceptible to insect attacks and pathogens (McDowell *et al*. 2008). Species react differently, however, with trees in drier environments being generally better adapted to deal with low water potential (Ryan 2011). A drying trend prior to the 1950's was also found for the western part of the country by Hoffman *et al*. (2009a) who highlighted the impact of the widespread droughts of the 1930s and 1940s in the region. Future drought projections for the Karoo Midlands are similar to those for the rest of the southern Africa region which suggest an increase in drought frequency in some areas and a corresponding increase in wet periods in others (Burke *et al*. 2006). While drought remains a characteristic feature of the Karoo Midlands climate, there is no evidence that the incidence of drought has increased over the course of the 20th century although the incidence of wet periods has increased in some areas.

2.5.4. Temperature trends and projections for the region

Globally, the hottest years of the last 140 years of recording, have occurred after 1990 (Hadley Center for Climate Prediction and Research 2003). Many parts of southern Africa, but especially the central interior regions, have experienced a significant increase in temperature since 1950 (Warburton & Schulze, 2005; Warburton *et al*. 2005). This has profound implications for hydrological process and regional water resources (Knoesen *et al*. 2009; Lumsden *et al*., 2009; Schulze 2011) and for the vegetation of the region (Midgley *et al*. 2008). Maximum temperature has also increased in the Karoo Midlands with the greatest increase occurring in the Albany Thicket and Grassland biomes. In contrast, most stations in the Nama-karoo biome showed no significant increase in maximum temperature. Several studies in east Africa have reported that change in temperature was greater for minimum than for maximum temperature (Makokha & Shisanya 2010). While minimum temperature increased in the Grassland and Nama-karoo biomes the opposite was true for the Albany Thicket biome which showed a decline in average annual minimum temperature values of as much as 0.04 °C per year. One explanation suggests that there has been an increase in cloud cover in the area covered by this biome although no data are available to support this view. Because of the increase in maximum temperature and the decrease in minimum temperature, the range in temperature has increased significantly for most stations in the Albany Thicket biome. While average annual minimum temperatures have declined in the Albany Thicket biome there has been a reduction in the length of the frost season in the Northern Cape and Free State provinces of South Africa (Warburton *et al*. 2005). Despite the differences between the weather stations of the Karoo Midlands region it is possible that annual temperatures could increase by as much as 4 °C by 2070 as suggested by global projections (Betts *et al*. 2011; New *et al*. 2011; Stafford-Smith *et al*. 2011; Thornton *et al*. 2011).

2.5.5. Pan evaporation trends and projections for the region

Evaporation is projected to increase in many regions of the world including southern Africa by more than 0.2 mm per day by 2090 (Dai 2011a, 2011b). However, several historical analyses in different parts of the world (e.g. Australia, China, North America) have reported a decline in pan evaporation especially in the last 30 years (Dai 2011b; McVicar *et al.* 2012). A general 'stilling' or reduction in wind speed and changes in radiation are thought to be primarily responsible for the decline in evaporative demand (McVicar *et al.* 2012). For arid and semi-arid regions in southern Africa Eamus & Palmer (2007) have reported a decrease in pan evaporation while large decreases have also been reported for the majority of sites studied in the winter rainfall Cape Floristic Region (Hoffman *et al.* 2011). Here a recorded decline in wind run provided the most plausible explanation for the reduction in pan evaporation rates. The pan evaporation data presented for the Karoo Midlands in this study, however, reflected a wide range of responses with different outcomes even for adjacent locations. No overall trend for the region is apparent. Furthermore, in the central interior of South Africa, wind speeds appear to be increasing as a result of the overlapping of strong wind zones caused by extra-tropical cyclones and thunderstorms (Kruger *et al*. 2010). This could explain why some weather stations in the Karoo Midlands show an increase in pan evaporation levels. Unfortunately, the full suite of climate variables (e.g. wind, radiation, temperature, relative humidity) needed to understand the complex drivers of evaporation (McVicar *et al.* 2012) are not available for most stations. An additional complication is that the difference in the length of the historical record between sites can also have an important influence on the slope and significance of the trend line.

2.6. Conclusion

This analysis presents a complex picture of historical climate change in the Karoo Midlands region. While some generalizations are apparent the paucity of climate stations with sufficiently long data series and the differences in trends between adjacent sites provides a low level of confidence in such conclusion. In general, however, annual rainfall appears not to have changed in the Karoo Midlands except for few localities in the Nama-karoo and Grassland biomes where it has increased and two sites in the Albany Thicket biome where it has decreased. The incidence of drought has not increased although the incidence of wet periods has increased at a few localities. Seasonal rainfall appears to have shifted in the latter part of the 20th century and peak rainfall has occurred a month or more earlier than was previously the case. Average annual maximum temperature has increased at most localities within all three biomes while minimum temperatures have increased only in the Nama-karoo and Grassland biomes. Minimum temperature has decreased in the Albany Thicket biome over the period of historical record. No consistent pattern in pan evaporation trend is apparent in this analysis with the majority of sites indicating no significant change over time.

Chapter 3: Vegetation change (1988-2010) in the Camdeboo National Park, South Africa using fixed-point photo monitoring: The role of herbivory and climate

3.1. Introduction

South African National Parks (SANParks) manages the largest protected area network not only in the southern African region but on the African continent. They are world-renowned for the vast areas of terrestrial biomes and marine biodiversity hotspots that they conserve as well as being host to some of the most magnificent and diverse landscapes on the African continent. Preserving and conserving natural areas, and reducing biodiversity loss are core principles of most protected area management programmes (Bruner *et al.* 2001; Ehrlich & Pringle 2008; Le Roux *et al.* 2010; Rodrigues *et al.* 2004). However, advancing and reaching these goals is complicated by the fast-changing global environment. Park and protected areas managers across the world are confronted with a range of critical decisions in terms of assessing and anticipating climate change impacts as well as land use impacts on biodiversity (Maraiano *et al*. 2008). These management decisions and solutions, however, are best made if they are informed by reliable monitoring data which documents the extent, nature and rate of environmental change over time as well as the key potential drivers of such change.

The Camdeboo National Park (CNP), which surrounds the town of Graaff-Reinet in the semi-arid Karoo Midlands, South Africa, achieved national park status in 2006, and conserves remnants of the main biomes in the region. For 27 years prior to this the area was managed as a provincial nature reserve after it had been used as a communal grazing area for several decades (Burdett, 1995). The impact of previous land uses has left a legacy of erosion and degradation in some parts of the landscape and active attempts have been made to restore these areas (CNP Newsletter 2011). Several studies document the natural resources of the CNP, particularly the vegetation (Palmer 1990). However, these studies are outdated and critical issues such as the recent rate of spread and impact of alien plants within different vegetation types is not known (CNP Plan 2006; Masubelele *et al.* 2009).

Outside the park, within the commercial livestock producing areas, the influence of rainfall and grazing by domestic animals has been well documented (Hoffman *et al*. 1990; O'Connor & Roux 1995). However, few studies have been conducted on the impact of wild herbivores on rangeland condition within either private- or state-owned protected areas. In the Karoo National Park, about 150 km west of CNP, a change in land use from small-stock farming to conservation and the reintroduction of wild ungulates resulted in an increase in perennial grass cover following a change in land use. However, rates of recovery were slower in areas exposed to heavy indigenous ungulate herbivory (Kraaij & Milton 2006). While a census of indigenous ungulates within CNP has been conducted since 1990 there has been no synthesis of this data. Little is known, therefore, of the concentration and impact of indigenous ungulates within different vegetation types of the park. Without this information it is difficult to determine the impact of indigenous ungulate herbivory on the vegetation of the reserve.

It is recognized that indigenous herbivore guilds may be responsible in the long-term, for the maintenance of biodiversity and ecosystem health across a range of spatial and temporal scales (Bakker *et al*. 2006; Cromsigt & Olff 2006; Cromsigt *et al*. 2009; Denyer *et al*. 2010). However, because of the relatively small size of the CNP it is possible that herbivores may be key drivers of vegetation change in the park, particularly if they become concentrated in localized areas. Such local concentrations are probably exacerbated by the fact that predators of the majority of the large ungulates are not present in the reserve. As a result of this, heavy grazing and browsing could result in vegetation and soil degradation via trampling and the creation of footpaths. Key palatable species, such as *Portulacaria afra* (Spekboom) could be affected by such concentrated grazing and browsing (Lloyd *et al*. 2002) but without a systematic record of the state of the vegetation this will remain unknown. Other national parks within the region (e.g. Addo Elephant National Park) with a similar composition of vegetation types have been heavily affected by indigenous ungulate herbivory (Kerley *et al*. 1999). Key resource areas in the more mesic parts of the CNP, such as the flood plains, as well as the areas around water points and dams could similarly be targeted by herbivores or be influenced by the movement of other grazers (Cain III *et al*. 2012; Grant *et al*. 2002; Macandza 2009; Macandza *et al*.

2012; Smit 2011). Such concentration of herbivory around key resource areas on livestock farms (Todd & Hoffman 1999) and in protected areas such as the Kruger National Park has been responsible for the disappearance of palatable species (Smit *et al*. 2007). Documenting the distribution of animals within protected areas in relation to such key resource areas will help to identify sites that are degrading and are in need of protection or even rehabilitation.

Another major concern for the conservation of biodiversity in protected areas is the impact that future climate change will have on biodiversity and ecosystem function. For example, rainfall is the key abiotic driver in the Karoo Midlands (O'Connor & Roux 1995) and extended droughts are common in the region. It is important for managers to understand the influence of periodic floods and droughts on vegetation structure and composition over time frames of several years and decades. An understanding of current rainfall-vegetation dynamics will enable conservation managers to plan more effectively for future changes in climate. Climate change projections for the region suggest that the area will become more arid with an increase in the occurrence of more extreme events such as drought (Midgley *et al*. 2002). Thicket vegetation around Graaff-Reinet, for example, is expected to be amongst the worst affected of all Albany thicket types in the Eastern Cape (Robertson & Palmer 2002). Current projections also suggest an increase in shrub cover at the expense of grasses with obvious knock-on effects for vegetation communities of the Nama-karoo biome as well as for grazer:browser herbivore ratios in the CNP (Midgley *et al*. 2002; Rutherford & Powrie 2011; Rutherford *et al*. 2012a).

Monitoring is an important tool for management. It helps in understanding how ecosystems are structured and how they function over time. However, few national parks, not only in South Africa but indeed, throughout the world, have a comprehensive, long-term monitoring programme in place, especially for the vegetation. Most studies on vegetation change in protected areas throughout the world, but especially in South Africa, are of less than 20 years duration. Conservation managers can only make informed decisions on the status and threats to biodiversity in our protected areas if long term monitoring data is available (Lepetz *et al*. 2009). For SANParks, strategic adaptive management and the use of Thresholds of Potential Concern (TPCs) has been valuable in both the short- and long-term depending on the availability of data (Biggs & Rogers 2003). This approach is consistently being adapted and improved to include the use of complex systems theory in management decisions, even though the latter approach is in its infancy (Biggs & Rogers 2003; Foxcroft 2009; Gaylard & Ferreira 2011). Ferreira *et al*. (2011), for example, suggest that a multivariate assessment of change within key communities is essential. This information can then be used to understand trends across the region. It also recognized that the determination and evaluation of different TPCs for different areas has not been undertaken for most protected areas largely because of the deficiency in data or the lack of a systematic monitoring programme. In addition, when data is available, there is often a lack of expertise to synthesize and summarize large data sets that usually arise from long-term monitoring efforts.

Repeat fixed point photography offers an important tool for monitoring vegetation changes particularly since the spatial scale of analysis ranges from local to landscape scale and is of direct relevance to park managers (Clark & Hardegree 2005; Hall 2001; 2002; Lucey & Barraclough 2001; Nicholls *et al*. 2009; Woodward & Hollar 2011). The potential of fixed point photo monitoring has also never been explored as a long-term monitoring tool for use in the arid and semi-arid national parks of South Africa. Camdeboo National Park is an essential case study to explore its potential as well as to develop a standard method of photo monitoring applicable for arid and semi-arid environments. A repeat fixed point photography monitoring programme was established in the CNP in 1988 but the efficacy and value of the results have not been assessed. This study is important because if it proves successful it will be recommended to SANParks as an appropriate monitoring tool for the assessment and monitoring of environmental change over long time frames.

The main objective of the study was to document the extent of vegetation change in the park in response to key climate drivers such as rainfall as well as land use drivers, especially herbivory by indigenous ungulates. A secondary objective was to evaluate the use of fixed-point photography as a monitoring tool for studying change in the main growth forms and vegetation types at CNP. In this synthesis of 22 years of fixed point monitoring data I have addressed the following main questions: (1) How has growth form composition changed within different vegetation types and land forms? (2) What influence have drought and flooding events as well as changes in seasonal rainfall patterns had on these patterns? (3) How has livestock density and concentration influenced vegetation cover and growth form composition? (4) Is fixed point photography an appropriate monitoring tool for addressing key management concerns within SANParks' conservation areas?

3.2. Study Area

The Camdeboo National Park (CNP) surrounds the town of Graaff-Reinet (see Figure 3.1), which is situated in the Camdeboo Municipality of the Eastern Cape Province of South Africa. CNP is located between -32.17577 S, 24.38314 E and -32.32069 S, 24.61405 E. The park lies from 740 to 1480 meters above sea level at the foothills of the Sneeuberg range, with a small section of low-lying plains included within the park boundaries. The climate is semi-arid with 32% of the average annual total of 336 mm of rain falling during the hottest months of the year (February-April). CNP also experiences snow, fog and frost, with maximum temperatures during summer of 43 ºC and minimum temperatures of -3 ºC in winter. The mean annual maximum temperature during the study period is 26 ºC whereas mean annual minimum temperature is 10 ºC. The hydrology of CNP is largely based on its location at the edge of the Great Escarpment from which six seasonal rivers (Sundays, Gats, Melk, Camdeboo, Pienaars and Erasmuskloof) drain into the Nqweba Dam in the central area of the park.

The geological system of CNP consists of very thick layers of near horizontal strata of sedimentary rocks of tertiary origin. Large areas of the park, however, are covered by alluvium, gravel, sand, mud and stone of more recent origin. Soils derived from these quaternary deposits have an important influence on the vegetation in the park since they represent the growth medium for many dwarf shrubs in the region (Lovegrove, 1993). The soils are generally calcareous duplex forms of secondary nature having been deposited as alluvium on the impermeable sandstone. They are subject to sheet and gully erosion, which is aggravated when vegetation cover is reduced.

The vegetation of CNP falls into three biomes, namely the Albany Thicket, Grassland and Nama-karoo biomes (Mucina & Rutherford, 2006). Although Palmer (1989) provided a detailed phytosociological analysis of the former Karoo Nature Reserve the main vegetation types currently recognized in the CNP follow Mucina &

Rutherford's (2006) classification. These are: Camdeboo Escarpment Thicket (AT14), Karoo Escarpment Grassland (Gh1), Eastern Lower Karoo (NKI2), Upper Karoo Hardeveld (NKu2) and Eastern Upper Karoo. Azonal vegetation also occurs around the Nqweba Dam which is classified by Mucina & Rutherford (2006) as Southern Karoo Riviere (AZi6). In this study, the vegetation types outlined above have been grouped into three broad physiognomic classes for analysis. These classes are broadly reflective of the major biomes in the region. Grassy Dwarf Shrublands represent vegetation types within the Grassland biome, while Dwarf Shrublands are comprised of Nama-karoo biome vegetation types. Albany Thicket, which was called Succulent Thicket by Palmer (1989) represents vegetation associated with the Albany Thicket biome. In addition to the three physiognomic classes outlined above, a fourth Azonal unit located within the ephemeral rivers and Nqweba Dam flood plain, was also recognized. This vegetation unit includes perennial rivers and drainage lines as recognized and mapped by Mucina & Rutherford (2006).

Although the CNP was first proclaimed and managed as a provincial reserve (called the Karoo Nature Reserve) in 1979, it became a national park in 2006 and is the 22nd protected area to fall under the management of South African National Parks (SANParks). The area has a very long history of land use. For example, before colonial settlement, the area which now forms part of the CNP was used for millennia by Stone Age hunter-gatherers and for the last 2,000 years by Khoi herders. White farmers settled the Camdeboo Plains and foothills of the Sneeuberg mountains in 1770, introducing merino sheep and angora goats, as well as exotic plants to the region (Burdett 1995). Immediately prior to the proclamation of the Karoo Nature Reserve in 1979, the area which now comprises the CNP, was used as part of the town commonage. The land was leased to tenant farmers who grazed their livestock on the property, thus contributing to overgrazing and the erosion of some areas (Burdett 1995; CNP 2006).

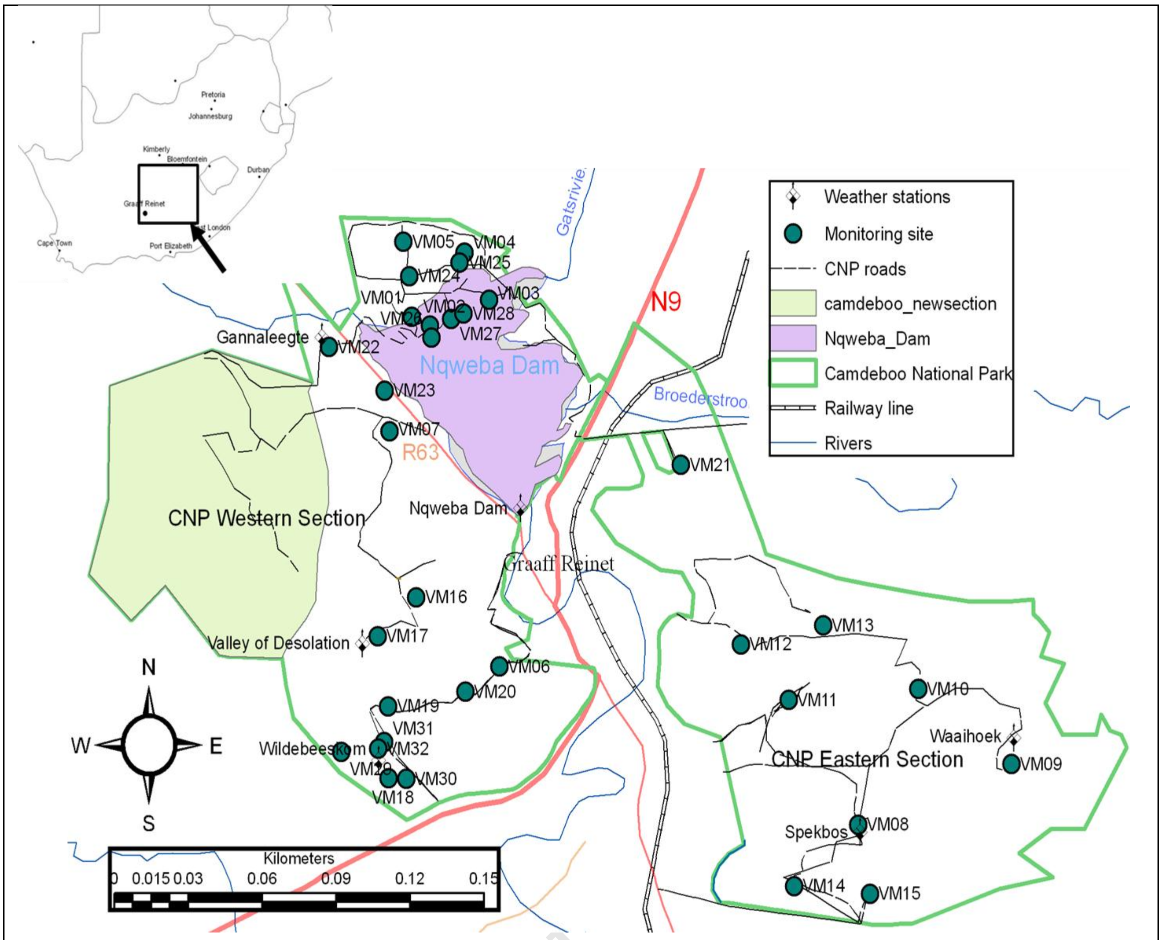


Figure 3.1: Location and extent of the Camdeboo National Park (CNP) at Graaff-Reinet in the Eastern Cape province of South Africa. The insert places CNP in context with the rest of South Africa.

3.3. Method and Materials

3.3.1 Photo monitoring procedure

The fixed-point photo monitoring system used in this study was started in 1988 by the two nature reserve managers at the time (Ken Coetzee & Peter Burdett) with the establishment of an initial 15 sites (Table 3.1). Additional sites were added in 1989 and 1992 by the current Park Manager (Peter Burdett) within each of the four main physiognomic classes to reach a total of 32 sites. The main objective of the monitoring programme was to document the impact that herbivores had on the different vegetation types of the reserve. Between 1988 and 2005 each of the sites was photographed a total of 12 times. After the proclamation of the Camdeboo National Park in 2006 the sites were not re-photographed until 2010 when this study was undertaken.

Table 3.1: The total number of sites in each vegetation unit and the year in which sites were established by the park manager at the CNP.

Date that sites was established	Vegetation Unit				Total number of sites
	Grassy Dwarf Shrublands	Dwarf Shrublands	Albany Thicket	Azonal	
1988	4	3	5	3	15
1989	0	1	4	0	5
1992	3	4	1	4	12
Total number of sites	7	8	10	7	32

Each of the 32 sites was permanently marked with a 70 cm square concrete block set in the ground to a depth of about 50 cm. In the centre of the concrete block a four-sided metal pole was fixed and allowed to protrude about 40 cm above the surface in such a way that each of the sides of the metal pole faced in one of four directions (North, East, South and West). This permanently-fixed basal pole was used to position a removable 1.7 m high metal pole with a slightly larger diameter which fitted securely over the basal pole. A flat plate, used to secure the camera was welded on the top of the removable pole.

A standard 50 mm lens mounted on a manual Single Lens Reflex (SLR) camera loaded with 35 mm colour slide film was used for most of the years prior to 2010 except in 2003 when a wider-angle (35 mm) lens was used at some of the sites. To replicate this process in 2010 a 50 mm lens, mounted on a Minolta X300s manual SLR camera and loaded with Fujichrome Sensia 35 mm colour slide film, was used. However, because of the ease of post-production processing and the saving in cost, a digital camera was also used (Canon Powershot Gll). All the original and 2010 colour slide images were scanned as TIFF images at 300 dpi, A3 output format using a high quality Nikon 5000 Scanner at the Plant Conservation Unit (PCU), University of Cape Town. This amounted to a total of 1152 images which, together with the metadata associated with each image, were archived on the PCU's database. An electronic copy of all of the photographs together with the metadata was sent to the park manager to whom the original material was also returned. All the dates and metadata for all the photos in this chapter have been included in Appendix 1. All the images were taken during the growing season except in 2003 and 2004 when images were taken in August.

Repeat photos were matched as accurately as possible and analyzed in Photoshop CS4. The cover of grasses, dwarf shrubs (<1 m) and tall shrubs (>1 m) was estimated using expert analysis for each individual image. Three ecologists, with field knowledge of the vegetation of the region, independently estimated the cover for each growth form on each of the images obtained in the different vegetation units. This was done separately for the N, W, S and E directions and then averaged to provide an individual site value for each growth form. Values for similar vegetation units were then grouped together to get the average value for the vegetation unit at each time period.

3.3.2 Vegetation classification and the grouping of sample sites

Vegetation cover data used for the grouping of sites into the four vegetation units was based on species composition and cover data collected using a step point sampling technique during 2010. The step-point surveys were carried out along a 100 m transect along each direction at a photo location. To assist in the grouping of these 128 transects (32 sites x four directions), a non-metric multidimensional scaling (NMS) ordination procedure using a Sorensen distance measure was undertaken within PC-Ord version 5.33 (McCune & Mefford 2006). This ordination technique is suitable for the analysis of ecological data because it makes no assumptions of linearity or underlying models of species relationships (Mcune & Grace 2002). NMS iteratively searches for ordering or grouping of samples in multidimensional space that minimizes the stress and number of dimensions in the solution. The stress value provides a measure of the goodness of fit of the data to the ordination solution.

Each of the 128 transects was also grouped into one of three landforms in which they occurred: rivers, plains and slopes. Change in the cover of different growth forms within each of these landforms was assessed over the sampling period.

3.3.3 Climate analysis

Annual (October-September) and monthly rainfall patterns were analyzed from data collected at four weather stations established within different sections of CNP since 1987 (Figure 1). Change in annual rainfall was assessed using a Mann Kendall non-parametric test for trend in time series data (Modarres & da Silva 2007). A Standardized Precipitation Index was also calculated to determine the change over time in the incidence of drought and wet periods (Roualt *et al*. 2004). To assess the extent of change in rainfall seasonality, monthly rainfall data were grouped into two time periods (1990-2000 and 2000-2010) and the results compared visually. In addition, the average values for the months of December, January and February for the four stations were summed to represent early summer rainfall. These values were then compared for each decade and tested for significance using a Univariate ANOVA. This analysis was repeated for autumn (March-May), winter (June-August) and spring (September-November) time periods. Long-term A-Pan evaporation data (1989-2008) from the Nqweba Dam site as well as the average maximum and minimum temperature for Graaff-Reinet (1992-2008) were also analyzed. Vegetation change at a site could not be related directly to climate through a direct statistical relationship largely because the climate data was not available at the resolution required for such an analysis.

3.3.4 Herbivore abundance

The location and abundance of different ungulate species were recorded annually by CNP field rangers from 1990 to 2010. Each species was converted to a Large Stock Unit (LSU) equivalent value (Furstenburg 2002) and multiplied by the number of individuals recorded for each species during each census event. During the annual census the location of each species was undertaken in the field using a grid reference system created by the Park Manager. The GPS co-ordinates of the centre of each grid were subsequently determined from GoogleEarth. In this way each observation record was assigned a GPS co-ordinate. These GPS points were used to create a shapefile in Diva GIS which was then geo-referenced in ArcToolbox. Stocking density maps were then created for each annual census period in Arc GIS 9.3. The Inverse Distance Weighted (IDW) interpolation technique, which is a spatial analysis tool, was then used to create a grazing impact surface for the CNP (Murwira & Skidmore 2005). In this technique the assumption is that herbivory at a certain location also influences the vegetation in the neighboring locations, since proximity of palatable plants can increase the impact of herbivores on palatable and unpalatable plants in the surrounding area (Baraza *et al*. 2006). Average stocking density values for each of the 32 vegetation monitoring sites were also calculated to determine how herbivore densities might have influenced the vegetation of the Camdeboo National Park over time.

3.4. Results

3.4.1. Vegetation change

3.4.1.1. Grouping of sample sites

Ordination results of the 2010 survey data from each of the four survey directions at the 32 photo locations grouped the sites into four main vegetation units (Figure 3.2). A two-dimensional solution with the final stress value of 19.1 and a final instability value of 0.00025 was recommended after 500 iterations. This analysis supports the more subjective grouping of photo location sites by the Park Manager into Grassy Dwarf Shrublands, Dwarf Shrublands, Albany Thicket and Azonal vegetation units. There is a clear separation of Azonal sites from the other vegetation units. Azonal sites were also the most diverse and spread out in the ordination diagram. Grassy Dwarf Shrubland were most closely related to Dwarf Shrublands. Based on the relatively tight grouping of sites in ordination space, species composition and cover in these two vegetation units appears relatively similar. Sites within the Albany Thicket were relatively more distant from each. In some cases, individual transects within an Albany Thicket site were more closely associated with Dwarf Shrublands, especially those transects located at the base of mountain slopes.

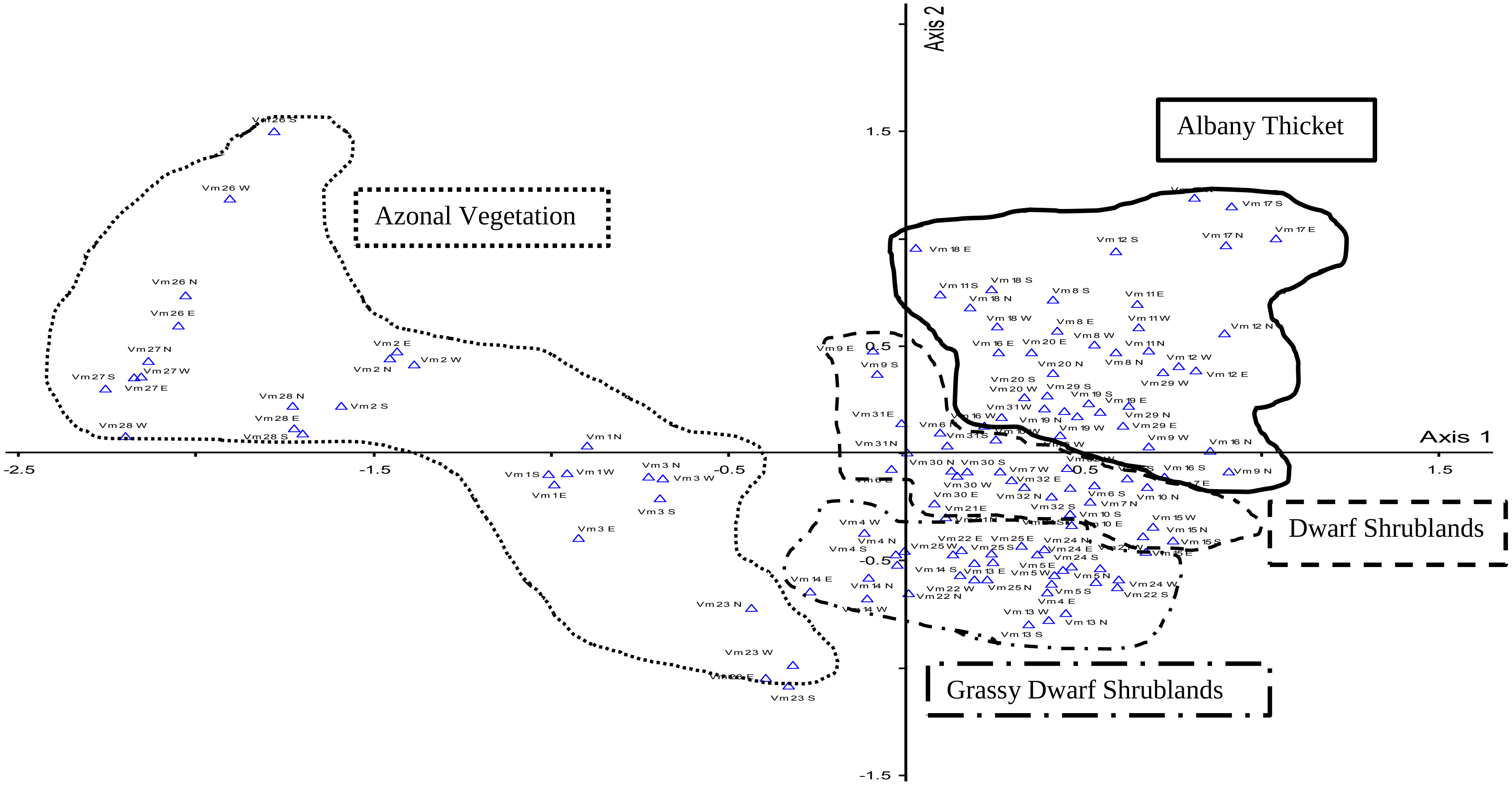


Figure 3.2: An NMS ordination of the four vegetation units at CNP based on species cover data of the survey carried out in 2010 (N=128 transects and 179 species).

3.4.1.2. Change in growth form cover within different vegetation units

Azonal vegetation

Sites within Azonal vegetation experienced a decrease in tall shrub cover between 1998 and 2003 (Figure 3.3). This pattern, however, is strongly influence by what happened at site VM03 (Figure 3.4) and to a lesser extent at site VM01 which are both located in the floodplain of the Nqweba Dam. New saplings, particularly of *Acacia karroo*, emerged at both of these sites after 2004 and by 2010 had reached 2-3 m in height. Tall shrub cover at the remainder of the sites within the Azonal vegetation unit remained relatively unchanged over the study period. Common tall shrub species within this vegetation unit are *Acacia karroo*, *Tamarix rammossisima* and *Salix babylonica*. Grass cover generally increased from 1996 to 2010 with a slight decline in 2005 (Figure 3.3). Different sites varied both in terms of their cover of grasses as well as how this changed over time. The increase in grass cover over the study period was not mirrored by a decline in dwarf shrubs which remained relatively stable over time. Much of the dwarf shrub cover was comprised of alien shrubs such as *Salsola tragus*, *Xanthium spinosum* and *X. strumarium*.

From the survey data it was clear that herbaceous alien plants species such as *Atriplex lindleyi*, *A. semibaccata*, *Cirsium vulgare*, *Salsola tragus*, *Xanthium spinosum* and *X. strumarium* as well as other woody species which include *Tamarix rammossisima*, *Salix babylonica* and *Melianthus major* are common largely in the floodplain and riverine habitats associated with the Nqweba Dam. Also, most of the areas that used to be dominated by alien herbs and shrubs are now covered by lawn grasses such as *Cynodon dactylon* as well as by *Phragmites australis* in wetter localities. *Chloris virgata* and *Cenchrus ciliaris* also occur away from the dam where *Atriplex* species used be common. *Tamarix rammossisima* saplings, however, were recorded in abundance during the 2010 survey and require active management.

Albany Thicket

Tall shrub cover within Albany Thicket vegetation remained unchanged over the study period (Figure 3.5 & 3.6). Common tall shrub species at these sites include *Buddleya saligna*, *Carissa haematocarpa*, *Diospyros austro-africana*, *Euclea crispa*, *E. undulata*, *Grewia occidentalis*, *G. robusta*, *Maytenus heterophylla*, *Portulacaria* *afra*, *Papea capensis*, *Searsia longispina* and *S. undulata*. The cover of dwarf shrubs varied greatly between different sites within this vegetation unit but remained relatively stable within a site over the study period. Common dwarf shrubs in this vegetation type include *Becium burchellianum*, *Cheilanthus ecklonii*, *Crassula* species, *Euryops spatheceus*, *Felicia filifolia* and *Rhigozum obovatum*. Although grass cover fluctuated during the course of the study, Albany Thicket vegetation was the most stable vegetation type within the Camdeboo National Park with very little change recorded in the cover of dwarf and tall shrubs.

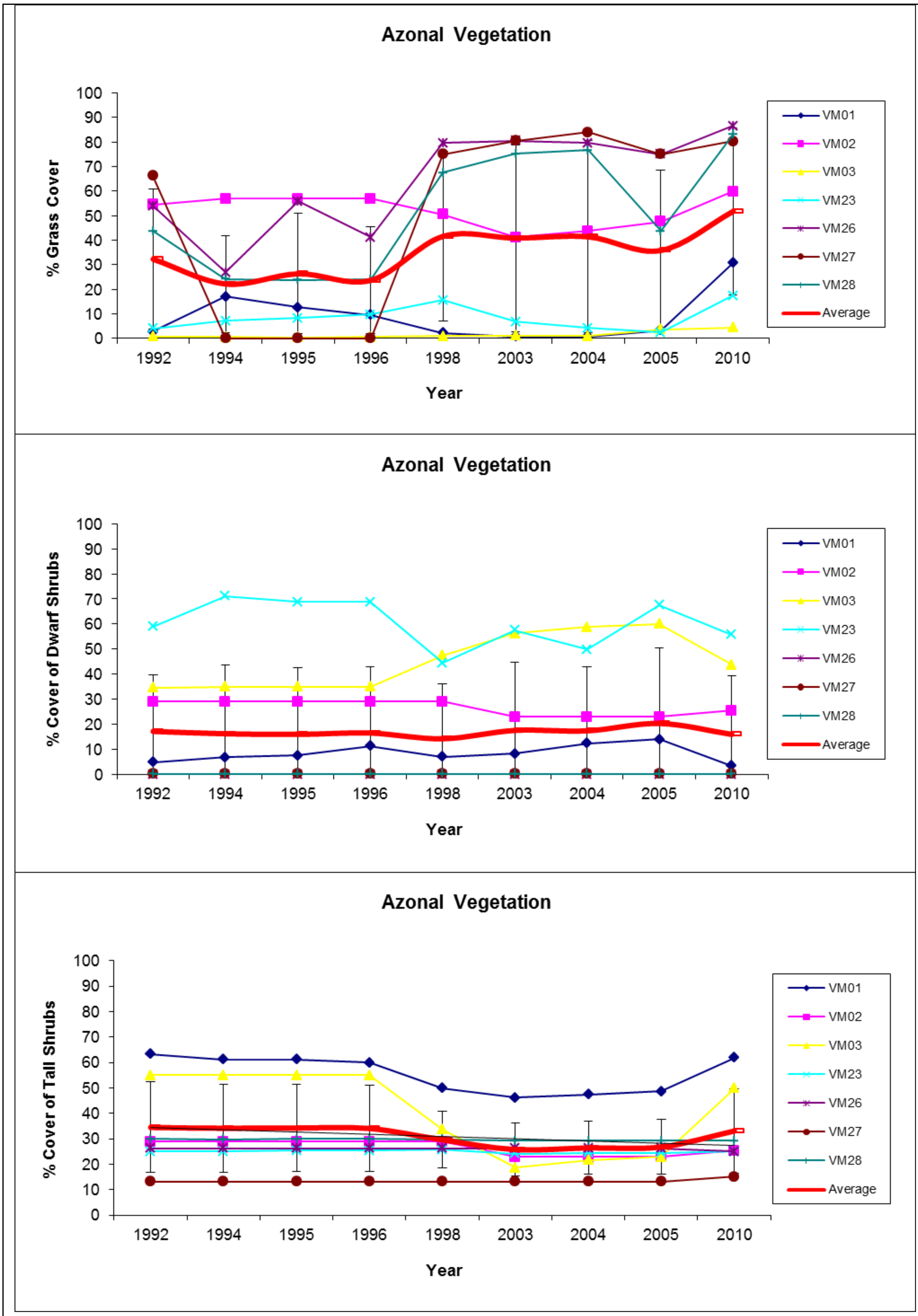


Figure 3.3: Percent cover (±sd) of Grasses (top), Dwarf Shrubs (middle) and Tall Shrubs (bottom) in Azonal Vegetation as determined from an analysis of fixed point photo monitoring sites between 1992 and 2010.

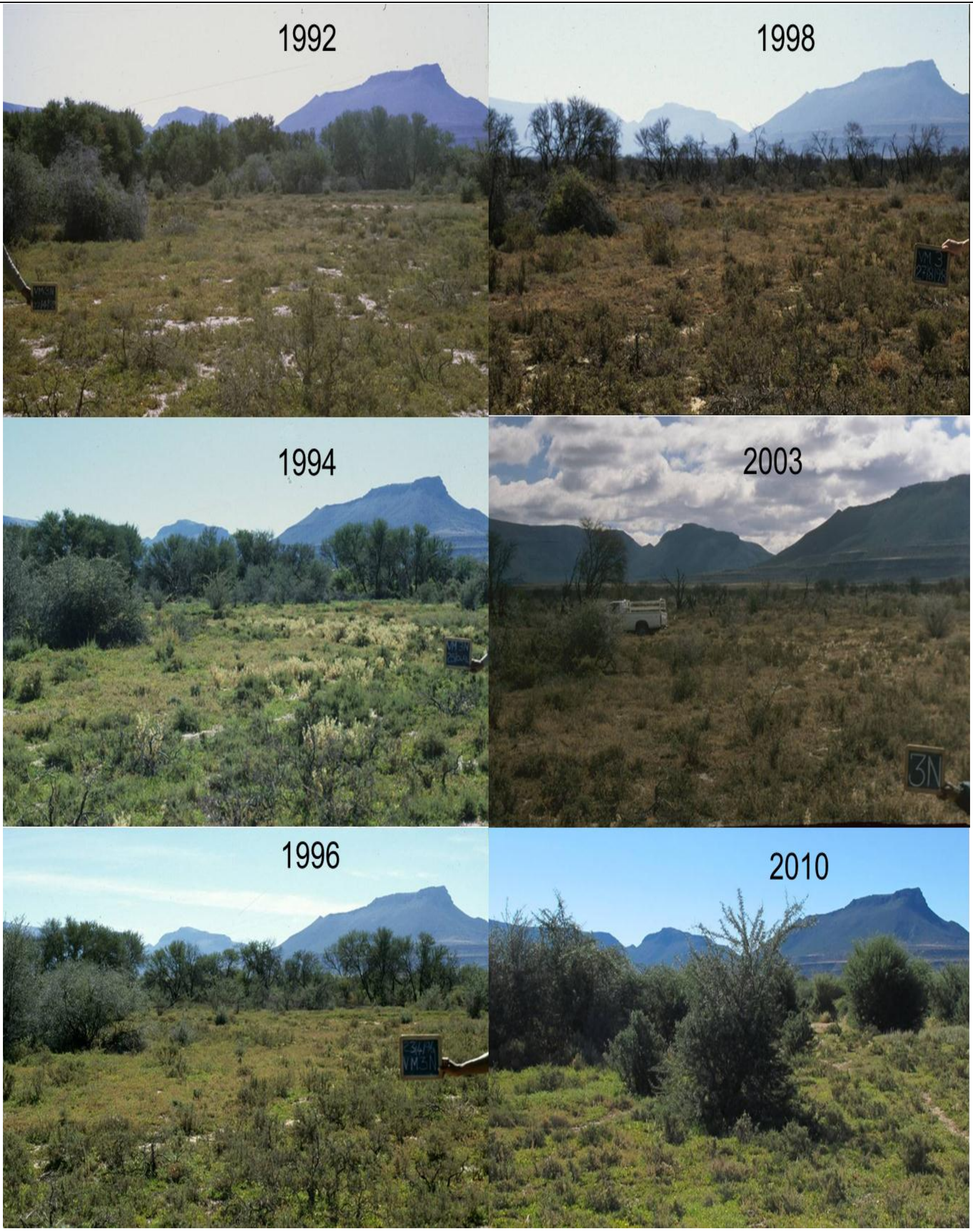


Figure 3.4: Loss of tall shrubs (primarily *Acacia karroo*) at VM03 N showing the decline between 1998 and 2003, and the subsequent increase in 2010 in the Azonal vegetation at CNP.

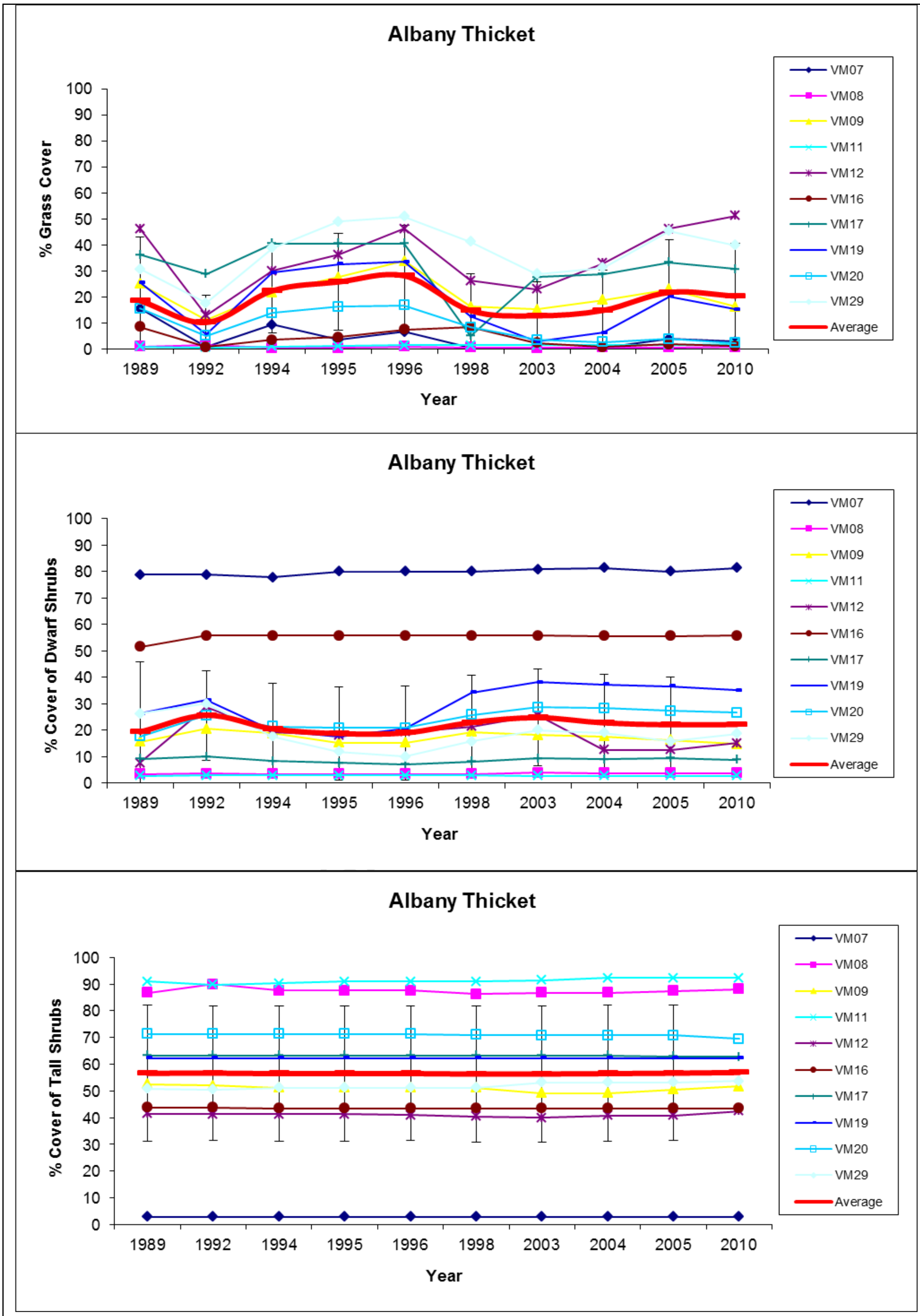


Figure 3.5: Percent cover (±sd) of Grasses (top), Dwarf Shrubs (middle) and Tall Shrubs (bottom) in Albany Thicket as determined from an analysis of fixed point photo monitoring sites between 1992 and 2010.

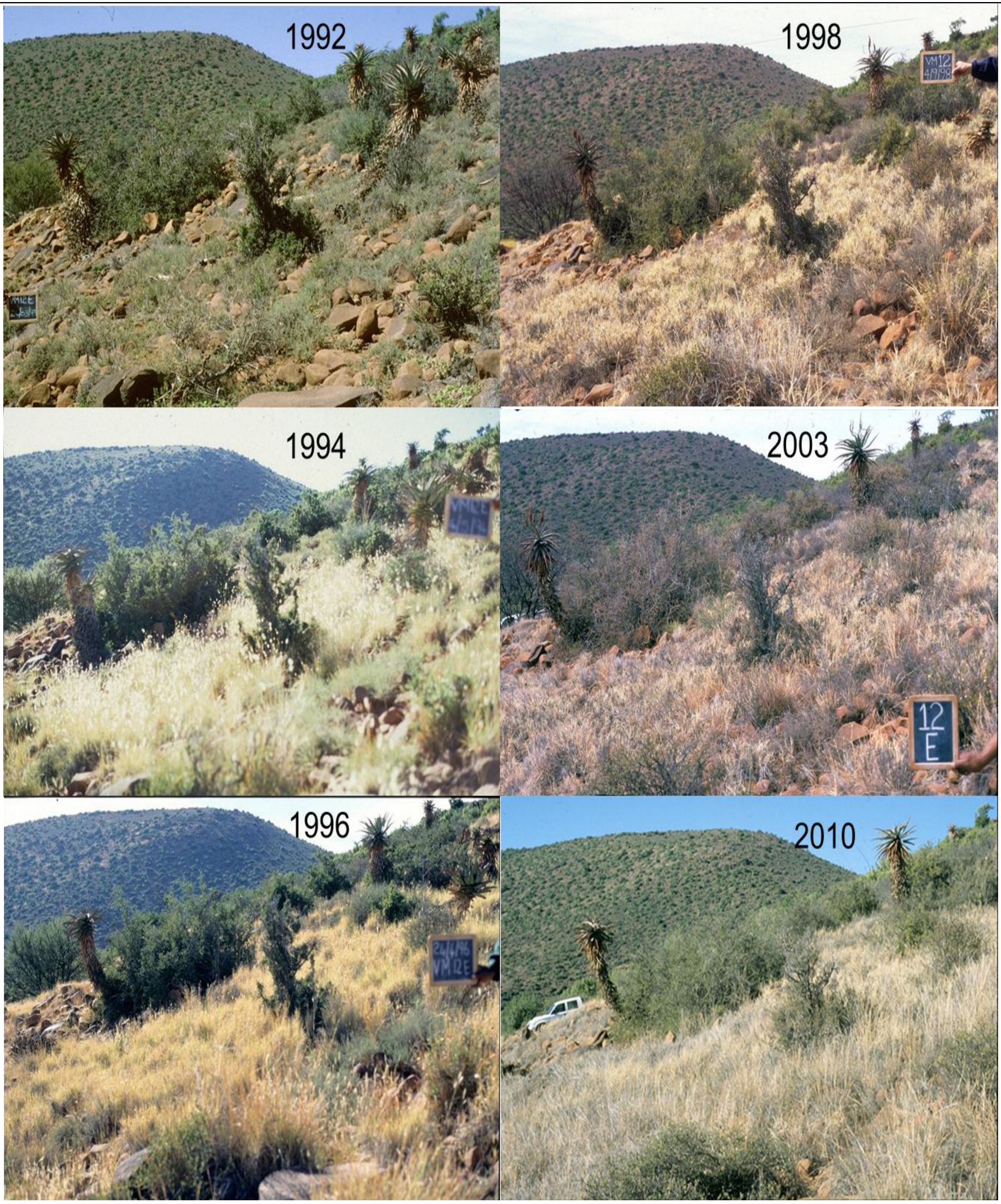


Figure 3.6: Albany thicket example as shown by VM12 E depicting stability of the various growth forms between 1992 and 2010.

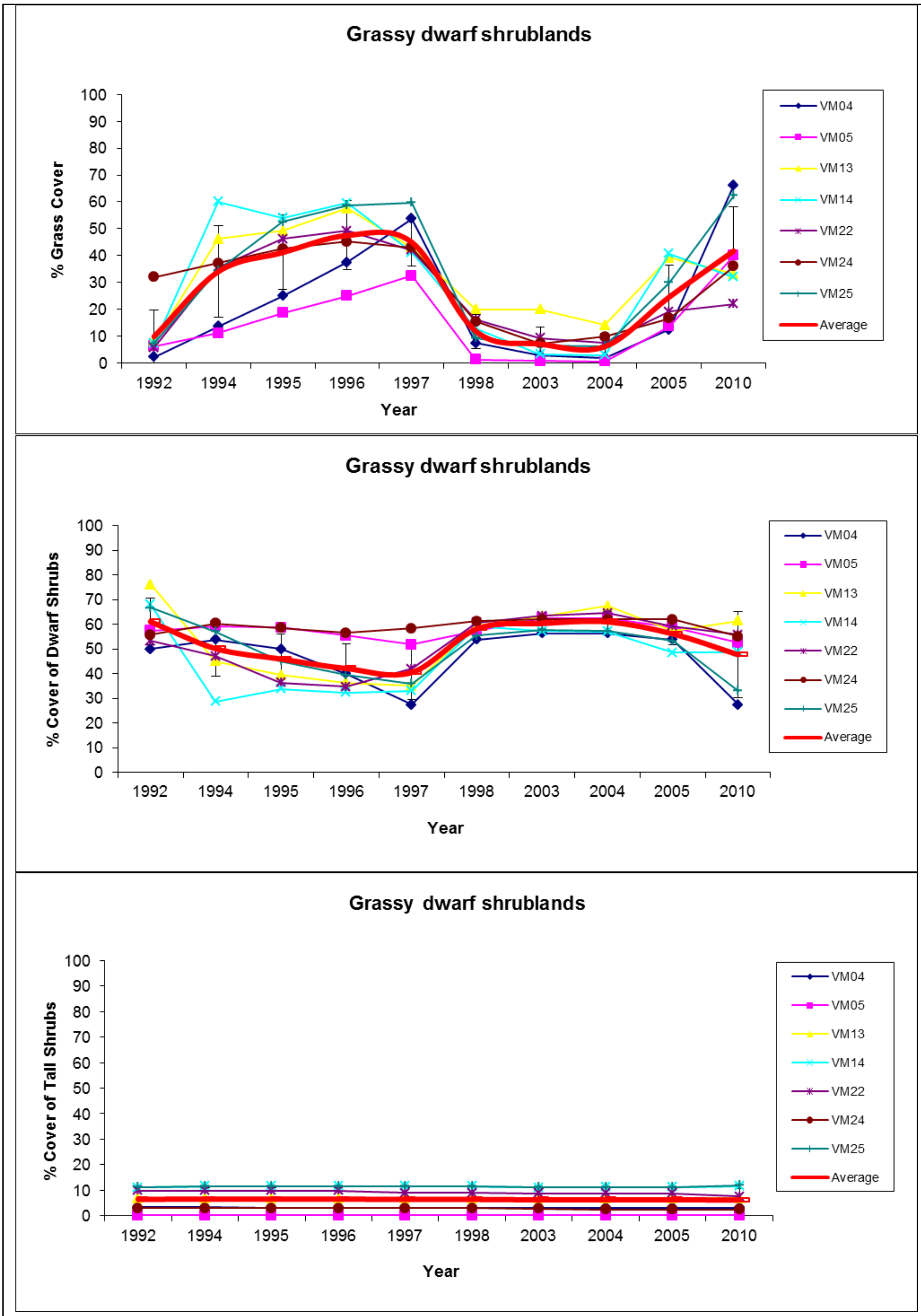


Figure 3.7: Percent cover (±sd) of Grasses (top), Dwarf Shrubs (middle) and Tall Shrubs (bottom) in Grassy Dwarf Shrublands (Grassland Biome) as determined from an analysis of fixed point photo monitoring sites between 1992 and 2010.

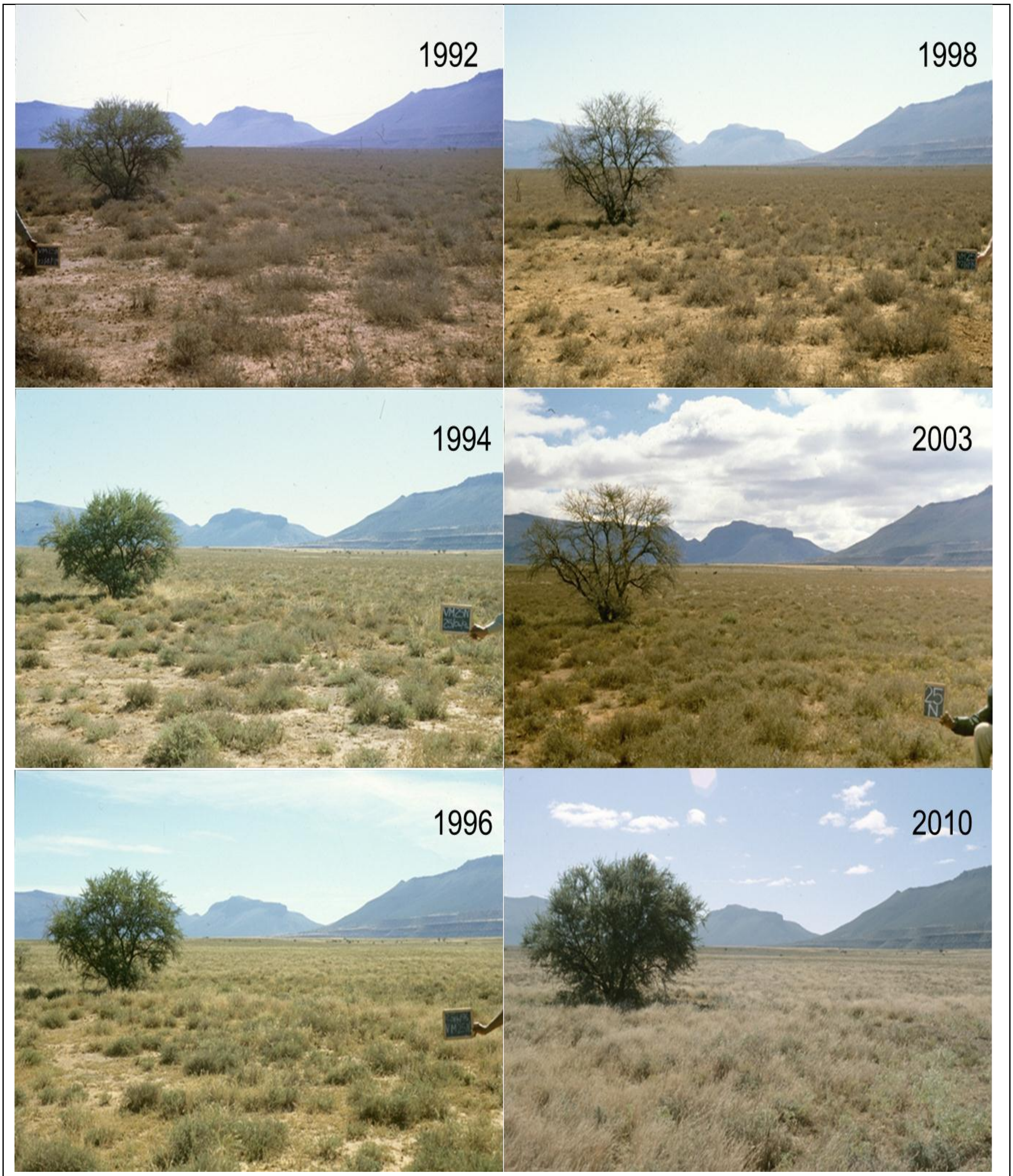


Figure 3.8 Grassy Dwarf shrublands example (VM25 N) showing cyclical pattern and switch between grass and dwarf shrub dominance at CNP while tall shrubs have remained stable from 1992 until 2010.

Grassy Dwarf shrublands and Dwarf shrublands

For sites within both the Grassy Dwarf shrubland (Figures 3.7-3.8) and Dwarf shrubland (Figures 3.9-3.10), periods of grass cover increase (e.g. between 1994-1997) were accompanied by a decline in dwarf shrubs. Conversely, the decline in grass cover between 1998 and 2004 was associated with an increase in dwarf shrub cover. Fluctuations in dwarf shrub cover were less extreme than for grasses which changed by 60% or more at a site. The response of grass cover appeared more pronounced in Grassy Dwarf shrubland sites than Dwarf shrubland sites. Tall shrub cover was lower in Grassy Dwarf shrubland than Dwarf shrubland sites but for both vegetation units, the cover of tall shrubs changed very little over the monitoring period.

3.4.1.3. Change in growth form cover within different landforms

The three growth forms responded differently between 1988 and 2010 within the main landforms at CNP (Figure 3.11). Within rivers the cover of grasses increased from an average of 30% to 50% over the study period. In contrast, the cover of grasses on the plains increased from 30-45% between 1994 and 1996 but declined thereafter to less than 20% in 2003 increasing again to reach average values of 35% in 2010. While grass cover also fluctuated on the slopes, responses were far less extreme and remained between 10-25%. The cover of dwarf shrubs was relatively stable on all landforms with slopes and rivers showing less variation over time than on the plains. Average cover values for this growth form were below 20% for rivers and slopes but around 50% on the plains. Changes in dwarf shrub cover on the plains in particular appeared to respond in an opposite direction to changes in grass cover. Tall shrub cover dominated the slopes (60%), was co-dominant within rivers (35%) and comprised a relatively minor component of the cover for plains environments (15%). Tall shrub and tree cover was relatively stable for plains and slopes over time. Within rivers, tall shrub cover declined between 1998 and 2003 but increased again over the next seven years.

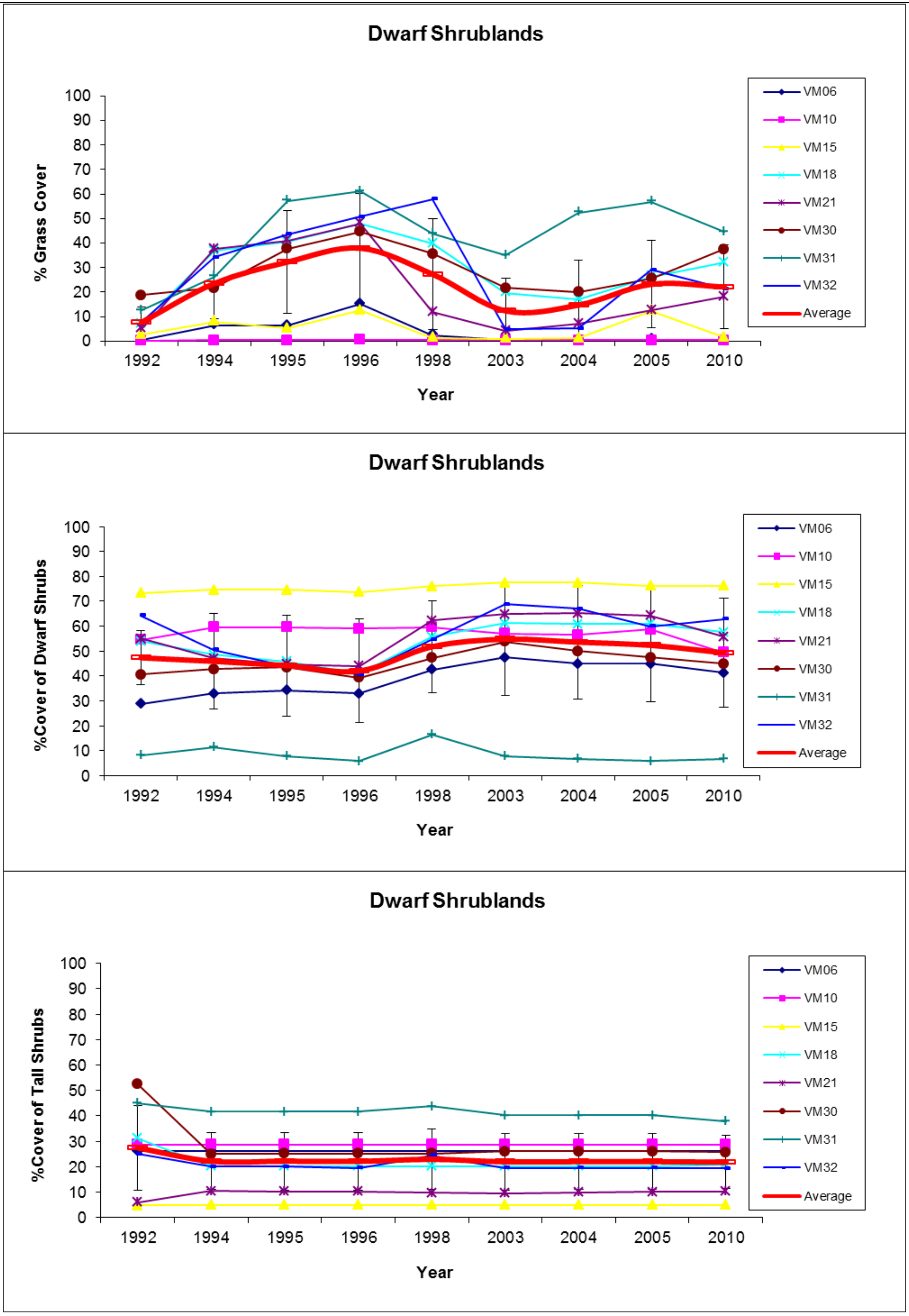


Figure 3.9: Percent cover (±sd) of Grasses (top), Dwarf Shrubs (middle) and Tall Shrubs (bottom) in Dwarf Shrublands (Nama-karoo Biome) as determined from an analysis of fixed point photo monitoring sites between 1992 and 2010.

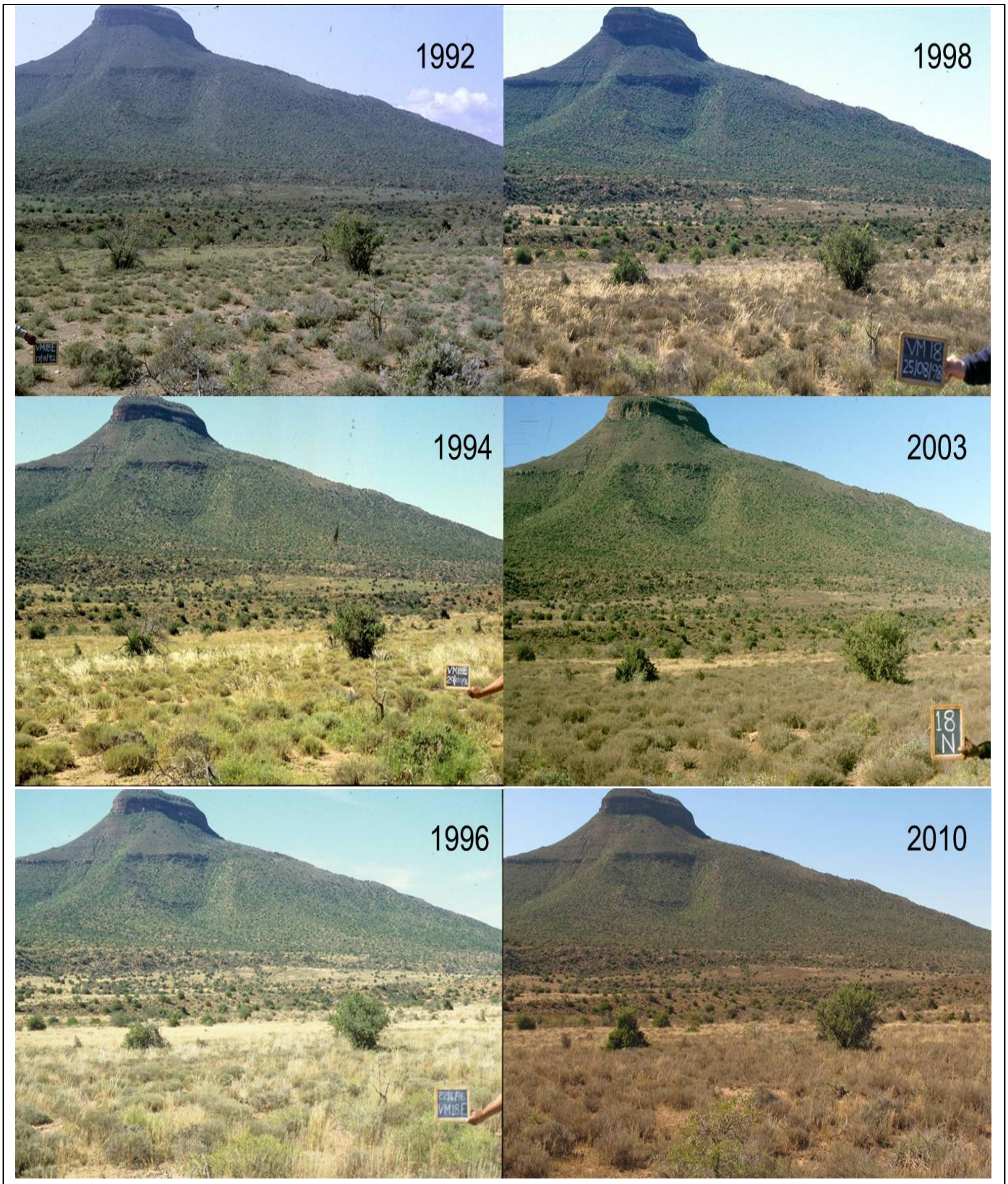


Figure 3.10: Dwarf shrublands example (VM18 N) showing a less pronounced cyclic patterns and switches between grasses and dwarf shrubs dominance from 1992 until 2010.

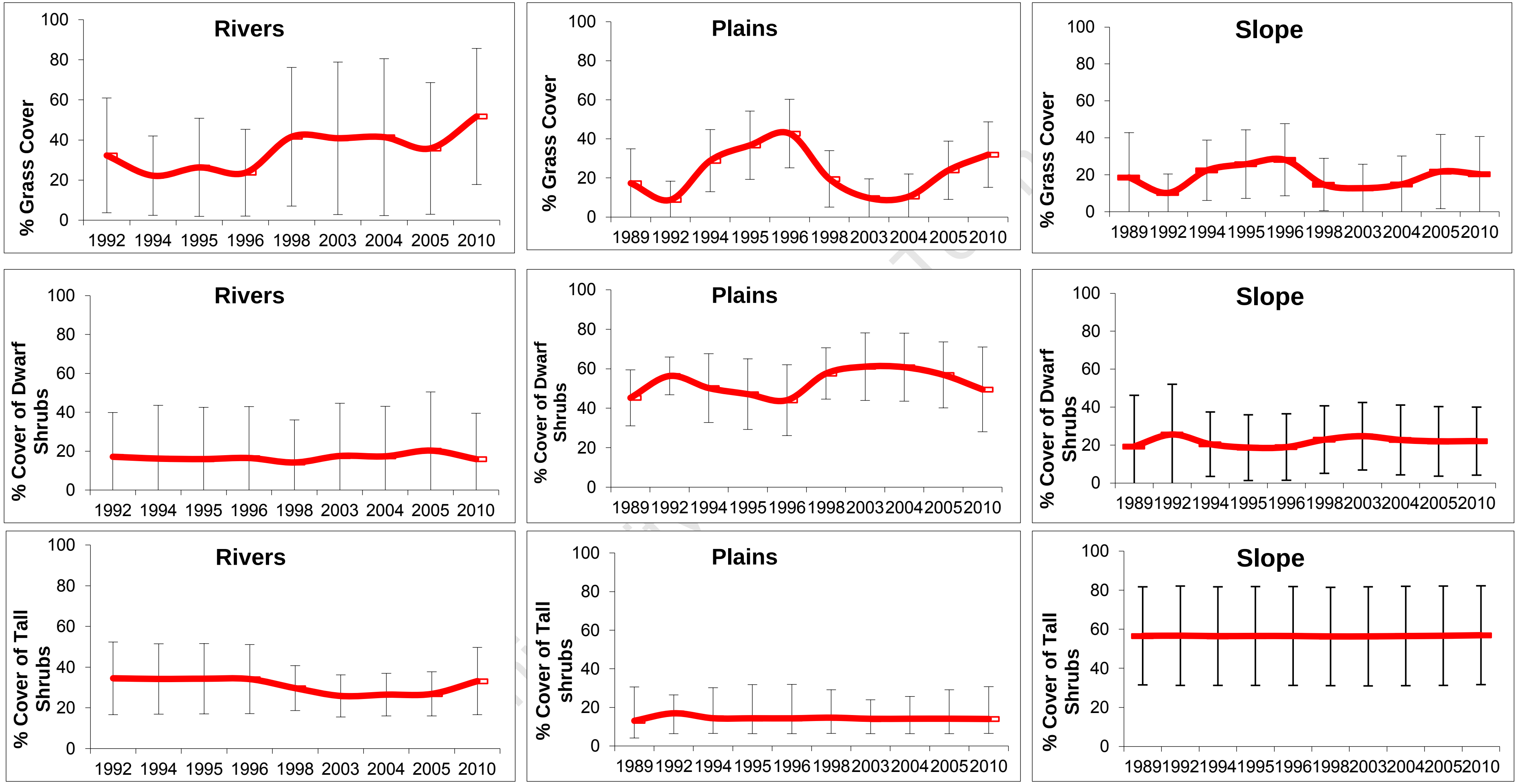
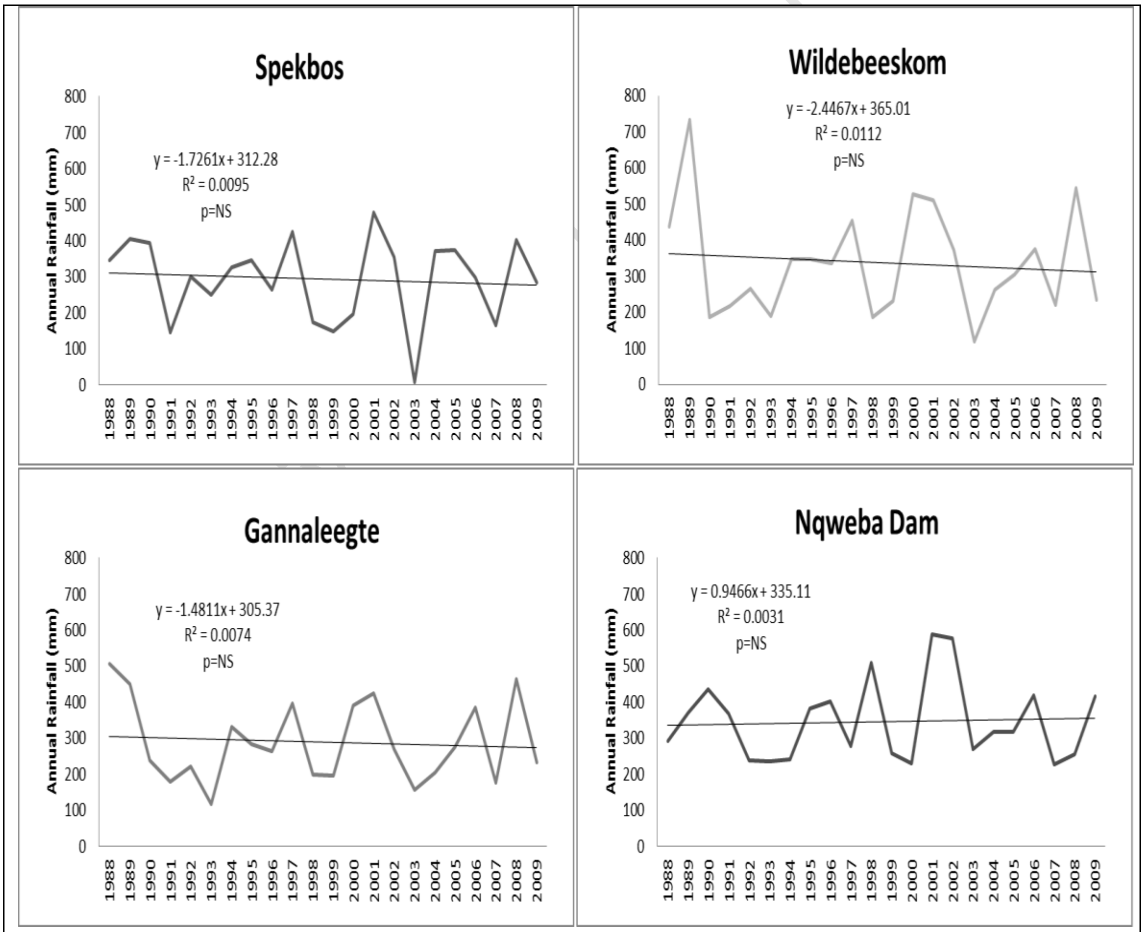


Figure 3.11: Percent cover (±sd) of the main growth forms on the different landforms as determined from an analysis of fixed point photo monitoring sites between 1992 and 2010.

3.4.2. Change in historical climate

3.4.2.1. Annual Rainfall

No significant change in annual rainfall was recorded over the last 18 years at the four climate stations within CNP (Figure 3.12). This pattern is consistent with the longer rainfall record for Graaff Reinet which has not changed significantly in the last 100 years. Annual rainfall totals varied across the landscape. They were highest for high elevation sites such as the Valley of Desolation and Waaihoek (not included in Figure 3.12 as records for these sites ceased at the end of 2005) which both had values of 358 mm. Sites slightly lower in elevation such as Nqweba Dam (345 mm) and Wildebeeskom (340 mm) received lower mean annual totals over the course of the study period. The lowest mean annual rainfall totals were recorded at Gannaleegte (294 mm) and Spekbos (293 mm) which were also the lowest in elevation.



3.12: Annual rainfall totals for four climate stations within the Camdeboo National Park over the period 1987 to 2010.

3.4.2.2. Seasonal rainfall

Monthly rainfall data for all four weather stations were grouped and the seasonal averages compared between two time periods (1990-1999 and 2000-2009). Results showed that the average amount of rain in summer (December-February) and autumn (March-May) was significantly greater for the decade between 2000 and 2009 than for the decade which preceded it (Figure 3.13). The increase in both summer and autumn rain was largely due to the significant increase in rain in February and in April respectively. Spring and winter rainfall amounts were not significantly different between the two decades.

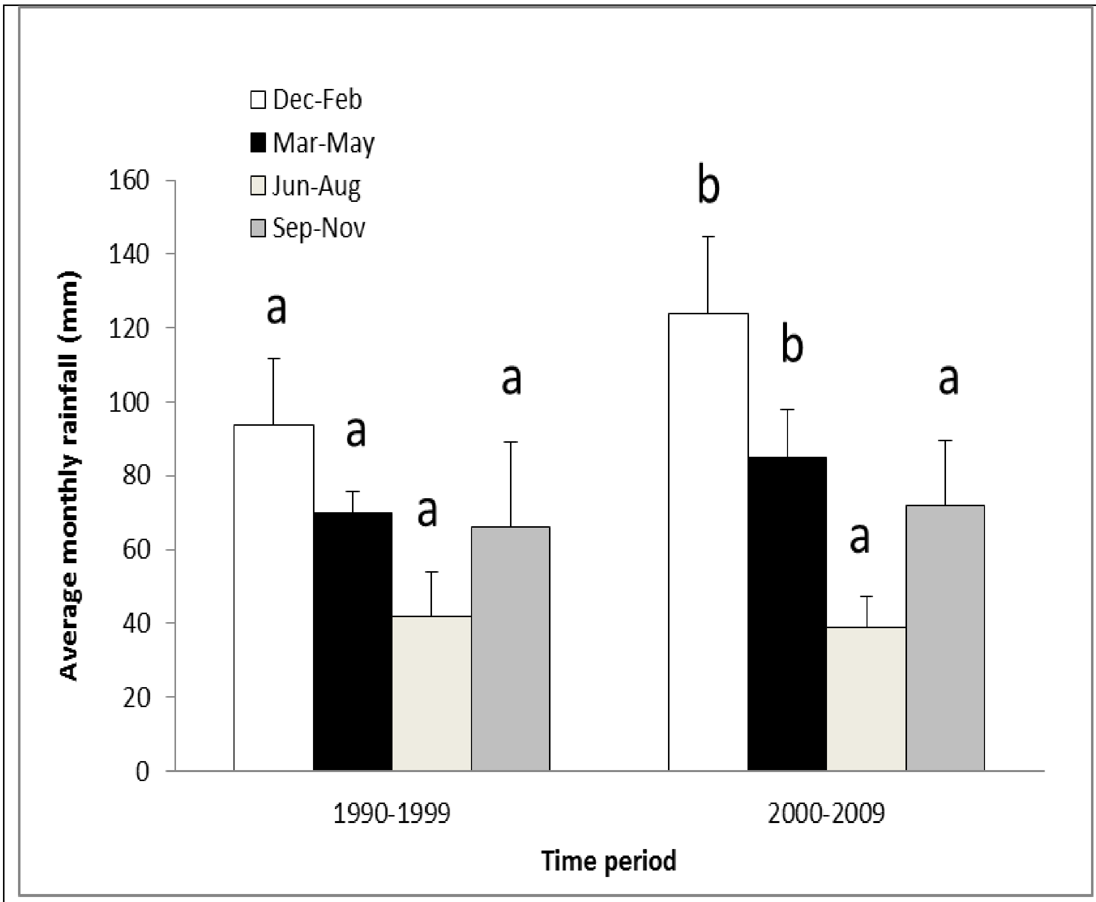


Figure 3.13: Change in seasonal rainfall per decade at CNP based on the results from four climate stations in the area. Dissimilar superscripts denote significant seasonal differences between the decades at $p<0.05$.

3.4.2.3. Standardized Precipitation Index

There was no significant change in the long-term standardized precipitation index at all four climate stations (Figure 3.14). The most severe drought years over the study period were 1990-1991, 1997-1998 and 2002-2003. The wettest periods were experienced in 1988, 1995, 2000 and 2006-2007. All four climate stations showed similar SPI profiles suggesting a high degree of spatial coherence in drought and wet periods across CNP.

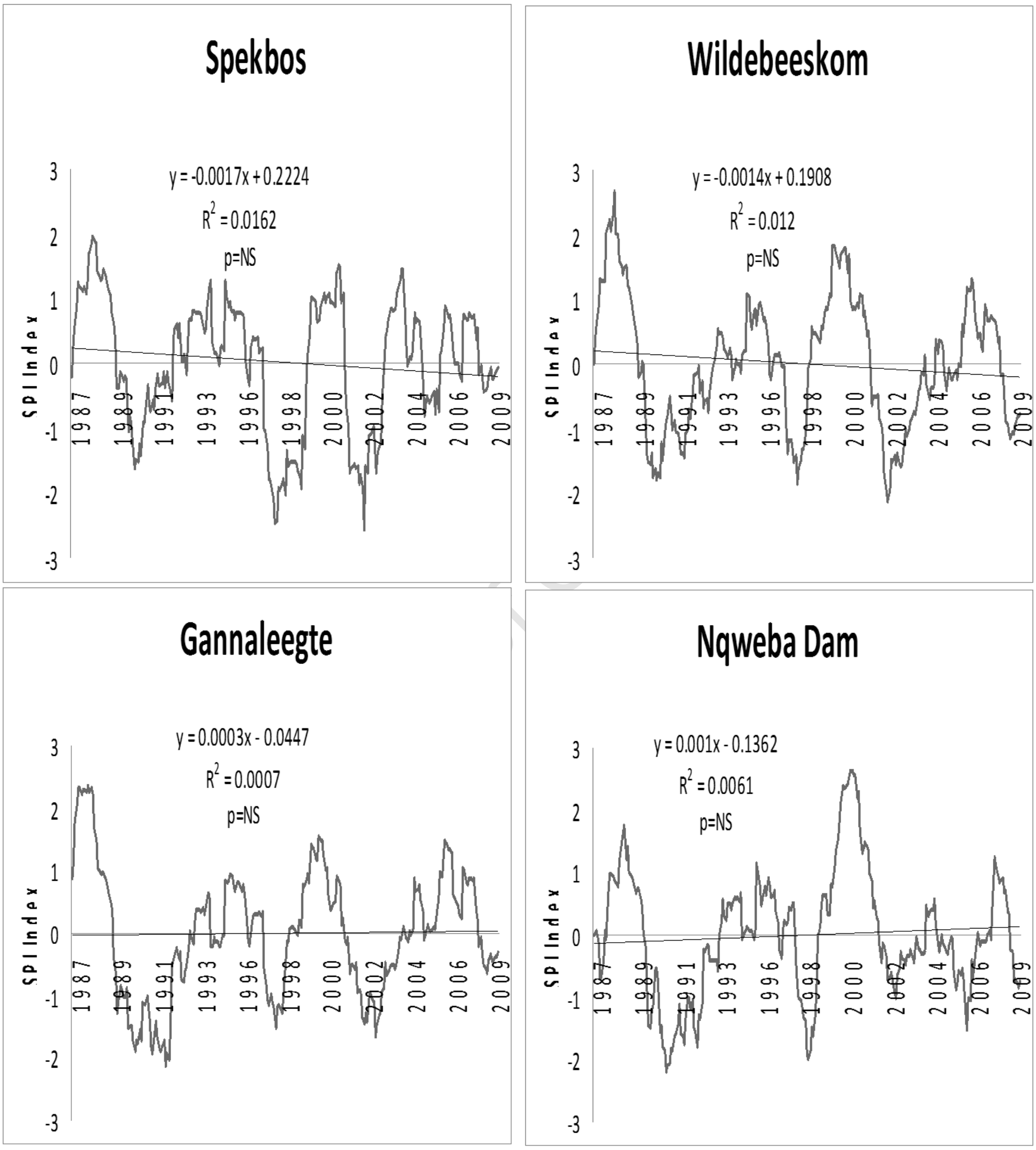


Figure 3.14: Standardized Precipitation Index (SPI) values based on a 24-month period for four stations at CNP.

3.4.2.4. Temperature

Although the average maximum temperature has increased by 0.001 ºC per year since 1992 and the average minimum temperature by 0.04 ºC per year the trends were not significant (Figure 3.15). The highest monthly maximum temperature was recorded in January 2003 at 34.6 ºC with the highest minimum temperature recorded in 2006 at 16.6 ºC. The highest average annual maximum temperature of 27.2 ºC was recorded in 1999. The lowest was recorded in 1996 at 25.4 ºC.

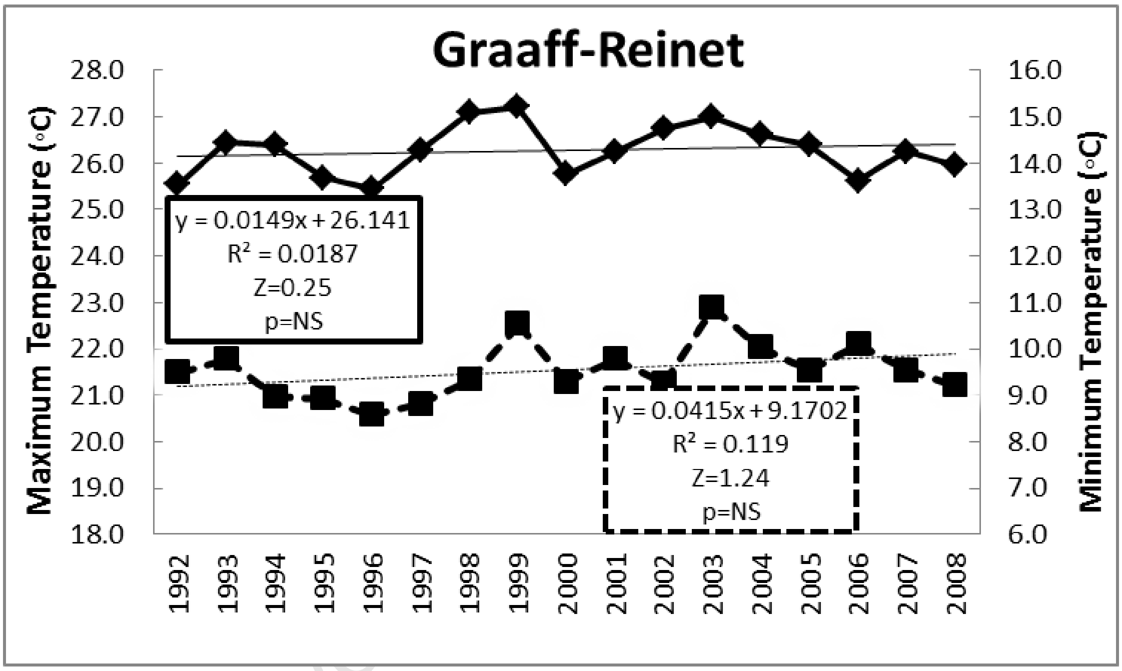


Figure 3.15: Long-term annual maximum and minimum temperature for the study area from 1992-2008.

3.4.2.5. Pan Evaporation

There was no significant trend between 1926 and 2008 in the long-term S-pan evaporation data for Nqweba dam. However, when analysed for the period from 1989 to 2008 only, there was a significant decline in S-pan evaporation values at Nqweba Dam (Figure 3.16). The maximum annual value for pan evaporation was recorded in 1993 at 2237 mm while the minimum value was recorded in the year 2009 at 1643 mm.

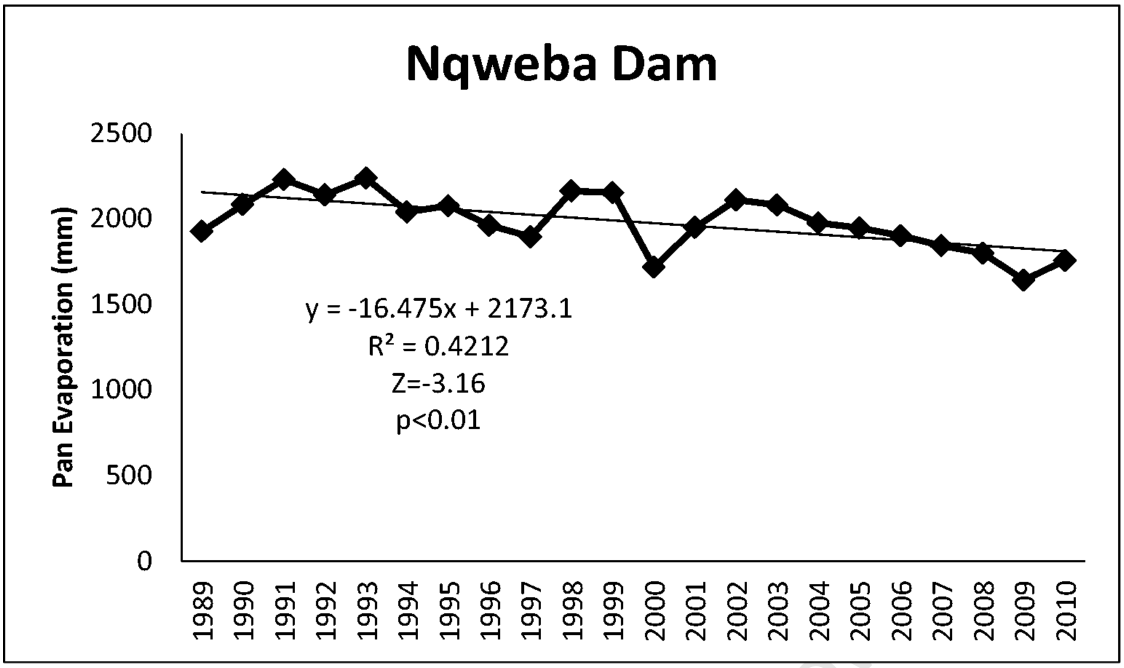


Figure 3.16: Changes in annual S-pan evaporation (mm) values over the period 1989 to 2010.

3.4.3. Animal distribution within CNP

3.4.3.1. Park scale

Over the course of the study, the highest herbivore stocking densities were recorded around the dam as well as near watering points on the plains while mountainous areas had the lowest densities (Figure 3.17.a-c). During the period between 1990 and 1994, when rainfall was below average, stocking densities remained high and animals were widely distributed throughout the park. Animals numbers have declined since 1995 (Figure 3.18) and they have also become less widely distributed in the landscape. The plains and the area around the dam support large bulk grazers such as buffalo (*Syncerus caffer*), blesbuck (*Damaliscus pygargus phillipsi*), black wildebeest (*Connochaetes gnou*) and eland (*Taurotragus oryx*) which are resident in these areas. Springbok (*Antidorcas marsupialis*) are mixed feeders and are also present at high densities in these areas of the park. The plains and area around the dam have a relatively high cover of grasses and animal densities have remained high compared to other areas in the park. In terms of browsers, kudu (*Tragelaphus strepsiceros*) is widespread throughout the park as well as within the Nqweba dam area where it feeds on *Acacia karroo*. Tall shrubs, such as *Portulacaria afra* which are dominant within the more mountainous areas of the CNP, are also heavily utilized by kudu.

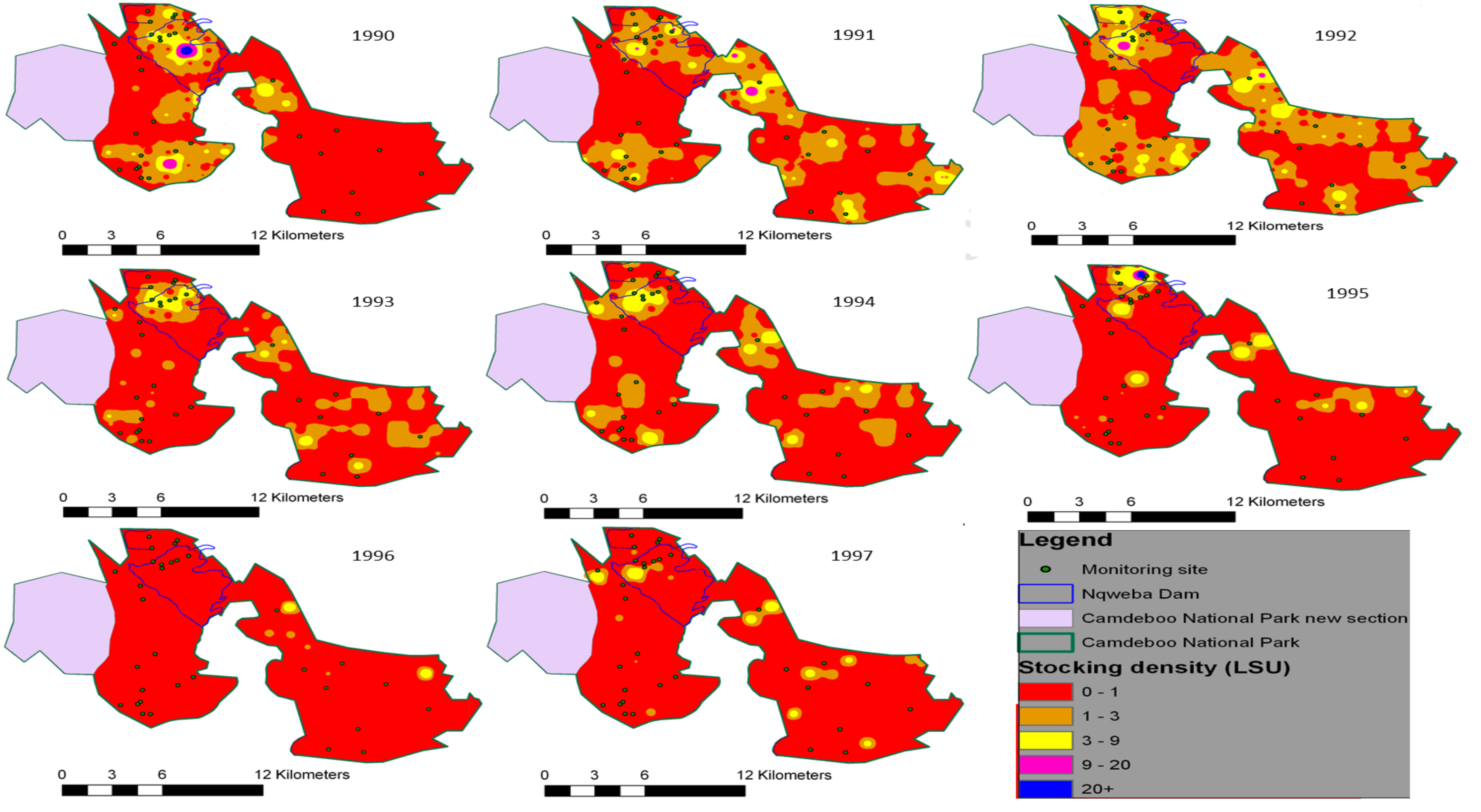


Figure 3.17a: Herbivore density at CNP as shown by average stocking density (LSU/km²) from 1990 until 1997.

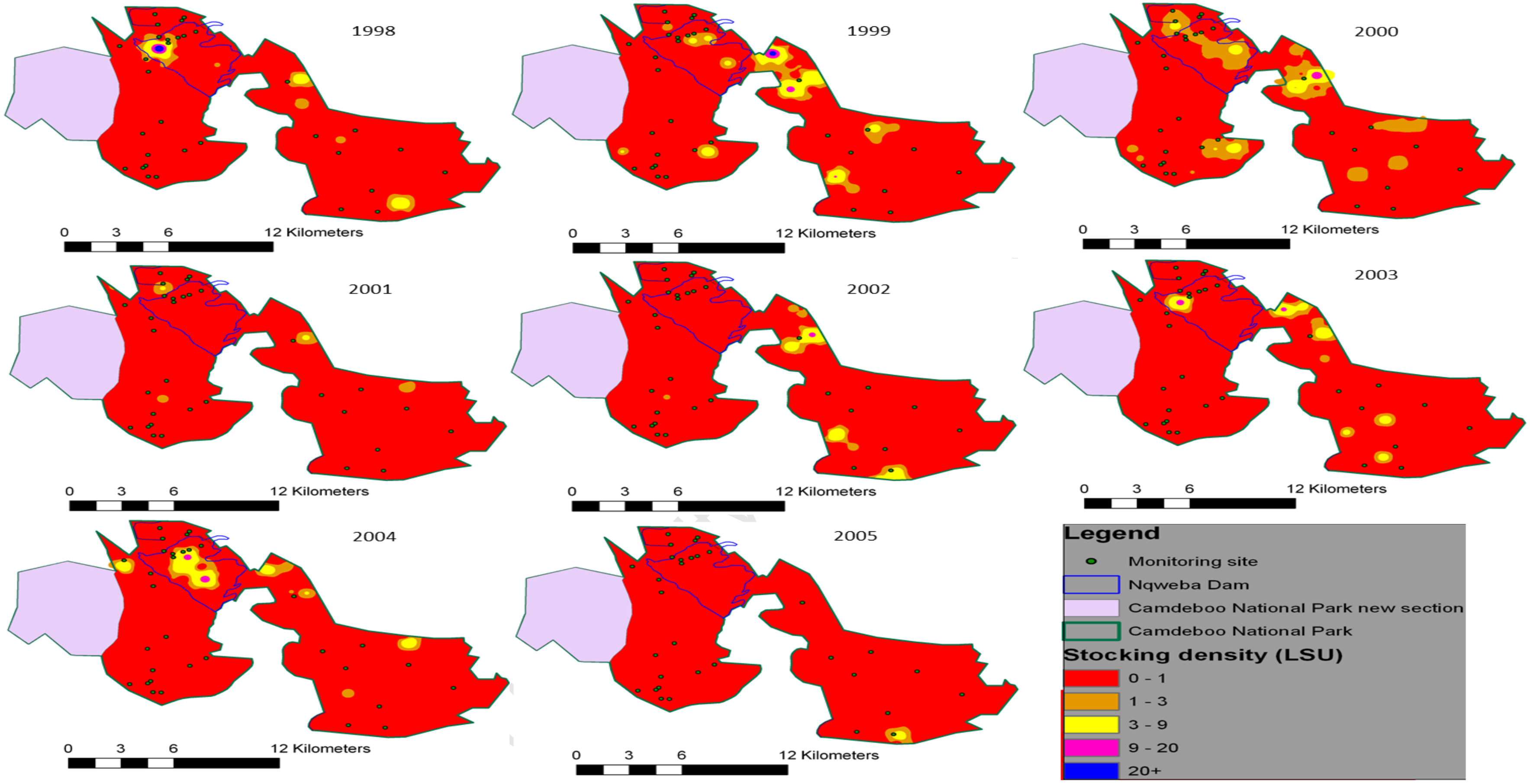


Figure 3.17b: Herbivore density at CNP as shown by average stocking density (LSU/km²) from 1998 until 2005.

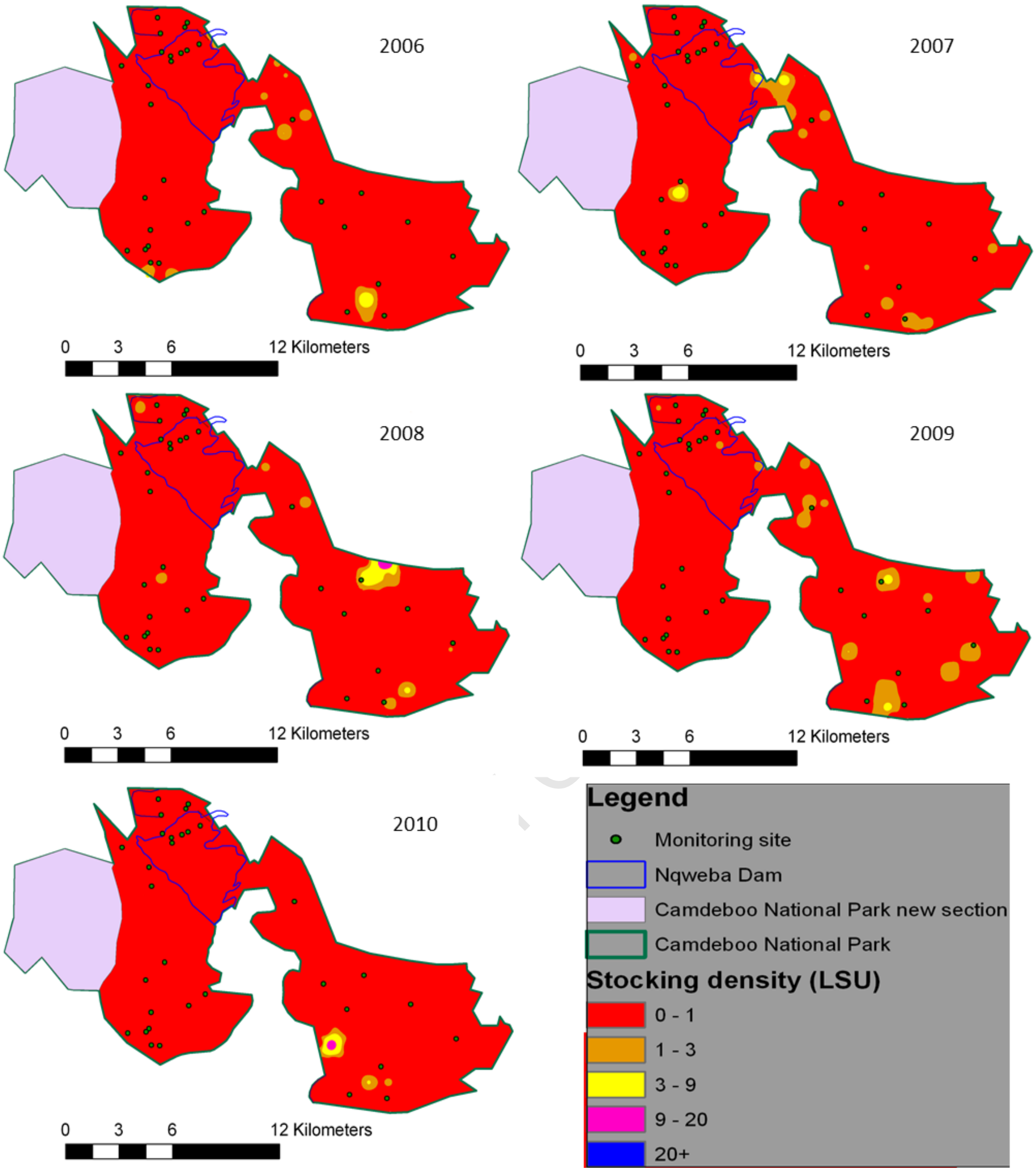


Figure 3.17c: Herbivore density at CNP as shown by average stocking density (LSU/km²) from 2006 until 2010.

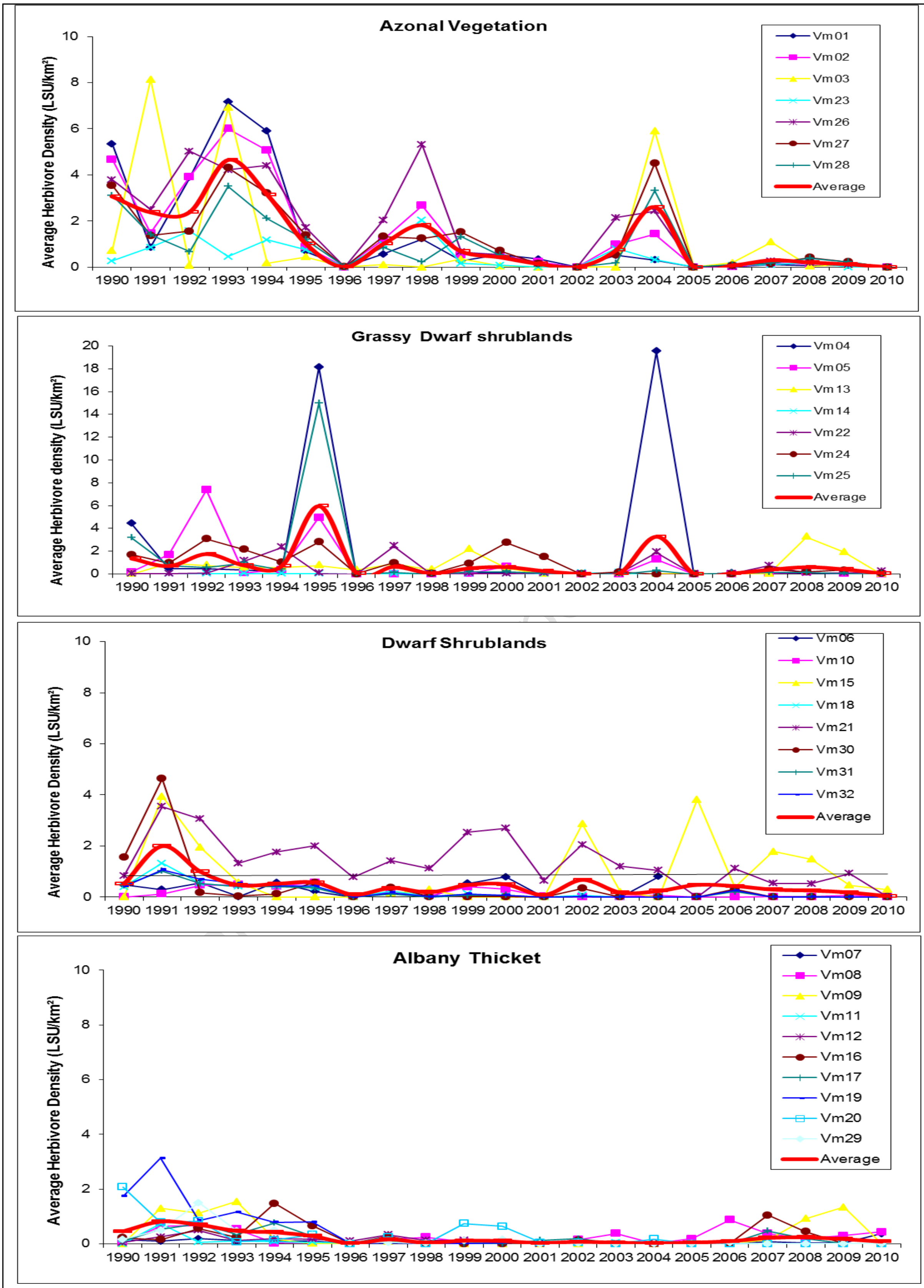


Figure 3.18: Average herbivore stocking density (LSU/ha) from 1990 until 2010 recorded at the 32 vegetation monitoring sites in CNP. Note the different y-axis scale for Grassy Dwarf Shrublands.

3.4.3.2. Herbivore densities associated with vegetation units

Average herbivore densities within the vegetation units showed that Azonal vegetation and the associated Grassy Dwarf shrubland areas supported the highest densities of herbivores whereas the Dwarf shrublands and the Albany Thicket had the lowest (Figure 3.18). Sites within Azonal vegetation had higher densities during the drought years of 1990-1992, 1997-1998 and 2003 whereas 1993 and 2004 had the highest densities of all. The surrounding Grassy Dwarf shrublands had higher stocking densities immediately after the drought years. The Dwarf shrublands and Albany Thicket communities on the other hand have supported relatively low densities of animals over the last 20 years.

3.5. Discussion

The main objectives of the chapter were to document the extent of vegetation change in the main vegetation units and landforms at CNP in the last 18 years and to determine the main drivers of this change. A secondary objective was to assess the value of fixed-point photo monitoring in documenting vegetation change in the park.

3.5.1. Change in vegetation cover and growth form composition since 1992

Vegetation cover and growth form composition are the most commonly used indicators of change in most terrestrial ecosystems (Godinez-Alvarez *et al*. 2009). In this study there was considerable variation in the total cover of vegetation as well as the cover of different growth forms between sites and even within the same vegetation unit. Although this variability makes it difficult to generalize across the CNP, some common patterns were evident in the response of different growth forms within different vegetation units and landforms.

Of all the growth forms grasses were the most dynamic in terms of how they changed over time as compared to the changes in dwarf and tall shrubs. While such changes were somewhat muted in Albany Thicket vegetation they were most noticeable within Azonal vegetation associated with rivers and floodplains as well as on the plains where Grassy Dwarf Shrubland and Dwarf Shrubland vegetation dominated. The response of dwarf shrubs in all vegetation units, appeared different to that of grasses and generally declined when grass cover increased. While the cover of dwarf shrubs might have been underestimated from the photographs because of the presence of taller grasses which might have obscured their view, the survey data in O'Connor & Roux (1995) suggests that grasses and shrubs compete for both above- and below-ground resources. Their survey data as well as evidence presented in Chapters 4 and 5 show that when grass cover is high shrub cover declines.

Shiponeni *et al*. (2011) have shown experimentally how grasses and shrubs compete for resources. Their results indicate that grasses are superior competitors and can out-compete dwarf shrubs in the ecotonal environments that occur between the arid Namaqualand and Bushmanland regions in the western part of the Karoo. They present a mechanism and suggest that increased grass cover results in reduced soil water availability for the nearest shrubs. Alvarez *et al*. (2011) have also shown within the Chihuahuan desert that when rainfall is abundant, increased competition occurs between shrubs and grasses. The cover assessments derived from a comparison of repeat photographs in this study thus appear to reflect real differences on the ground between shrub and grass cover (Hoffman & Rohde 2011a). However, more detailed experimental work is needed to determine the competitive interactions between grasses and shrubs within eastern Karoo rangelands, where fluctuations in grass and shrub cover can occur over relatively short time periods (Hoffman *et al*. 1990). Experimentally-induced drought and above-average rainfall events would be especially helpful in this regard and would serve to test the state-and-transition model proposed by Milton & Hoffman (1994) for the region.

The cover of tall shrubs in all vegetation types except Azonal vegetation was remarkably stable over the course of the study. With few exceptions, the cover of tall shrubs in 2010, at almost every site within Albany Thicket, Grassy Dwarf shrublands and Dwarf shrublands, was the same or very similar to what it was at the beginning of the study when the first photographs were taken. This was not the case, however, for several sites within Azonal vegetation where tall shrub cover responded relatively quickly to fluctuations in the hydrological environment. *Acacia karroo* appeared particularly dynamic on the flood plain above the Nqweba Dam. For example, the dry period between 1998 and 2003 had a negative impact on the abundance of *Acacia karroo* which appeared unable to survive long periods of hydrological drought. Other studies report a similar decline in tree and shrub cover under drought conditions (Carnicer *et al*. 2011; Schmiedel *et al*. 2012; Allen *et al*. 2010). In CNP, however, populations of *Acacia karroo* responded quickly again to the increase in moisture levels after the relatively good rains experienced in the region in the 2007/2008 rainy season. Hoffman & Rohde (2011b) have indicated the dynamic nature of river systems in Namaqualand which have also shown a significant increase in the abundance of *Acacia karroo* over time. However, their repeat photograph study, which usually only has two time steps, does not capture the dynamic nature of river systems in arid environments where shorter observation periods of five or ten year time steps are preferable. While riparian vegetation communities are generally acknowledged to be spatially and temporally dynamic as a result of fluvial disturbance amongst other drivers (Capon & Dowe 2007; Naimann & Decamps 1997; Tockner & Stanford 2002), there is a lack of long-term monitoring data to show the nature, extent and rate of this dynamism (Webb *et al*. 2011).

3.5.2. Changes in climate and its influence on the vegetation

It should be noted that statistical analysis (especially generalized linear models) that would have linked vegetation change to the climate drivers was not possible. This was largely because the climate drivers could not be recorded for each site or for each vegetation type. The climate data is simply not available at the resolution required for such an analysis. These limitations should be recognized in the interpretation of the key drivers of vegetation change.

3.5.2.1. Rainfall

Trends in climate parameters measured at CNP over the last 20 years are consistent with those reported elsewhere for southern Africa (Warburton *et al*. 2005; see chapter 2). For example, there was no significant trend in annual rainfall or the incidence of drought at all climate stations within CNP over the course of the study period. There were, however, significant fluctuations in annual rainfall between years with important implications for the vegetation of the region (Milton & Hoffman 1994). The analysis of seasonal rainfall patterns, suggests that the amount of rain falling in late summer and autumn increased in the second decade of the study when compared to the first. This appeared not to be the case for spring and winter rainfall patterns which did not differ significantly over the course of the study. This finding is consistent with du Toit (2010) who reported a similar increase in summer rain at a climate station at Middleburg about 100 km north of CNP.

Inter-annual fluctuations in rainfall have important implications for the response of different growth forms in the region as evidence by the repeat photograph survey. Grasses tend to respond to short-term fluctuations in annual rainfall far more than tall shrubs and trees (Scanlon *et al*. 2005; Holdo *et al*. 2009). Summer rainfall, derived from convective thunderstorms, often contributes short-term pulses to soil moisture that can be utilized quickly by annual plants and C_4 grasses in particular (Schwinning *et al*. 2003, 2008). Evidence from the photomonitoring programme suggests that the increase in summer rainfall over the first decade of the 21st century has influenced grass cover within the Grassy shrubland and Azonal vegetation units at Camdeboo National Park as well as within the dominant landforms with which they are associated.

Extreme rainfall events such as droughts and floods or above normal rainfall influence the temporal dynamics of vegetation as observed in the photomonitoring assessments. The two wet events that occurred in 2001 and 2006, for example, resulted in an increase in grasses and annual herb cover. The floods were also probably responsible for the cohort of smaller *Acacia karroo* and *Tamarix rammosisima* saplings which became evident soon after these events. Drought events, such as were recorded in 1998 and 2003, also influence vegetation dynamics and in the CNP, contributed to a decline in grass cover but not that of dwarf shrubs. This was particularly evident in the Grass Dwarf shrublands and Dwarf shrublands where grass-shrub interactions are mediated in part by extreme drought events (Browning *et al*. 2008; 2011; Hoffman *et al*. 1990a; Gao & Reynolds 2003; Scholes & Archer 1997).

Evidence from the photomonitoring assessment also suggests that in arid and semi-arid environments drought years can significantly influence the structure of riparian and azonal habitats by eliminating large trees especially when droughts occur in combination with increased temperature (Allen *et al*. 2010; Breshears *et al*. 2005; 2009). In this study drought and higher temperatures in 1998 and 2003 might have influenced the structure of the vegetation within the Nqweba dam floodplain through the elimination of older and therefore taller individuals of *Acacia karoo*.

3.5.2.2. Temperature and Pan Evaporation

As is the case in many parts of southern Africa over the last 20 years (Warburton *et al*. 2005; Engelbrecht *et al*. 2009; Makhokha & Shisanya 2010), minimum temperature has increased at CNP at a faster rate than maximum temperature. Despite this, however, pan evaporation values declined significantly from 1989. This decline has been reported elsewhere in southern Africa (Eamus & Palmer 2007; Hoffman *et al*. 2011) and appears part of a global phenomenon (Roderick *et al*. 2011) which has as yet not been adequately explained

(McVicar *et al*. 2012). In the winter rainfall region of South Africa a significant decline in wind run appears the most plausible explanation (Hoffman *et al*. 2011) but more work is needed to resolve this issue.

Increased temperature has been shown to result in small increases in the cover of shrubs while C_4 grasses do not respond as much and C_3 grasses appear to decline (Morgan *et al*. 2011; Munson *et al*. 2011b). There is some evidence, therefore, to support the hypothesis that grass cover will decline under more arid and warmer futures while shrub cover will increase (Midgley *et al*. 2008). Evidence for the CNP, however, suggests that critical thresholds in this regard have probably not been reached as grass and shrub cover respond to moisture in a relatively predictable manner and there is little direct evidence for temperature playing an important role in structuring the vegetation of the CNP. In addition, experimental work is needed to evaluate the influence of elevated CO_2 in combination with warmer temperature on the vegetation of the region. Early results from other semi-arid environments suggest that elevated CO_2 could promote an increase in grass cover through improved soil moisture (Morgan *et al*. 2011). Knowledge of the thermal tolerances of the dominant species of grass, shrubs and trees in the various vegetation types would also enable the development of more useful hypotheses about future environmental change. For example, it has been suggested that many dwarf succulent leaved shrubs of the Succulent Karoo biome, might be close to their thermal tolerance limits and that future warming will lead to widespread impacts on this growth form in particular (Musil *et al*. 2009; Musil *et al*. 2010).

3.5.3. Herbivory and its impact on the vegetation

An understanding of the spatial and temporal use of the landscape by the herbivores is an integral part of ecosystem management (Bailey *et al*. 1996; Groom & Harris 2010). Herbivores are known to affect ecosystem structure through the loss of tree cover and to influence ecosystem processes such as productivity and carbon storage at local to regional scales (Asner *et al*. 2009; Speed *et al*. 2010; Tanentzap & Coomes 2012). It is therefore important to understand the temporal and spatial dynamics of herbivory at community to landscape scale at CNP. Animal census data indicated that ungulate densities have declined over time and have also varied considerably over space within the CNP. While herbivore density appears significantly influenced by the location of the Nqweba dam as well as the water points within the park, the occurrence of floods and droughts also affects the movement and densities of animals. Herbivore density remained relatively low on the slopes of the CNP while higher animal densities were generally recorded on the plains environments nearest to the watering points. The years with the highest herbivore density included 1992, 1995, 1998 and 2004. The majority of the high animal density records were returned during drought years. The lack of available moisture in the landscape might have forced animals to concentrate around artificial water points in the park and would have influenced the ease with which animals were observed and counted.

Animal densities were highest in the Azonal vegetation followed by the Grassy Dwarf shrublands. The location of several artificial water points in this vegetation unit as well as the good cover of high quality grasses could have influenced this. It is well known that both slope and location and distance to water points can exert a major influence on the movement and distribution of herbivores (Bailey *et al*. 1996). The density of herbivores was significantly lower on slopes with only areas near water points having slightly higher herbivore densities. This is largely due to the difficulty and restriction of movement by the dense vegetation on steep slopes which also reduces the ability of rangers to observe and record animals during the census activities (Morellet *et al*. 2007). However, even within vegetation units and landforms which supported relatively high densities of animals, there is little evidence from the photomonitoring assessment that herbivory played a significant role in influencing the cover of the dominant growth forms or species. Fluctuations in rainfall and major changes in the hydrological dynamics of the Nqweba dam floodplain appeared far more important in influencing the cover of grasses, dwarf shrubs and tall shrubs than changes in animal densities. However, the use of a photomonitoring approach might be an inappropriate tool to measure the impact of herbivory on the structure and function of CNP ecosystems. As for other semi-arid conservation areas (Hoffman *et al*. 2009b) it appears that herbivore densities currently observed at CNP are too low to have had a major influence on the vegetation especially when compared to those commonly recorded for livestock in surrounding areas. The selective feeding nature of wild herbivore guilds compared to the concentrated heavy grazing and browsing associated with livestock (Laca 2009; Laca *et al*. 2010) may explain why the impact of animals on the vegetation of CNP appears to have been negligible (Groom & Harris 2010; Hopcraft *et al*. 2012; Pita *et al*. 2011). However, a more detailed assessment of the spatial use of the Camdeboo National Park by different herbivore guilds is urgently needed.

3.5.4. The use of photomonitoring as a management tool

A biodiversity monitoring framework for each of the protected areas managed by SANParks has recently been developed by park managers, research scientists, regional ecologists and rangers working within this institution (McGeoch *et al*. 2011). The relative priority of each of nine key monitoring areas was assessed for each protected area. The relative scores within and across parks, form the basis for the prioritization of planning, management and monitoring activities (see Table 2 in (McGeoch *et al.* 2011)). Six of the 19 terrestrial parks evaluated are located in arid and semi-arid environments and include Namaqua National Park, West Coast National Park, Mountain Zebra National Park, Tankwa Karoo National Park, Karoo National Park and Camdeboo National Park. In all of these parks, the monitoring of potential climate change impacts, including changes in rainfall and temperature, was considered important. Other critically important biodiversity monitoring activities, which were ranked highly for the Camdeboo National Park in particular, included the monitoring of soil erosion, habitat degradation and rehabilitation as well as the impacts of herbivory and resource use. In terms of soil erosion, however, only a few sites in the Dwarf Shrublands areas could be identified from the photomonitoring assessment as being severely eroded and in need of rehabilitation. These sites all had a long history of erosion which existed prior to the CNP becoming a conservation area (CNP Newsletter 2011).

Park managers use photos regularly to inform their decisions and to effect policy change (Clark & Hardegree 2005; Hall 2001; 2002; Hendrick & Copenheaver 2009; Lucey & Barraclough 2001; Nichols *et al*. 2009; Woodward & Hollar 2011). This study has shown that a regularly updated and properly archived set of fixed point photographs provides a relatively inexpensive and easily implemented monitoring programme which addresses most of the key monitoring areas outlined above. This monitoring technique carried out over 18 years at 32 locations in CNP was able to document short-term changes in growth forms in different vegetation units and land forms and long-term fluctuations of several individual species as well as alien plants. This data, when collected over decades, is essential in separating directional change from short-term variability in the environment. Coupled with detailed rainfall and livestock census records the relative importance of the underlying drivers of change can also be determined. This is the sort of information that Park Managers consider necessary for both their day-to-day management decisions as well as their long-term strategic planning activities. A sound historical assessment of the pattern of change can also help to assess possible future trajectories based on land use and climate change scenarios (Hendrick & Copenheaver 2009; Munson *et al*. 2011c, d; Peters *et al*. 2011; Webb *et al*. 2009). Many of SANParks' biodiversity monitoring objectives (McGeogh *et al.* 2011) could be met if such a programme were implemented across all of SANParks' terrestrial conservation areas.

However, the use of repeat photographs within a long-term monitoring programme is not without its problems. For example, while the estimation of vegetation cover from photographs is largely accurate and similar in precision with point-frequency estimates (Symstad *et al*. 2008) it is influenced by observer bias. Experienced observers tend to underestimate vegetation cover while less experienced observers often overestimate this value (Lucey & Barraclough 2001). It is also often difficult to identify smaller shrubs in the landscape when grass cover is high which leads to an underestimation of this growth form in the photograph, particularly in the Grassy Dwarf shrublands. Similarly, large trees, especially when they have established close to the camera station, can also obscure the field of view as was the case for some images within the Azonal and Albany Thicket vegetation units photographed in CNP.

This study has also emphasized that a set of repeat photographs without more detailed survey data is of limited value only. The inclusion of vegetation survey data at each camera station along the direction of the field of view adds further depth to the analysis particularly in terms of an assessment of changes in species diversity, range condition and other species-dependent metrics of ecosystem structure and function (Lucey & Barraclough 2001). Furthermore, without the vegetation surveys undertaken at each location in 2010 little insight into the looming alien plant problem (Masubelele *et al*. 2009), nor the efficacy of the alien clearing programme, would have been gained. These observations point to the value and importance of a long-term monitoring programme but also suggest that other, more directed survey and monitoring tools need to be developed to actively manage invasive plants and related problems. Associated metadata such as stocking rates, rainfall and specific management interventions also help in the interpretation of landscape-level changes and are essential components for any photomonitoring programme. The nature of these monitoring tools, exactly what is recorded, as well as the frequency of measurement will probably differ between conservation areas. However, monitoring approaches could be similar within the programmes developed for groups of national parks such as those in the arid and semi-arid areas of South Africa.

3.6. Conclusion

Using a repeat photomonitoring approach this study has documented the varied response of vegetation cover within three main growth forms in different major vegetation units and landforms within the Camdeboo National Park since 1988. Sites within Albany Thicket and Dwarf Shrublands showed the least change in vegetation cover while Azonal vegetation and Grassy Dwarf shrublands were more dynamic in their response to rainfall and flood plain hydrology. Abiotic factors such as rainfall amount, changes in the distribution of rain between seasons and the occurrence of flood and drought events in combination with high temperatures appeared to have the greatest influence on growth form dynamics. Grasses generally responded to above average rainfall events and because of their superior competitive ability, negatively influenced the cover of dwarf shrubs. Dwarf shrubs appeared less affected by drought conditions while grass cover declined. The cover and abundance of tall shrubs and trees declined under drought conditions and increased significantly after major flood events, particularly within the flood plain associated with the Nqweba dam. Biotic factors such as herbivory appear to have had a negligible impact on the vegetation of the CNP, at least in terms of how this could be determined from the photomonitoring techniques used in this study. The lack of any visible impact is primarily because animal densities have remained low over the course of the study, relative to values for commercial livestock production systems in the area. The type of herbivore also appeared to be an important factor in this regard. Finally, the potential for using a photomonitoring programme to document the nature, extent and rate of vegetation change over decades is clearly demonstrated. However, the value of a well maintained, properly archived and easily accessible collection of repeat photos would be considerably enhanced by the collection of additional field survey data at the same time that the photographs were taken. Well-designed experiments are also needed to determine the relative influence of different drivers identified in this study at community and landscape scales.

Chapter 4: The influence of climate and land use on long-term (1962-2009) vegetation change at a shrubland-grassland boundary in semi-arid South Africa.

4.1. Introduction

Biome boundaries are recognized globally as areas where changes in the distribution of core terrestrial biomes are likely to first become apparent (Churkina & Svirezhev 1995; Hufkens *et al.* 2009). Boundaries between grassland and shrubland biomes have already shifted in many parts of the world (Buffington & Herbel 1965; Chapin *et al.* 1996; Heshmati & Squires 2011) and are predicted to undergo considerable change in the future (Archer *et al.* 1995; Henderson-Sellers & McGuffie 1995; Lioubimtseva 2004; Neilson 1993; Parton *et al.* 1995; Pearson & Dawson 2003; Pompe *et al.* 2008; Prentice *et al.* 1992; Sala *et al.* 2000). Most projections suggest that C_4 grasslands will be replaced by C_3 shrublands with shrublands becoming increasingly dominant at the boundary between the two (Baez & Collins 2008; Bestelmeyer *et al.* 2007; DeSimone & Zedler 2001; Fensham *et al.* 2005; Jetz *et al.* 2007; Knapp *et al.* 2008; Scholes & Archer 1997; van Auken 2000; van Vuuren *et al.* 2006). There is further concern that the encroachment of shrubs will impact on community stability and species richness (Alvarez *et al*. 2012; Baez & Collins 2008) and reduce biodiversity.

While the reason for the expansion of shrubs is complex, most drivers are linked to changes in climate and land use (Archer 2010; Chapin *et al.* 1996; Frederickson *et al.* 1998; Munson *et al*. 2012; Okin *et al.* 2009; Peters 2002; Peters *et al*. 2004, 2006, 2010, 2011; Sala *et al.* 2000; van Auken 2009). Climatic factors include increases in temperature, drought frequency, wind and CO_2 concentration (Archer *et al.* 1995; Bond & Midgley 2012; Midgley *et al.* 2002, 2008; Munson *et al*. 2011a; b; Parton *et al*. 1995; Peters *et al*. 2011). Because frost is limiting for many shrubs, an increase in minimum temperature and a reduction in the frequency of frost under future climate change scenarios (D'Odoricko *et al.* 2010) will favour their expansion. Shrubs are also able to outcompete grasses during drought periods as they have access to deeper soil water (Clary *et al.* 2004; Letts *et al.* 2011; McLaren *et al.* 2004; Potts *et al*. 2006). The water use efficiency and growth rate of C_3 shrubs are both positively influenced by the higher concentration of CO_2 in the atmosphere (Archer *et al.* 1995; Tietjen *et al.* 2010; Ward 2010) while for C_4 grasses both negative and positive increases in growth rate at elevated CO_2 have been documented (Adams *et al.* 2000; Clark *et al*. 1999; Dijkstra *et al*. 2010; Emmerich 2007; Jasoni *et al*. 2005; Leakey *et al*. 2009; LeCain & Morgan 1998; Polley *et al*. 2002; Seneweera *et al*. 1998).

Land use change is expected to greatly modify climate change effects and may overwhelm the impact of climate change in some areas (Parton *et al*. 1995). For example, the effect of CO_2 enrichment on soil carbon in the grasslands of the Great Plains is relatively small compared to the impact of ploughing and nutrient fertilization of crops (Burke *et al*. 1990). Land use on its own is also able to cause a switch from grass to shrub dominance in many semi-arid grassland environments especially when stocking rates and carrying capacity are exceeded (Acocks 1953; Costa & Rehman 2005; Turner *et al.* 2007). Bestelmeyer *et al.* (2007), for example, has suggested that the consumption of grassland seedlings by native herbivores has played a role in promoting shrub dominance.

An increase in shrub cover is generally thought to be symptomatic of desertification especially when caused by a combination of livestock grazing and drought (Archer *et al.* 1995; Brown & Archer, 1999; Brown *et al.* 1997; Fredrickson *et al*. 1998, 2006; Gibbens *et al.* 2005; Polley *et al.* 1996; Schlesinger *et al.* 1990; Weltzin *et al.* 1997). These two factors likely contributed to the degradation of habitat and the switch from grassland to shrubland between the 1870s and 1930s not only in South Africa (Acocks 1953) but in many drylands of the world. In some areas, however, an altered climatic regime that consisted not of drought, but of increased winter precipitation is also thought to have been responsible for this switch from grasses to shrubs. Under these conditions, the availability of moisture in the cool season favours the establishment of C_3 woody shrubs over C_4 grasses which are generally more active during the warmer, summer months (Brown *et al.* 1997; Booth *et al.* 2003; O'Connor & Roux 1995).

While the majority of studies suggest that shrublands have expanded over time, there are a few studies of grassland/shrubland boundary dynamics which suggest that grasses can recover and dominate shrublands under conditions of high rainfall and low grazing pressure (Peters 2002). For example, in an earlier study of the Grassland/Nama-karoo shrubland interface in South Africa, Hoffman & Cowling (1990b) used repeat photography and a resurvey of existing vegetation data and showed that grass cover had increased significantly at most sites that were previously dominated by shrubs. However, future climate change projections for this and many other semi-arid grassland environments suggest that they will become drier and therefore shrubbier in response to an increase in temperature and drought frequency (Beaumont *et al.* 2011; Gibbens *et al.* 2005; Midgley *et al.* 2002; Midgley & Thuiller 2011).

4.1.1. Climate change in the Eastern Cape, South Africa

In South Africa, changes in rainfall patterns, intensities and amounts as well as large increases in temperature and carbon dioxide are predicted for the next 100 years (Midgley *et al*. 2008; Tadross *et al.* 2005). The region is also expected to get drier due to the increase in drought frequency (Midgley *et al.* 2008). For the eastern Karoo, the direction and nature of vegetation change anticipated for these rangelands under most future climate change scenarios is similar to the position espoused by Acocks in 1953 although he emphasized the importance of land use and not climate as the main driver of change in the vegetation. Under future climate change projections, both the Nama-karoo and Grassland biomes are predicted to be reduced in area. The projections suggest that they will contract to more mesic bioclimatic regions which characterise the region today (Driver *et al.* 2005, 2012; Ellery *et al.* 1991; Midgley & Thuiller 2011). While climate change projections are illustrative of what changes are possible, it is equally important to know how vegetation has changed over historical time frames. The best place to investigate such biome changes and the relative influence of land use and climate change on the dynamics of grasses and shrubs is along the boundary between them. Such a boundary or ecotone between the Nama-karoo and Grassland biomes occurs in the semi-arid, Eastern Karoo of South Africa.

4.1.2. Long-term historical vegetation changes in the Eastern Karoo

The Eastern Karoo ecotone has been the focus of a number of degradation studies during the 20th century. Initial reports, rooted in a desiccationist paradigm, warned of the creation of deserts as a result of over-grazing and poor management (Anonymous 1923). Acocks (1953) provided a comprehensive synthesis of this view and suggested that, because of overgrazing, the area would be dominated by desert and succulent plants by 2050 as conditions would be so harsh that only these plants would be able to grow. This view prevailed for nearly 40 years until Hoffman & Cowling (1990b) provided evidence for an increase in grass cover over the second part of the 20th century. Their findings from photographic and survey evidence did not support Acocks' (1953) view of an expansion of dwarf shrubs. Even though grasses and shrubs have co-existed in the region for centuries (Bond *et al.* 1994) historical evidence suggested that there had been an increase in grass cover at most sites in the region. Hoffman (1995) suggested further that a more comprehensive understanding of the relative roles of anthropogenic and climatic influence on the composition and productivity of the vegetation of the Nama-karoo biome was required. Several authors have shown that both climate and grazing influence species composition and function in the Nama-karoo (Milton & Hoffman 1994; O'Connor & Roux 1995; Rahlao *et al.* 2008). Vegetation cover in these semi-arid environments is clearly influenced not only by short- and long-term fluxes in rainfall but stocking rates, grazing rotations and land management practices are also important (Archer 2004). Land degradation due to poor management is often associated with an increase in rill and gully erosion which in turn has led to the replacement of grassland by shrub vegetation in parts of the Eastern Karoo (Boardman *et al*. 2003). A decrease in plant cover due to overgrazing in the past has also exacerbated land degradation (Keay-Bright & Boardman 2006; 2009) but there have been signs of a recovery due to de-stocking and better land management (Boardman *et al*. 2010). The impact of stocking rate has been clearly demonstrated by Todd (2006) who used degradation gradients around water points to show that the intensity of grazing had a negative impact on vegetation cover and composition. His results suggest that grazing-sensitive species only become dominant at distances away from water points even though they might have been the dominant species in the past.

In this study of the Nama-karoo/Grassland ecotone, of the Karoo Midlands region of South Africa, the nature and extent of long-term rainfall and vegetation change was determined. Firstly, changes in rainfall and drought incidence were assessed to determine if there was evidence in the historical record for the predicted drying trend which has been projected by global climate change models. Secondly, by building on the data sets of Hoffman & Cowling (1990b), the nature and extent of vegetation change within grassland and shrubland communities over the last 20 years was considered in terms of future biome-level projections for the region (Midgley *et al.* 2008). Is there evidence that shrublands have expanded at the expense of grasslands as suggested by future biome-level projections or does the trend of an increase in grass cover, reported 20 years ago by Hoffman & Cowling (1990b), still hold? This analysis also explored the relative influence of land use (particularly stocking rate) and rainfall on shrub/grass dynamics. Which key drivers best explain the changes in vegetation cover and composition along this biome boundary and what do these findings mean for key policy and land management debates in the region?

4.2. Study Area

The study took place along a 500 km transect in the central interior of South Africa from Richmond in the Nama-karoo biome in the south west to Dewetsdorp in the Grassland biome in the north east (Figure 4.1). Eight sites, which were previously surveyed by Roux (1968) and Hoffman & Cowling (1990b) were resurveyed in January 2009. All sites were located on colluvial slopes of wide valleys in the region (Roux 1968). The location and description of each site is summarized in Table 4.1.

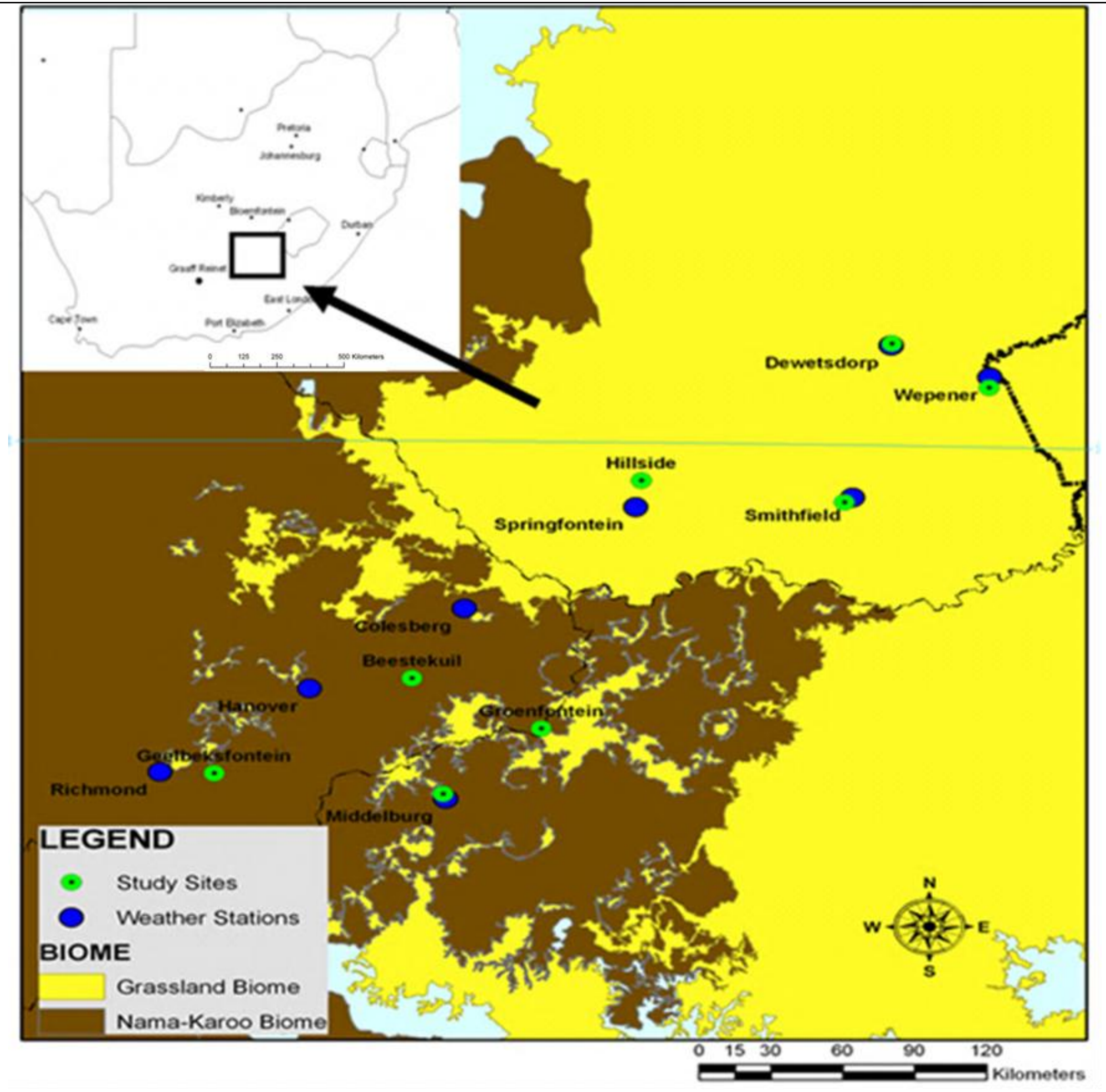


Figure 4.1: Location of the study sites and weather stations used in this study within the Nama-karoo and Grassland biomes of South Africa. Inset shows the location of the study area in South Africa.

Table 4.1: Site features of the eight study sites in the Eastern Karoo. Veld Type and Vegetation Type classification follows Acocks (1953) and Mucina and Rutherford (2006) respectively.

Locality name	Location	Altitude (m)	District	Biome	Veld Type	Vegetation Type
Beestekuil	31º14'56.621 S 24º34'45.762 E	1403	Hanover	Nama-karoo	False Upper Karoo	Eastern Upper Karoo (NKu4)
Middelburg Commonage	31º28'56.009 S 24º59'41.022 E	1300	Middelburg	Nama-karoo	False Upper Karoo	Eastern Upper Karoo (NKu4)
Geelsbekfontein	31º23'49.091 S 24º07'01.260 E	1551	Richmond	Nama-karoo	False Upper Karoo	Eastern Upper Karoo (NKu4)
Groenfontein	30º53'41.754 S 25º09'25.422 E	1436	Colesberg	Nama-karoo	False Upper Karoo	Eastern Upper Karoo (NKu4)
Hillside	30º09'28.578 S 25º43'33.576 E	1488	Springfontein	Grassland	False Upper Karoo	Xhariep Karroid Grassland (Gh3)
De Draai	30º13'10.013 S 26º23'05.441 E	1503	Smithfield	Grassland	False Upper Karoo	Aliwal North Dry Grassland (Gh2)
Wepener Commonage	29º44'25.78 S 27º01'52.62 E	1454	Wepener	Grassland	Transitional Cymbopogon-Themeda Veld	Ecotone Gh2 & Mesic Highveld Grassland (Gm3)
Dewetsdorp Commonage	29º34'25.799 S 26º39'52.620 E	1543	Dewetsdorp	Grassland	Transitional Cymbopogon-Themeda Veld	Central Free State Grassland (Gh6)

4.3. Methods

A combination of approaches incorporating analyses of historical rainfall and land use data, repeat photography and long-term ecological monitoring was used to assess changes in the vegetation along a 1,000 km transect from the Nama-karoo biome in the southwest to the Grassland biome in the northeast.

4.3.1. Rainfall

Long-term change in rainfall at representative sites along the transect was assessed. Data were obtained from the South African Weather Service (www.weathersa.co.za). All the time-series data were visually inspected for discontinuities and missing values. Empty cells were replaced with average values for a specific month. Data sets which appeared unreliable with many missing values and discontinues, such as Wepener, were replaced with the nearest adjacent site for which reliable data were available (e.g. Hobhouse). Annual rainfall was recorded as the sum of values from October the previous year to September in the current year. Changes in average monthly rainfall values over three time steps were also assessed. The time steps corresponded broadly to the decades which preceded each of the vegetation and photographic surveys (i.e. 1940-1962, 1963-1989, 1990-2009). The historical incidence of drought along the transect was assessed for a 24 month time scale using the Standardized Precipitation Index (SPI) (Hoffman *et. al.* 2009a; McKee *et. al.* 1993; Roualt & Richard 2003). Changes in rainfall and drought incidence over time were assessed using a non-parametric Mann Kendall test for trend (Modarres & da Silva 2007).

4.3.2. Land use

The number of domestic livestock (cattle, sheep and goats) censused over the period 1911-1996 within magisterial districts (Table 4.1) along the Nama-karoo/Grassland biome ecotone was obtained from the Agricultural Census Database of the Department of Agriculture. The total number of cattle, sheep and goats recorded each year in a magisterial district was converted to a Large Stock Unit (LSU) value by using the conversion tables in Meissner *et al*. (1983). LSU values were summed for a magisterial district and stocking densities calculated by dividing the LSU value by the total area of each magisterial district. The results for the four magisterial districts in the study area which occurred predominantly in the Nama-karoo biome were grouped and compared with the grouped results for the four magisterial districts which occurred predominantly in the Grassland biome.

4.3.3. Photography

At each of the study sites, matched photos previously taken by Roux (1968) and Hoffman & Cowling (1990b) were re-photographed in January 2009 following the approach outlined in Rohde (1997). At each site, the original photo station and exact camera position was relocated, and GPS co-ordinates and altitude recorded. Three cameras were used in order to minimise the risk of spoiled film and to record images in black and white, colour and digital formats. The cameras used were a Minolta X-300s with a standard 50 mm Minolta lens using Ilford FP4 Plus (ASA 125) 35 mm format black and white film; a Minolta X-70 with a 35-200 zoom lens using Fujichrome Sensia 35 mm format colour slide film (ASA 100); and a Canon EOS 400D, 12 megapixel digital camera with an 18-70 mm lens. All cameras were mounted on a sturdy tripod and for each frame the camera type, film type, focal length, f-stop, shutter speed and exact time of the image was recorded. This information is important for archival purposes and helps when processing the images. Repeat photographs for the full time series (1969, 1990 and 2009) were matched and analysed in Photoshop CS4. Visual estimates of grass and shrub cover in the photographs were undertaken using the matched images. The complete series is shown in Appendix 1 while the original photographs and repeated images as well as the completed data sheets have been archived with the Plant Conservation Unit's repeat photograph database kept at the University of Cape Town.

4.3.4. Vegetation sampling

In addition to the photographs repeated at each site and analysed on-screen, a quantitative estimate of species cover was also undertaken in the field. This was done by recording the species found at a point every 1.5 m along a transect using the same approach outlined in Roux (1968) and Hoffman & Cowling (1990b). At each site in 2009 a total of about 600 points were recorded within 3 parallel transects of 200 points each. The percentage cover estimate for a species reflects the number of points out of 600 (multiplied by 100) recorded for a species. Following the approach by Hoffman & Cowling (1990b) the different species were assigned to one of the following five growth forms and changes in the percentage cover of each growth form over time was determined: forbs, geophytes, grasses, sedges (Cyperaceae/Juncaceae), shrubs. In addition, the Grazing Index Value (GIV) was determined for each sample at each time step. This provides a relative measure of the potential forage availability at a site and is a proxy assessment of rangeland condition. It is based on the individual properties of species at a site and is derived from decades of field observations and grazing trial research carried out at the Grootfontein Agricultural College in Middelburg (Du Toit *et al.* 1995a). Using species-specific information, each species was assigned a forage factor on a scale from zero to ten and then multiplied by the percentage cover of the species at the site. This was then summed for all species at the site to indicate the forage potential or GIV for the site for a specific year (Du Toit *et al*. 1995a; Du Toit 2010b).

4.3.5. Data Analysis

Vegetation cover data for all three time steps (1969, 1990 and 2009) was analysed in PC Ord 5 (McCune & Mefford 2006) using Non-Metric Multidimensional Scaling (NMMS). Changes in vegetation cover over the time series were related to a range of environmental variables including mean annual precipitation, mean annual temperature (MAT), Relative humidity (RH), solar radiation, frost, potential evapotranspiration (PET), mean annual net primary productivity (NPP), altitude and soil fertility index. Values for all the variables were obtained from the digitally-available South African Atlas of Climatology & Agrohydrology (Schulze *et al.* 2008).

4.4. Results

4.4.1. Rainfall and drought incidence

4.4.1.1. Annual Rainfall

Long-term annual rainfall did not change significantly at any of the Grassland sites nor at three of the four Nama-karoo sites in the 20th century (Fig. 4.2). Middelburg was the only site where annual rainfall has increased significantly over time. The years 1974, 1988 and 2006 reflect periods when annual rainfall was generally higher than normal at most sites while 1933 and 1969 were years of low rainfall at most localities.

4.4.1.2. Seasonal Rainfall

Monthly rainfall patterns appear broadly similar at all rainfall stations for the three time steps immediately preceding the surveys (1940-1962, 1963-1989, 1990-2009) (Fig. 4.3). The trend for several stations (e.g. Middelburg, Richmond, Hanover, Smithfield and Dewetsdorp) indicates that rainfall has increased in the last two decades in the early growing season period (Dec-Feb) when compared to the first two time steps while late growing season rainfall (Mar-May) has generally declined. Winter rain (Jun-Aug) was higher during the 1963-1989 period while spring rain (Sep-Nov) appears not to have changed over the course of the study period.

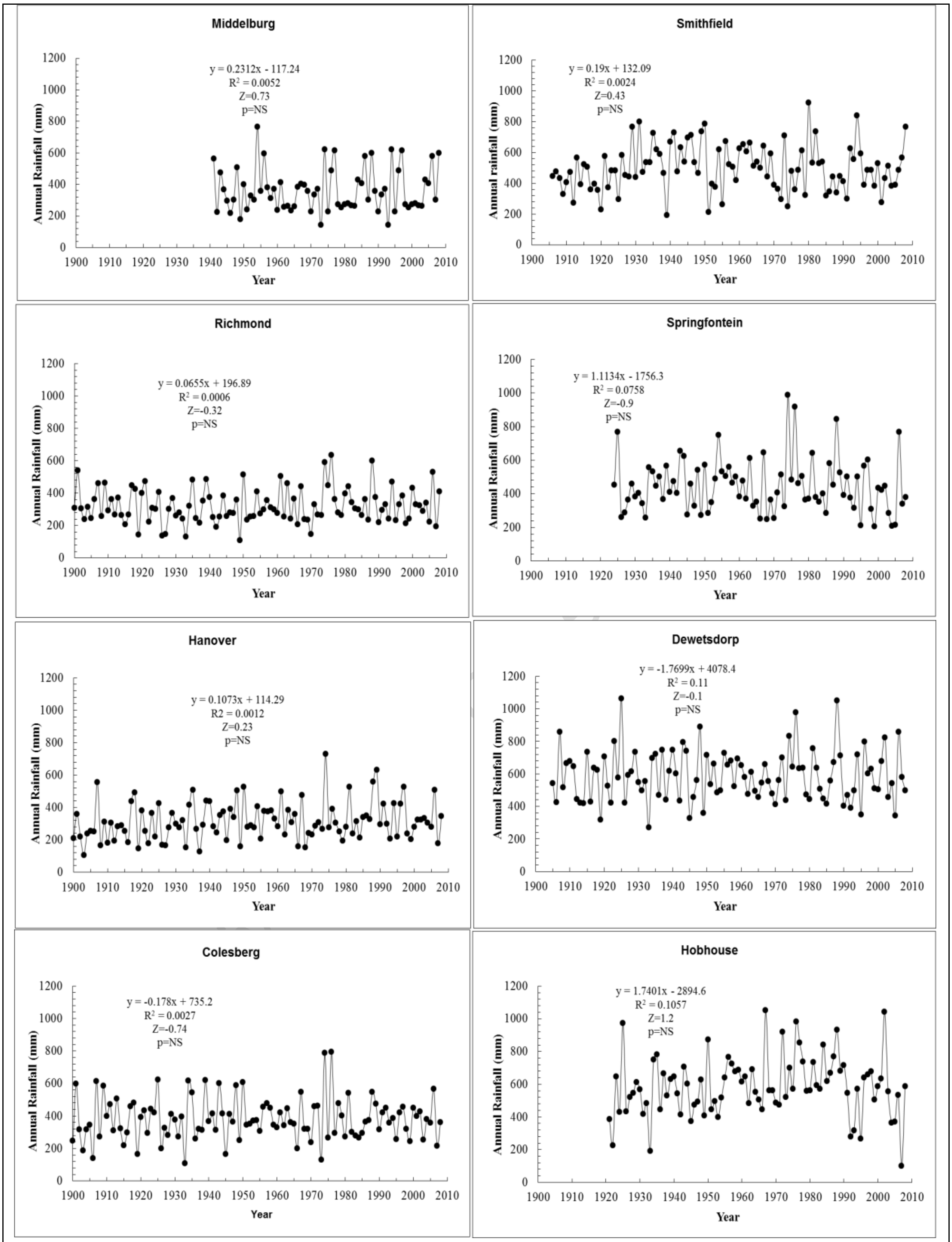


Figure 4.2: Changes in long-term annual rainfall (Oct-Sep) at four Nama-karoo biome sites (left) and four Grassland biome sites (right). The linear trend in the time series and significance of the slope estimate are also shown.

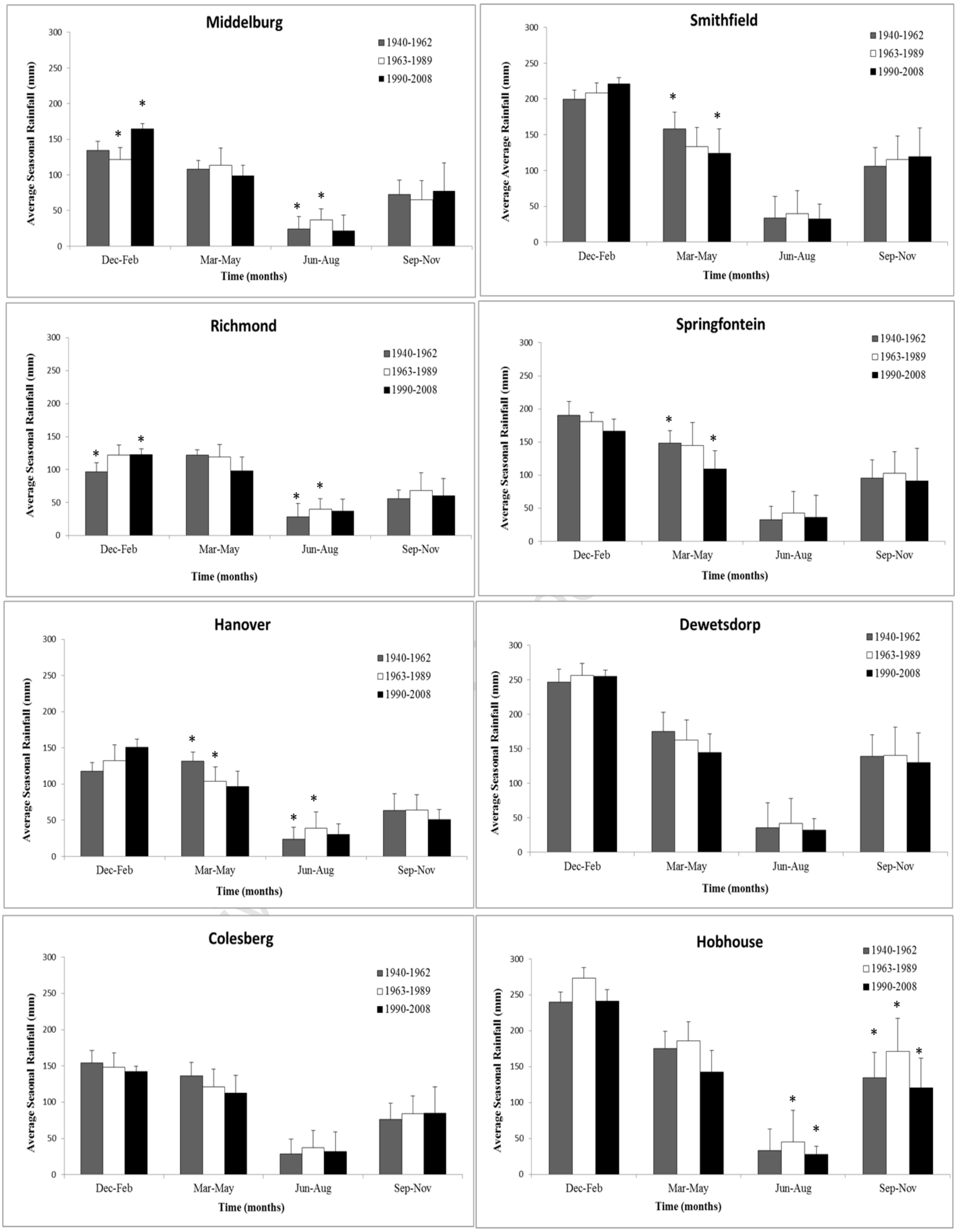


Figure 4.3: Average Seasonal rainfall values at four Nama-karoo biome sites (left) and four Grassland biome sites (right) over three time periods (1940-1962 (N=27), 1963-1989 (N=23), 1990-2009 (N=19)) corresponding to the two decades preceding the photographic and vegetation surveys at the study sites. * indicate time period significant from the other. Error bars represent standard deviation.

4.4.1.3. Standardised Precipitation Index (SPI)

Trends in SPI values for all rainfall stations in the Nama-karoo biome showed a significant increase in wetter conditions over time while there was no change in all Grassland biomes stations (Fig. 4.4). The periods between 1976-1978 and 1988-89 stand out at most stations as being years of extremely wet conditions. Severe drought conditions prevailed in the Nama-karoo biome in 1928 and 1969 while data from Grassland biome sites were more variable. For Springfontein and Hobhouse the first decade of the 21st century was one of the driest on record.

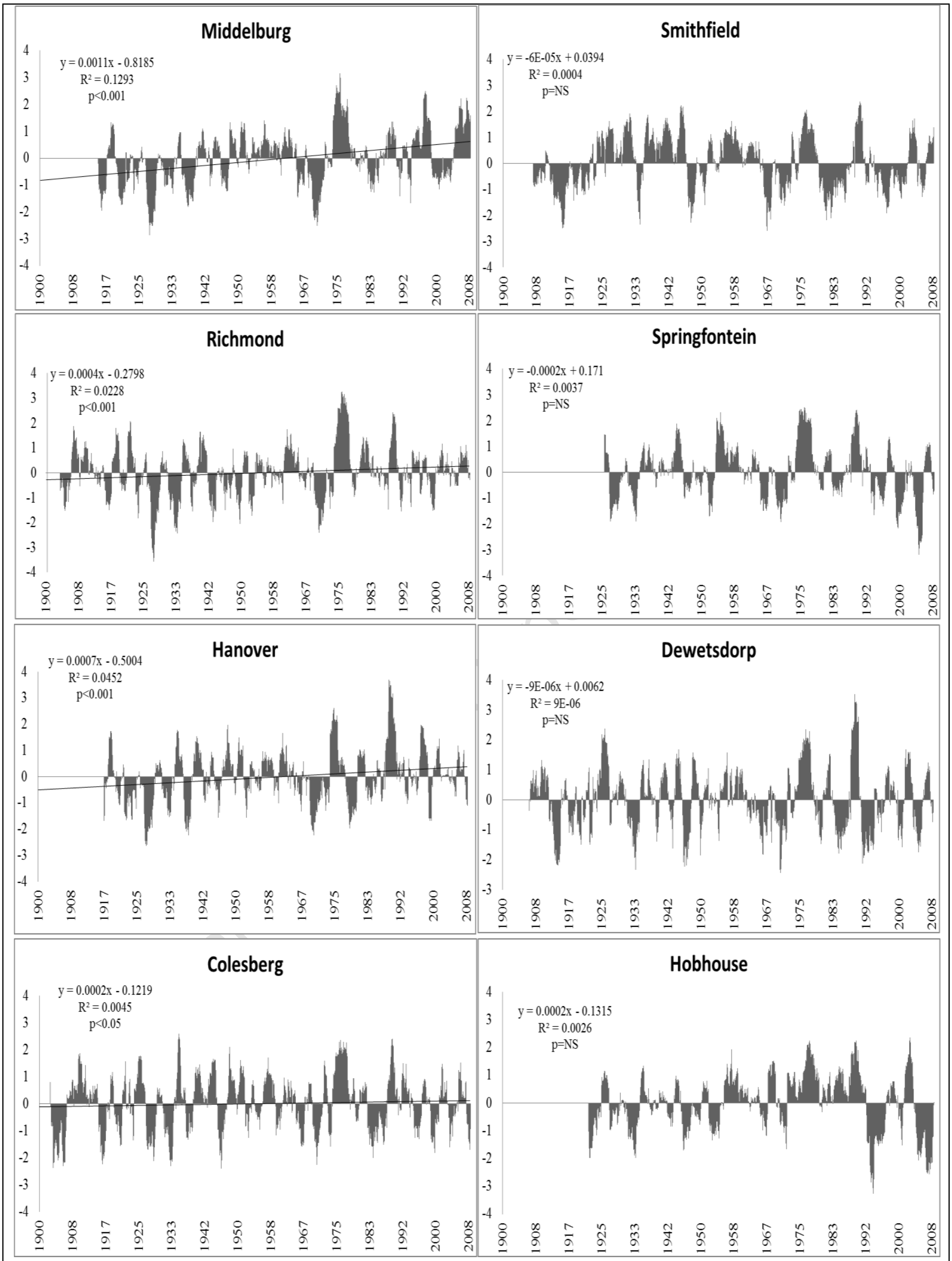


Figure 4.4: Standardised Precipitation Index (SPI) values for four Nama-karoo biome (left) and four Grassland biome rainfall stations (right). The linear trend in the time series and significance of the slope estimate are also shown.

4.4.2. Land use

Livestock data between 1911 and 1996 show that stocking rates declined in magisterial districts in both the Nama-karoo and Grassland biomes (Fig. 4.5). This suggests that land use impacts as a result of grazing animals have declined in both biomes (Dean & Milton 1994; Nel & Hill 2008).

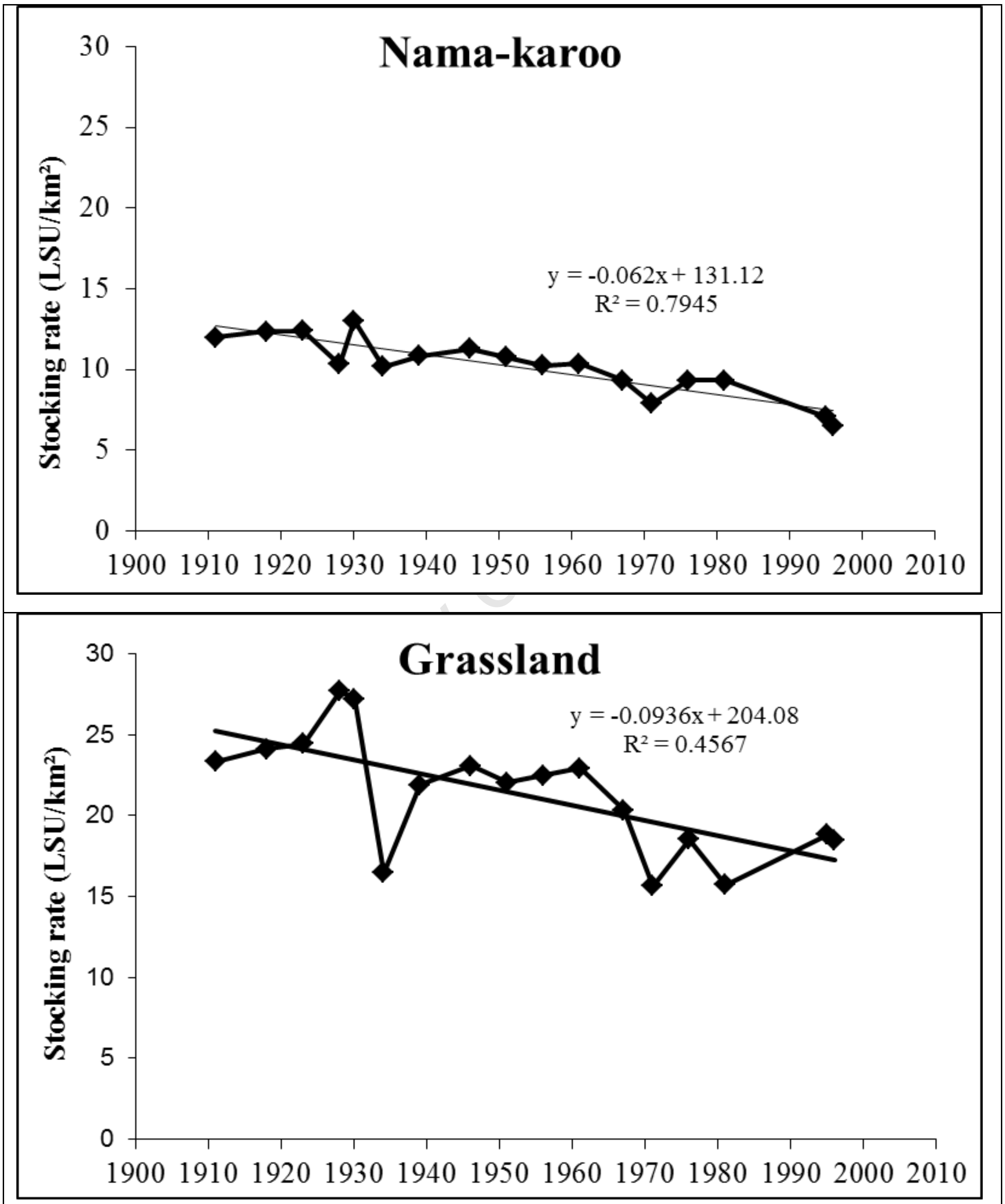


Figure 4.5: Average change in stocking rates within four magisterial districts within the Nama-karoo biome and four within the Grassland biome.

4.4.3. Vegetation Change

4.4.3.1. Nama-karoo biome sites

The change in species richness between 1961/2 and 1989 varied between the four Nama-karoo biome sites (Table 4.2). At all sites, however, species richness declined in 2009 to values below those first recorded in 1961/2. Total canopy cover increased between 1961/2 and 1989 but declined in 2009. The cover of forbs, geophytes and sedges was generally low at all sites for the three time periods except at Groenfontein in 1989 when forb cover was relatively high. Grass cover increased at all Nama-karoo sites between 1961/2 and 1989 and declined again in 2009 although not to the same relatively low levels measured at the start of the survey in 1961/2. At three of the four sites shrub cover declined while at all sites the shrub:grass ratio declined between the start and end of the survey period. At all sites in the Nama-karoo biome the Grazing Index Value (GIV) increased between 1961/2 and 1989 but declined again at three of the four sites in 2009.

Table 4.2: Changes in species richness, vegetation and growth form cover and the Grazing Index Value (GIV) at four Nama-karoo biome sites for the periods 1961/2, 1989 and 2009.

Parameters	**Beestekuil**			**Middelburg**			**Geelbeksfontein**			**Groenfontein**		
Date	Dec	Jan	Jan	Feb	Jan	Jan	Feb	Jan	Jan	Dec	Jan	Jan
	1962	1989	2009	1962	1989	2009	1962	1989	2009	1961	1989	2009
Number of points	1000	800	782	1000	550	578	1000	600	599	1000	1000	960
Total number of species	16	30	11	27	25	24	29	27	17	25	26	16
Canopy spread cover (%)	42	62	49	52	72	60	47	66	63	52	59	39
Growth form canopy spread cover (%)												
Forbs	2	2	0	0.5	3	0.4	1	5	0	3	14	0.3
Geophytes	0	0	0	0.1	0	0	0	0	0	0	0	0
Grasses	8	33	21	35	45	44	10	27	18	17	33	24
Sedges	0	0	0	0	0	0	0.4	0	0	3	0.2	1
Shrubs	32	28	28	17	24	16	36	35	45	29	12	13
Shrub:Grass	3.9	0.9	1.4	0.5	0.6	0.4	3.6	1.3	2.5	1.7	0.4	0.6
GIV	107	259	187	186	275	282	160	251	277	189	202	137

4.4.3.2. Grassland biome sites

Three of the four grassland biome sites showed an increase in species richness between 1961/2 and 1989 and all showed a decline in 2009 to values below those recorded in the first survey in 1961/2 (Table 4.3). Total canopy cover increased at three of the four sites between 1961/2 and 1989 but generally declined again in 2009.

The cover of forbs, geophytes and sedges was higher in grassland than in Nama-karoo biome sites but never dominated cover values. Grass cover increased at all grassland biome sites between 1961/2 and 1989 and declined again at three of the four sites in 2009 although usually not to the same relatively low levels measured at the start of the survey in 1961/2. At three of the four sites shrub cover as well as the shrub:grass ratio declined over the course of the survey period. At all grassland biome sites the Grazing Index Value (GIV) increased between 1961/2 and 1989 but declined again in 2009 usually to values above those recorded in 1961/2.

Table 4.3: Changes in species richness, vegetation and growth form cover and the Grazing Index Value (GIV) at four Grassland biome sites for the periods 1961/2, 1989 and 2009.

Parameters	**Hillside**			**Smithfield**			**Wepener**			**Dewetsdorp**		
Date	Feb	Jan	Jan	Feb	Jan	Jan	Feb	Jan	Jan	Feb	Jan	Jan
	1962	1989	2009	1962	1989	2009	1962	1989	2009	1962	1989	2009
Number of points	1000	600	587	1000	600	580	1000	600	595	1000	600	395
Total number of species	24	25	21	21	25	13	25	23	17	26	30	17
Canopy spread cover (%)	64	68	50	65	93	57	80	62	83	69	94	87
Growth form canopy spread cover (%)												
Forbs	2	0.4	0	0.4	2	0	0.2	1	0.5	1	2	3
Geophytes	0	0	0.2	0	0	0	1	0	0	0	0	0
Grasses	54	58	35	51	79	54	66	75	79	63	88	83
Sedges	0.2	0	0	1	3	0	0.2	1	1	0	0	0
Shrubs	10	9	14	14	9	3	13	3	3	5	4	2
Shrub:Grass	0.2	0.2	0.4	0.3	0.1	0.05	0.2	0.04	0.03	0.08	0.05	0.02
GIV	352	398	333	273	613	353	340	378	534	412	770	710

4.4.4. Trajectories of vegetation change

An NMMS ordination of the sites for the three study periods showed that Nama-karoo biome and Grassland biome sites have remained separate from each other over time (Fig. 4.6). Based on their distance in ordination space, Grassland biome sites appear more dissimilar in composition from Nama-karoo biome sites in 2009 than they were in 1961/2. There was no suggestion in the data that individual sites within the two biomes have converged on each other over the course of the study period. For the majority of sites, the difference in composition appeared more different between the period 1961/2 to 1989 than for the time step from 1989 to 2009.

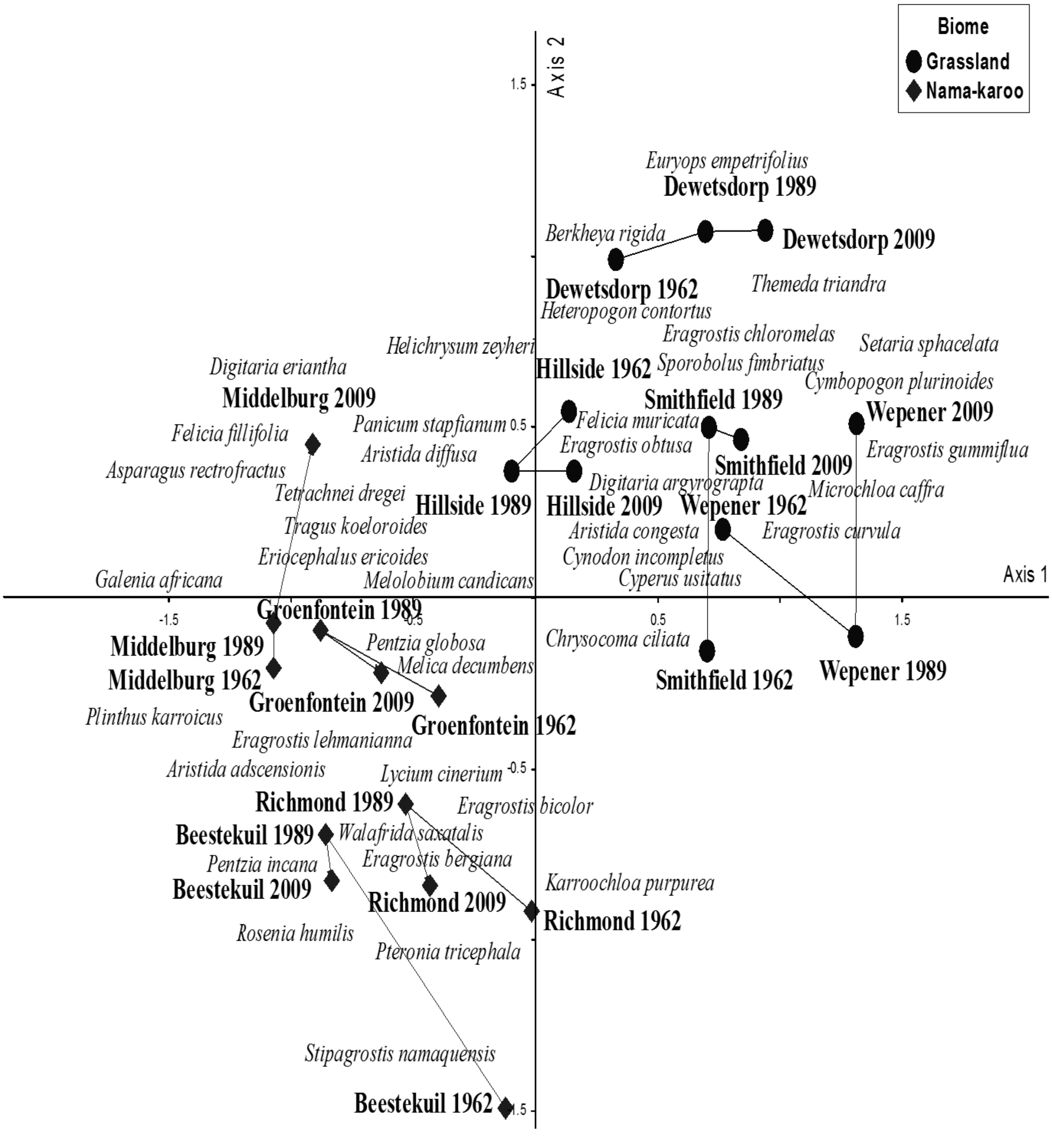


Figure 4.6: NMS ordination of the trajectories of change for species in four Nama-karoo biome and four Grassland biome sites over three time steps (1961/2, 1989 and 2009). The two axes explained 76% of the total variation in the dataset. A two-dimensional solution with a final stress value of 11.4 was recommended after 144 iterations (p=0.004).

An analysis of the relationship between the study sites and environmental variables showed that precipitation (tau_1=0.58, tau_2=0.66), solar radiation (tau_1=0.50, tau_2=0.71), mean annual net primary productivity (tau_1=0.58, tau_2=0.66) and the number of frost days (tau_1=0.52,

tau_2=0.61) had a strong positive relationship with both Axis 1 and Axis 2 (Fig. 4.7). Their association with Axis 2 and the Kendall tau scores, however, suggest that these variables were more strongly related to the Grassland biome sites (axis 2) than the Nama-karoo biome sites. Mean NPP is largely correlated with precipitation and was also higher for Grassland biome sites as compared to Nama-karoo biome sites. The latter, however, had a stronger negative relationship with potential evapotranspiration (PET) (tau_1=-0.72, tau_2=-0.26) and mean annual temperature (tau_1=-0.41, tau_2=-0.25) whereas relative humidity was positively correlated (tau_1=0.64, tau_2=0.32).

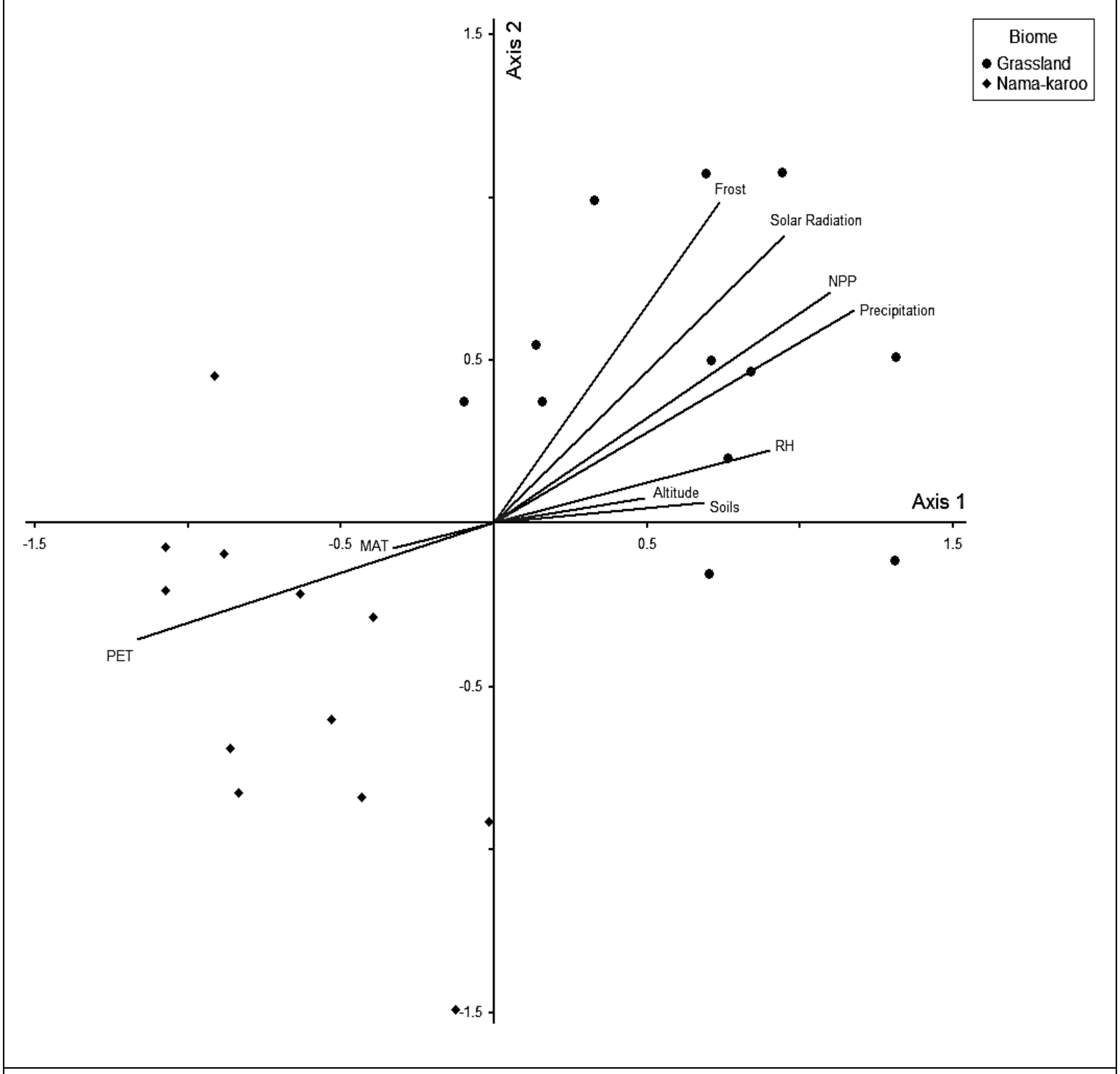


Figure 4.7: An NMMS ordination of the relationship between environmental variables and four Nama-karoo and four Grassland biome sites for the periods 1962, 1989 and 2009. The length of the line indicates the direction and strength of the correlations between the two NMS axes and the labelled variables.

4.4.4. Photographic evidence of change

A complete collection of all photographs in the time series for all sites is provided in Appendix 1. Two representative sites, one in the Nama-karoo biome and one in the Grassland biome are shown below to illustrate the major trends in each of the biomes, particularly with regard to changes in the abundance of grasses and shrubs over time.

Middelburg Commonage (Nama-karoo biome)

This set of three repeat photographs reflects changes within a wide colluvial valley of the Eastern Upper Karoo (NKu4) (Mucina & Rutherford 2006) over the periods 1962-1989 and 1989-2009 (Fig. 4.8). The west-facing site is located on state land at the edge of the town of Middelburg and has not been grazed over the course of the study period. Photographic evidence and survey data show that between 1962 and 1989 there was a substantial increase in cover of grasses such as *Eragrostis lehmanniana*, *Aristida adscensionis* and *Tetrachne dregei* which replaced *Pterothrix spinescens,* a spiny shrub with low forage potential. Other shrubs, with higher forage potential as determined by their Grazing Index Value, such as *Helichrysum lucilioides* and *Plinthus karooicus*, increased in cover between 1962 and 1989. Grass cover in 2009 appeared little different to that of 1989 although the dominant species had changed to *Aristida diffusa*, *Eragrostis lehmanniana* and *Tetrachne dregei*. Several new, relatively palatable grass species, such as *Heteropogon contortus* and *Digitaria eriantha*, were also present in 2009. Dominant shrubs in 2009 were *Pterothrix spinescens*, *Eriocephalus ericoides*, *Helichrysum lucilioides* and *Chrysocoma coma-aurea* which reflect a range of GIV values.

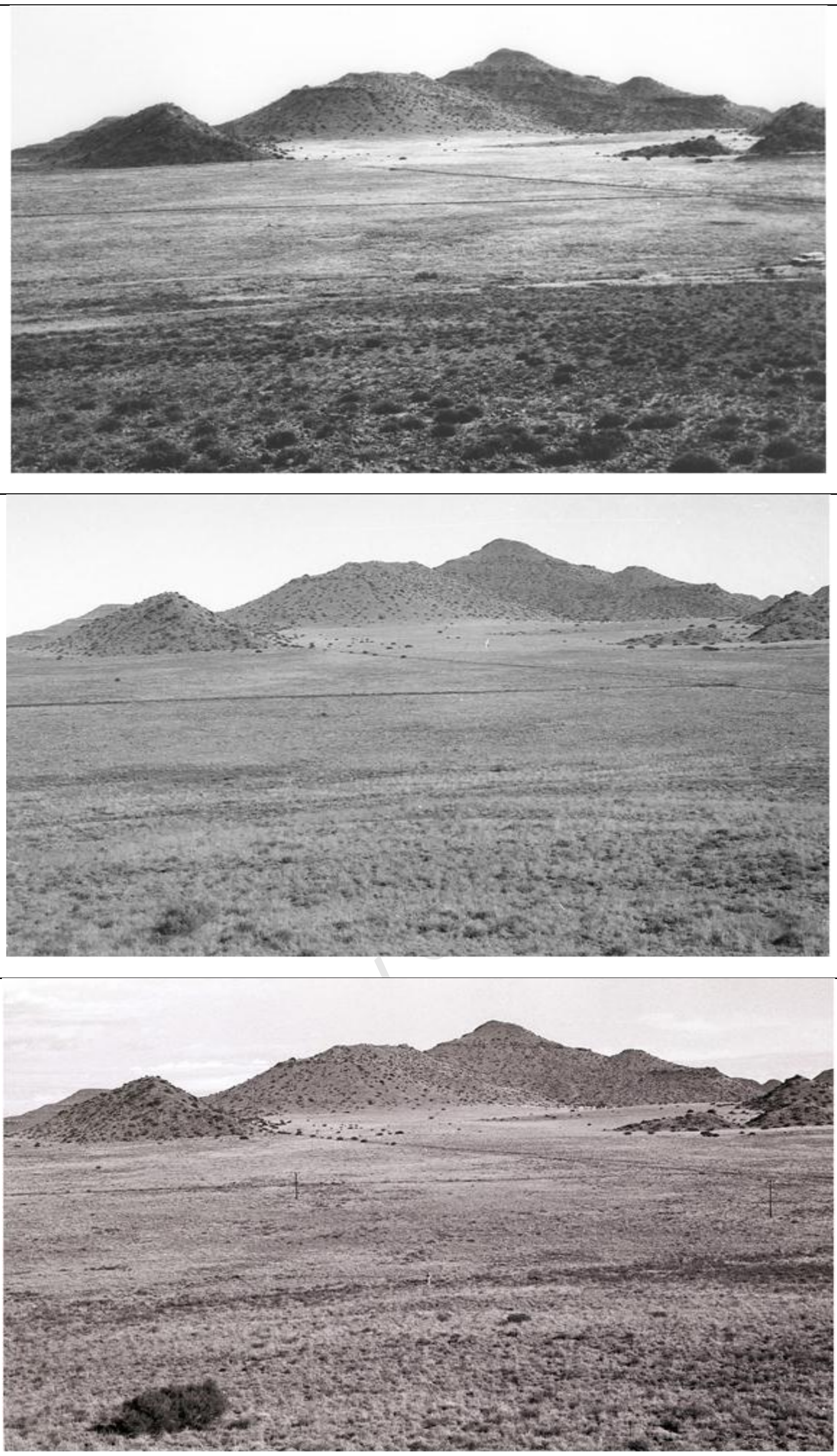


Figure 4.8: Middelburg Commonage as photographed in January 1962 (top), January 1989 (middle) and January 2009 (bottom). The photo station is located at S 31.2856.001, E 24.5941.022 at an altitude of 1300 m.

Wepener Commonage (Grassland biome)

This site is situated close to the town of Wepener and has been leased as grazing land to several different commercial farmers in the region over the course of the study period (Fig. 4.9). It is located on a gentle north-facing slope at the ecotone between the Dry Highveld Grassland (Gh2) and Mesic Highveld Grassland (Gm3) vegetation types (Mucina & Rutherford, 2006). The cover of shrubs was relatively high in 1962 and was comprised mostly of *Chrysocoma ciliata*, *Felicia muricata*, and *Helichrysum dregeanum*. By 1989 shrub cover had declined significantly and *Chrysocoma ciliata* had all but disappeared from the study site. In 2009, the dominant shrub was *Felicia muricata* and is barely evident in the repeat photograph since the presence of a dominant grass sward has hidden the lower-growing shrub species at the site. Changes in the grass sward are characterized by substantial shifts in the dominance of different species in different survey periods. For example, the dominant grass species in 1962 were *Eragrostis chloromelas* and *Setaria sphacelata* although *Cymbopogon plurinodis* and *Themeda triandra* were also present but at lower abundance values. In 1989 *Eragrostis curvula and Themeda triandra* dominated the survey site while in 2009 *Cymbopogon plurinodis* was dominant. Other grass species such as *Setaria sphacelata, Eragrostis curvula* and *Microchloa caffra* were also common in 2009 while *Eragrostis obtusa* was recorded at the site for the first time.

Figure 4.9: Wepener Commonage as photographed in February 1962 (top), January 1989 (middle) and January 2009 (bottom). The photo station is located at S 29.4425.78, E 27.0152.62 at an altitude of 1454 m.

4.5. Discussion

In this study I used long-term data derived from ecological surveys and repeat photographs to describe the major changes that have taken place in the region over the last 50 years. These changes in cover and composition are related to the major trends in historical climates and land use practices that have occurred over the course of the 20th and early 21st centuries. The historical trajectories in vegetation change are also assessed in terms of the future climate change scenarios that have been proposed for the Nama-karoo and Grassland biomes (Midgley *et al*. 2008). A focus on this broad ecotone between two distinct biomes is important as this area is perceived to be sensitive to environmental change, and changes due to global warming are likely to be evident first in the region. Furthermore, climatic conditions in the region are expected to change dramatically over the next 50-100 years with an increased frequency in drought conditions and significant impacts on biodiversity (Midgley & Thuiller 2011). Therefore, an assessment of climate, land use and vegetation change over the previous 50 years is important for assessing whether the predicted impacts are already being experienced in the region.

4.5.1. Changes in annual rainfall and the incidence of drought

An analysis of the long-term rainfall record suggests that annual totals have remained relatively consistent over the historical period in both the Nama-karoo and Grassland biome sites. This supports the findings of Nel (2009) for the high lying areas of the Grassland biome in KwaZulu Natal east of our study which recorded no significant change in annual rainfall. It also supports the findings from another recent study undertaken in the Succulent Karoo biome to the west of the Karoo Midlands which found no change in annual rainfall (Hoffman *et al*. 2009a). Overall there is a general agreement for the whole of southern Africa that there has been no significant change in annual rainfall over the course of the 20th century (Mason & Jury 1997; Kruger 2006; Kane 2009). However, some studies which have analysed trends in a few localised regions suggest that significant changes in rainfall have occurred. For example, Kruger (2006) suggests that there has been a significant increase in rainfall in the ecotonal region investigated in the current study.

Although annual rainfall has not changed, changes in the Standardized Precipitation Index (SPI) over time suggest that localities within the Nama-karoo biome have experienced a significant increase in wet periods while those within Grassland biome sites have remained unchanged. This clearly supports the notion that South African droughts occur at different intensities, spatial extents and durations (Roualt & Richard 2004). Most studies for different regions in South Africa suggest no significant change in the incidence of drought although there is some evidence that the incidence of wet periods appears to have increased since 1970 (Hoffman *et al*. 2009a; Roualt & Richard 2004; Ujeneva 2011; Warburton & Schulze 2005). Roualt & Richard (2004) argue that the most severe droughts occurred in 1983 and 1992 while results of the current study indicate that the droughts in 1945 and 1969 were most severe. A drying trend prior to the 1950's is supported by Hoffman *et al*. (2009a) for the western part of the country.

The analysis of seasonal rainfall points to an increase in early season rainfall in all Nama-karoo sites although this was not as pronounced for sites within the Grassland biome (see Figure 4.3). Although only significant for January, rainfall over the entire Dec-Jan period was greater between 1990-2009 than it was prior to 1990. Late summer rainfall has remained relatively unchanged throughout whereas winter (Jun-Aug) rainfall was slightly higher between 1963 and 1989. This supports the findings of du Toit (2010) who analysed data for Middelburg only and suggested that an increase in early season rainfall may be more widespread than previously indicated.

4.5.2. Land use change

The majority of rangelands in the study area are privately-owned and during most of the 20th century have been used primarily for the commercial production of sheep and cattle under extensive ranching conditions (Hoffman *et al*. 1999). Evidence from agricultural census records from four magisterial districts in the Nama-karoo biome and four in the Grassland biome show that stocking rates have declined by 45.2% in the former and by 30.2% in the latter biome between 1910 and 1996 when the last agricultural census took place. Dean *et al*. (1995) also suggest that stocking rates have declined more in arid areas than in mesic areas of the Karoo. This decline in stocking rate is supported by several other studies (Archer 2004; Dean & Macdonald 1994; Hoffman 1995; Hoffman *et al*. 1999) although explanations for the decline vary. Dean & Macdonald (1994) ascribe this decline in stocking rate to the loss of primary production and degradation of rangelands as shrub cover has increased. Hoffman *et al*. (1999), however, suggest that effective paddock development combined with the widespread practice of rotational grazing have been responsible. Nel & Hill (2008) suggests a decline of more than 60% in total numbers of sheep in the last 84 years in the

Karoo which he ascribes to a shift in farming objectives from commercial livestock production to game ranching in the last decade.

Changes in the palatability of the species within the rangelands investigated in the current study do not support the view that the decline in stocking rate has occurred because of a decline in productivity over time (Dean & Macdonald 1994). Instead the data point to a consistent increase from 1962-2009 in Decreaser and Increaser I species (Du Toit *et al*. 1995a) which are relatively productive and palatable to domestic livestock (e.g. *Aristida diffusa*, *Cymbopogon plurinodis*, *Heteropogon contortus*, *Tetrachnei dregei*, *Setaria sphacelata*, *Themeda triandra* and *Eragrostis curvula*). In addition there has been a decrease over the same period in less palatable Increaser II species such as *Stipagrostis namaquensis*, *Pterothrix spinescens*, *Eriocephalus spinescens*, *Pentzia incana*, *Walafrida saxatalis* and *Chrysocoma ciliata*. This suggests that rangelands within both the Nama-karoo and Grassland biomes have improved in both quality and production over time.

4.5.3. The dynamics of grasses and shrubs in response to rainfall and grazing

The results of the present study can be interpreted in terms of the general models available for the study area. For example, both Hoffman *et al*. (1990) and O'Connor & Roux (1995) show how seasonal rainfall affects the relative proportions of grasses and shrubs within the ecotone between the Nama-karoo and Grassland biomes. High summer rainfall favours an increase in grass cover while autumn and winter rains are thought to favour shrubs. Furthermore, Milton & Hoffman (1994) present a 'state-and-transition' model for the eastern Karoo in which both grazing and rainfall interact to influence the proportion of grasses and shrubs in an area over years or decades. Under this model, an equal mixture of grasses and shrubs in the landscape (State 1) can shift to a grass-dominated state (State 2) either by an increase in above-average summer rainfall combined with very minimal grazing or resting. However, a shift from State 1 to a shrub-dominated condition (State 3) can also occur under continuous summer drought and above-average winter rainfall together with summer grazing at recommended or higher stocking rates. Conversely, above-average summer rainfall with winter drought and rotational grazing at recommended stocking rates could return vegetation in State 3 back to State 1. Other vegetation states (4, 5 and 6) reflect a drop down the degradation gradient with a concomitant loss in grasses, palatable shrubs and perennial cover and an increase in erosion.

The results from the current study validate Milton & Hoffman’s (1994) state-and-transition model. However, unlike many other such models which have limited data and are based on a combination of informal historical observations, expert knowledge and space-for-time substitution (Bestelmeyer *et al*. 2006; 2009; Briske *et al*. 2003) this study has been better able to consider the full complexity of scale as well as temporal and spatial heterogeneity. The results from this study suggest that most of the Nama-karoo biome sites, although relatively patchy across the landscape, can be characterised as being in State 1, having recovered from State 2 and even State 3 in some cases. Most of the Grassland biome sites are now dominated by perennial grasses and could also be considered to be in State 1.

Long-term survey data together with photographic analyses suggest that Nama-karoo biome sites have recovered over time. This finding is similar to the individualistic model proposed by Peters (2002) for New Mexico shrublands. The improved cover and composition within Nama-karoo biome sites since the 1960s should result in greater moisture retention and less run-off relative to their shrub-dominated earlier condition. This should enable grasses to continue to dominate if rainfall and stocking rate conditions remain the same. Furthermore, if fires were to increase in frequency in the Nama-karoo then grasses would become even more dominant in the landscape than they are at present. While changes in rainfall and land use over the last several decades are probably responsible for vegetation changes in the study area, the direction of change is in the opposite direction to that espoused by both Acocks (1953) and Midgley *et al*. (2008).

4.5.4. Is there evidence that the Nama-karoo biome is expanding as a result of overgrazing or that the Grassland biome is contracting as a result of aridification?

Ecotones between distinct grass-dominated and shrub-dominated ecosystems occur in many parts of the world in both the northern (Munoz-Reinoso 2009; Peters 2002; Schlesinger *et al*. 1990) and southern hemispheres (Archer 2010; Hoffman & Cowling 1990b). The majority of such ecotone studies suggest that shrubs have either expanded or will expand in the future as a result of heavy grazing pressure as well as changes in climate (Betancourt 1996; Brown *et al*. 2001; Desmond & Montoya 2006; Gibbens *et al.* 2005; Midgley *et al.* 2008; Neimejer *et al.* 2005; Peters *et al.* 2006; Schlesinger *et al*. 1990; van Auken 2000; Yanoff & Muldavin 2008). In only a few cases has evidence been presented of an increase in native grass species over time (Cramer *et al.* 2001; Fischlin *et al.* 2007; Hoffman & Cowling 1990b; Peters 2002).

The present study addressed two key hypotheses. In the first instance the study updates previous work which investigated the Acocksian hypothesis of an expanded Nama-karoo as a result of overgrazing and land cover change (Hoffman & Cowling 1990b). In the second, it explores the somewhat related and more recent hypothesis which suggests that because of future aridification in the region as a result of anthropogenically-induced climate change, karroid shrubs will expand in future into a significantly contracted Grassland biome (Ellery *et al*. 1996, Midgley *et al.* 2008).

In terms of these hypotheses the results of the present study provide evidence of a general improvement in the vegetation throughout the study area. Grass cover has increased in both the Nama-karoo and the Grassland biome sites even though there were no significant differences in rainfall in the periods immediately preceding the sampling periods. These findings support those of Hoffman & Cowling (1990b) who analysed the same sites but over a shorter time period and showed a similar trend in shrub and grass cover in response to a decline in stocking rates. The analysis from the current study, however, further suggests that the increase in grass cover might also be related to both an increase in wet periods as well as a shift in rainfall seasonality as suggested by Du Toit (2010a).

Acocks findings were based on the assumptions that most farmers in the region had overgrazed their land in order to achieve maximum animal production and that karoo shrubs increased with overgrazing. He predicted that if this situation of high stocking rates was to continue unabated, the land would become more degraded with karroid shrubs favoured under heavy grazing impacts. The substantial role of overgrazing in promoting shrub encroachment between the 1800’s to the late 1900’s is well recognized in many shrubland-grassland ecotones around the world (King *et al*. 2008; Peters *et al.* 2006; Yanoff & Muldavin 2008). Ironically, however, it was probably Acocks’s dire warning of future desertification which raised awareness of the impact of overgrazing and resulted in a reduction in stock numbers in the region. His study appears to have been crucial in reversing the desertification trends over much of the semi-arid regions of South Africa at the time (Hoffman & Ashwell 2001).

The second hypothesis of aridification due to climate change suggests that increases in the frequency of drought and an increase in evaporative demand under significantly higher temperatures will result in the contraction of C_4 grass cover and an increase in C_3 shrubs (Ellery *et al*. 1996, Midgley *et al.* 2008). Although output from most GCMs support this view, recent FACE experiments in the USA mixed prairie (Morgan *et. al*. 2011) and output from an adaptive Dynamic Global Vegetation Model (aDGVM) (Higgins & Scheiter 2012) suggest that C_4 grasses might benefit more from temperature and CO_2 increase than previously expected. There is some evidence also that soil moisture content might be improved under higher CO_2 conditions. The results of the survey presented here support the view that an increase in CO_2 might benefit C_4 grasses. There is little evidence as yet that C_3 shrubs have been favoured under higher CO_2 concentrations. Unravelling the effects of changes in rainfall seasonality, land use and CO_2 enrichment, however, are difficult and require further observation as well as experimental work.

Chapter 5: Vegetation change over the last 100 years in the major biomes of the semi-arid Karoo Midlands, South Africa, in response to land use and climate

5.1. Introduction

The distribution of vegetation in a landscape is influenced by a range of factors including climate, geology, soils, local drainage patterns and land use (Adams 2011). Together, climate change and land use represent two major intertwined forces of human-induced global change (Dale *et al*. 2011) that can have a significant influence on vegetation and its distribution. Such fundamental changes may also modify the characteristics of regional atmospheric circulation patterns and cause large-scale external moisture fluxes which in turn may affect soil properties, productivity and decomposition processes (Savikumar 2007).

There is evidence to suggest that changes in climate and land use are already having a significant effect on the composition and biodiversity of terrestrial and marine ecosystems in southern Africa (Chown 2010). For example, a recent increase in woody biomass has been reported in both mesic and semi-arid savannas of southern Africa (Rohde & Hoffman 2012; Scheiter & Higgins 2009; Wigley *et al.* 2010). This has been ascribed here, and in other parts of the world where it has been observed, to an increase in temperature (Roush *et al*. 2007), an increase in atmospheric CO_2 concentration (Bond 2008; Morgan *et al*. 2007), and a change in land use practices, particularly cultivation and fire (Ellis 2011; Ellis *et al.* 2010; Turner *et al*. 2007; Wigley *et al*. 2009). There is a further expectation in southern Africa that woody plants will spread into higher-altitude grassland environments where they would previously have been limited by lower nutrients, lower temperatures and more frequent fires (Acocks 1953; Bond 2008; Midgley & Thuiller 2011; Wakeling *et al*. 2010, 2011, 2012).

Biome shifts, however, can occur in a range of different directions depending on climatic conditions, land use change as well as on historical contingencies. For example, Shiponeni (2007) observed a directional change over 25 years in plant growth forms in the ecotone between the Succulent Karoo and Nama-karoo biomes in the western part of South Africa. She reported an increase in grassiness and a decline in shrub cover over time which she attributed to the strong competitive ability of grasses, particularly under conditions of reduced grazing pressure. This is surprising as future projections for the area under increased aridity and higher CO_2 conditions suggest that the switch will be from grassy (C_4-dominated) to woody (C_3-dominated) vegetation (Midgley *et al.* 2008).

Historical trajectories of vegetation change in other parts of the Succulent Karoo and Nama-karoo biomes (Hoffman & Rohde 2007, 2011; Rohde & Hoffman 2012) also do not corroborate projected future trends in the distribution and relative abundance of key growth forms in the region (Midgley *et al.* 2008). Evidence from repeat historical photography suggests that rangelands in the Succulent Karoo and Nama-karoo biomes have either changed very little over the 20th century in terms of both growth form composition and vegetation cover or they have increased in cover and in some cases even undergone a complete shift from shrublands to grasslands over the last 50 years. Rohde & Hoffman (2008) emphasise the importance of understanding the social and historical context of change particularly as it affects land use practices such as cultivation, stocking rates and management regimes.

The Nama-karoo and Grassland biomes of the eastern part of South Africa are important for small stock production and ecotourism and have undergone significant changes in land use in the recent past (Archer 2004; Nel & Hill 2008; Smith & Wilson 2002). Such large-scale changes in land use, together with changes in climate and atmospheric CO_2 concentration projected for the future will likely influence vegetation structure and composition as well as the distribution of biomes in the region. A gain in woody plant cover at the expense of grasses is expected in response to an increase in aridification and drought conditions associated with an increase in temperature and a decline in rainfall (Midgley & Thuiller 2011).

The direction and nature of vegetation change anticipated for these rangelands under most future climate change scenarios (Midgley *et al.* 2008) is similar to the position espoused by Acocks in 1953 although a different mechanism for this change has been suggested. While Acocks (1953) argued that land use was the most important driver of vegetation change in the region, projections derived from climate models (Midgley & Thuiller 2007; Midgley *et al.* 2008) suggest that if the trends in key climate variables (particularly rainfall and temperature) occur as predicted, then by 2050 the biomes of South Africa will have undergone rapid and unprecedented transformation. Under these climate change scenarios, the Nama-karoo and Grassland biomes are predicted to undergo range contractions to core habitat areas within the more mesic bioclimatic regions which characterise these two biomes today. Shrublands should therefore expand under these conditions and come to dominate former grassy habitats.

Knowledge of the past is important, not only for providing insights into the nature, rate and extent of past change, but also for testing model projections (Costanza *et al*. 2007, 2012; Hendrick & Copenheaver 2009). Clearly both climate and land use are important in the southern Africa context but it is difficult, for several reasons, to separate the role that each plays in influencing this change. Firstly, climate is intrinsically variable, especially inter-annual rainfall, so it is difficult to detect the climate change signal against a ‘noisy’ background. Secondly, land use practices can have major impacts on vegetation, especially in more arid regions such as most of South Africa. While this suggests that much could be done to manage land to reduce the impacts of climate change, its interaction with climate, is still poorly understood. Land use might well supersede the global change impact in altering the vegetation in the future particularly at local spatial scales and in the short term.

In this study, long-term changes in the vegetation of the Karoo Midlands are assessed in terms of the nature, extent and direction of change. Evidence for the expansion of single species as opposed to groups of species or even whole communities is also evaluated. Shifts in biome boundaries, species distributions and local area extinctions should provide powerful arguments for policy makers and conservation planners, particularly if the cause and influence of the change is isolated. This is important for conservation managers such as those within the South African National Parks (SANParks) service since the study area is at the interface between several biomes, including the Nama-karoo, Grassland and Albany Thicket biomes and straddles the putative Camdeboo-Mountain Zebra Mega Reserve.

The main objectives of this chapter are (1) To determine the nature, extent and rate of change in the cover of the major growth forms within biomes of the Karoo Midlands region over the course of the 20th century; (2) to investigate these changes within the major landform units of the region (e.g. slopes, plains and ephemeral or perennial rivers); (3) To assess the role of key drivers such as climate and land use in influencing these changes.

5.2. Study Area

A combination of approaches incorporating analyses of historical climate and land use data and repeat photography was used to assess changes in the vegetation in the central interior of South Africa. This region, which is also called the Karoo Midlands, encompasses a variety of landforms dominated by three main biomes and several different vegetation types (Mucina & Rutherford 2006) (Figure 5.1). The Nama-karoo biome is dominant on the plains in the central and western part of the Karoo Midlands. The Grassland biome occurs on both plains and hillslopes in the eastern and northern parts of the study area. The Albany Thicket biome occurs primarily on the slopes and narrow valleys in the south east. Azonal vegetation is common along the main perennial and ephemeral rivers in the region and around dams. A comprehensive outline of the study area is provided in chapter 2.

5.3. Method and Materials

5.3.1. Climate

An analysis of long-term changes in rainfall (including the incidence of drought), temperature and evaporation for the Karoo Midlands is detailed in Chapter 2. Findings from this analysis are used to explain some of the growth form changes observed in the repeat photographs examined here. In addition, location-specific climate variables (mean annual rainfall, mean annual temperature and mean annual potential evapotranspiration) were derived from BIOCLIM (Hijmans *et al*. 2005) for each photographic location. These values were also related to changes in different growth forms.

5.2.2. Land use

The number of domestic livestock (cattle, sheep and goats) censused over the period 1911-1996 within magisterial districts of the study area was obtained from the Agricultural Census Records (the so-called “Blue Books”) produced by the Department of Agriculture. The semi-regular census records exist in an unpublished database held by the Plant Conservation Unit. No national agricultural censuses have been published since 1996 and more recent data are therefore not available. The total number of cattle, sheep and goats recorded each year in a magisterial district was converted to a Large Stock Unit (LSU) value by using the conversion tables in Meissner *et al*. (1983). LSU values were summed for a magisterial district and stocking densities calculated by dividing the LSU value by the total area of each magisterial district. Data from six magisterial districts (Richmond, Hanover, Philipstown, Colesberg, Hofmeyr and Middelburg) which occurred predominantly in the Nama-karoo biome were grouped to provide a summary for the biome. Eleven magisterial districts (Bedford, Bethulie, Dewetsdorp, Edenburg, Fauresmith, Molteno, Philippolis, Smithfield, Steynsburg, Tarkastad and Wepener) comprised the Grassland biome data set while six (Cradock, Graaff-Reinet, Jansenville, Pearston, Somerset East and Steytlerville) occurred predominantly in the Albany Thicket biome.

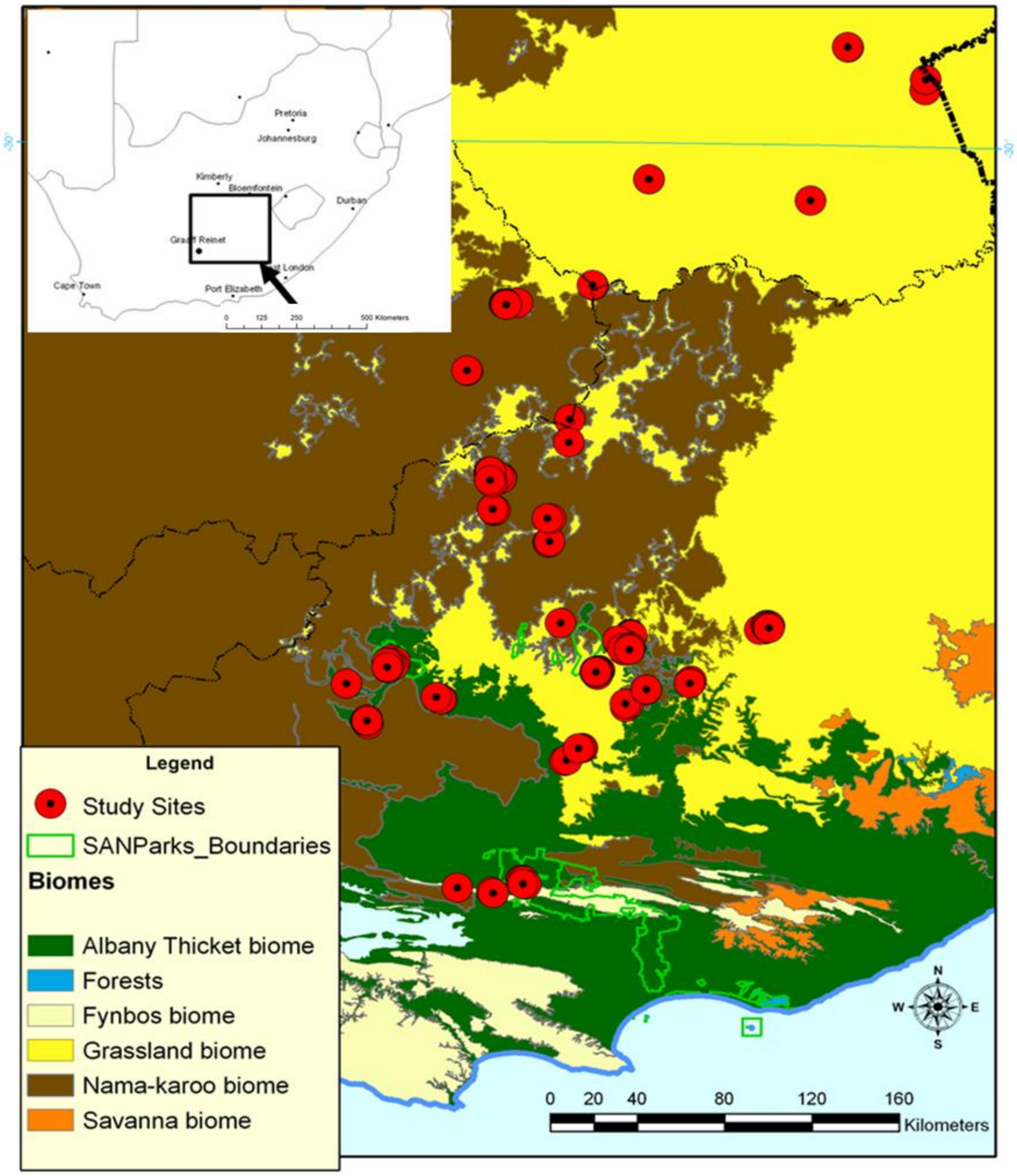


Figure 5.1: The location of the repeat photographs utilized in the study of the Karoo Midlands region. Inset: Location of the study area in South Africa.

5.3.3. Photography

Historical landscape photos of the Karoo Midlands were sourced from the Plant Conservation Unit's photographic data base, relocated and re-photographed between January 2009 and October 2010. Major historical photographic collections used in this analysis included those of Lidbetter from 1899-1902 of the Cradock region as well as Hexton's Boer war photograph collection taken around the same period in the Colesberg region. Roux's collection of photographs of the southern Free State grasslands and the Nama-karoo shrublands, which were analysed in Chapter 4, were also used in this chapter. Most of the photographs, however, came from John Acocks' collection of images which covered the period 1940-1970 and were widespread across the Karoo Midlands (Figure 5.2).

The general approach described by Rohde (1997) for taking repeat photographs was used in this analysis (see Chapter 4). At each photographic location the camera position was relocated as close to the original site as possible and a new photograph taken. The GPS co-ordinates of the camera station were recorded as well as the altitude, date and time of the repeat photograph. In addition, a sketch of the location was drawn and several additional notes completed on site including the source and date of original photo, veld type and vegetation type, soil type, geological features, landscape description and notes on major changes. Three cameras were used when taking the repeat images and are detailed in Chapter 4. A photographic information data sheet was used to record the details of each repeat image and included information on camera make, film type, focal length, f-stop, shutter speed and exact time at which the image was taken. This information has been archived in the repeat photograph database maintained by the Plant Conservation Unit at the University of Cape Town. Upon return from the field one image was selected and an exact match of the original image was obtained using Photoshop CS 4 (Adobe Systems 2008).

5.3.4. Data Analysis

A total of 63 matched photograph pairs obtained from the three main biomes as well as Azonal vegetation in the Karoo Midlands region was used in this analysis (Figure 5.3). With the aid of notes compiled in the field each image was divided into one of three landform units, namely slopes, plains or rivers. In some images only one landform unit was present while in others all three could be identified. A total of 130 landform units were recorded in the 63 photograph pairs. Next, the percentage cover of grasses, dwarf shrubs (<1 m), tall shrubs (>1 m), tall succulent shrubs (mostly *Portulacaria afra*, *Aloe* spp. and *Euphorbia* spp.) and alien plants was estimated within each landform unit for each time step. The change in cover for each growth form in each landform unit was then calculated. In order to compare the rate of change between photographs of different ages the change in cover was relativized by dividing the difference in cover between the two time steps by the number of years between photographs to derive an annual rate of change in cover for each growth form. This was then multiplied by 10 in order to derive the % change in cover per decade. This value was then correlated with the BIOCLIM climate variables obtained for each site using JUMP version 5.01 statistical software (Sall *et al*. 2005).

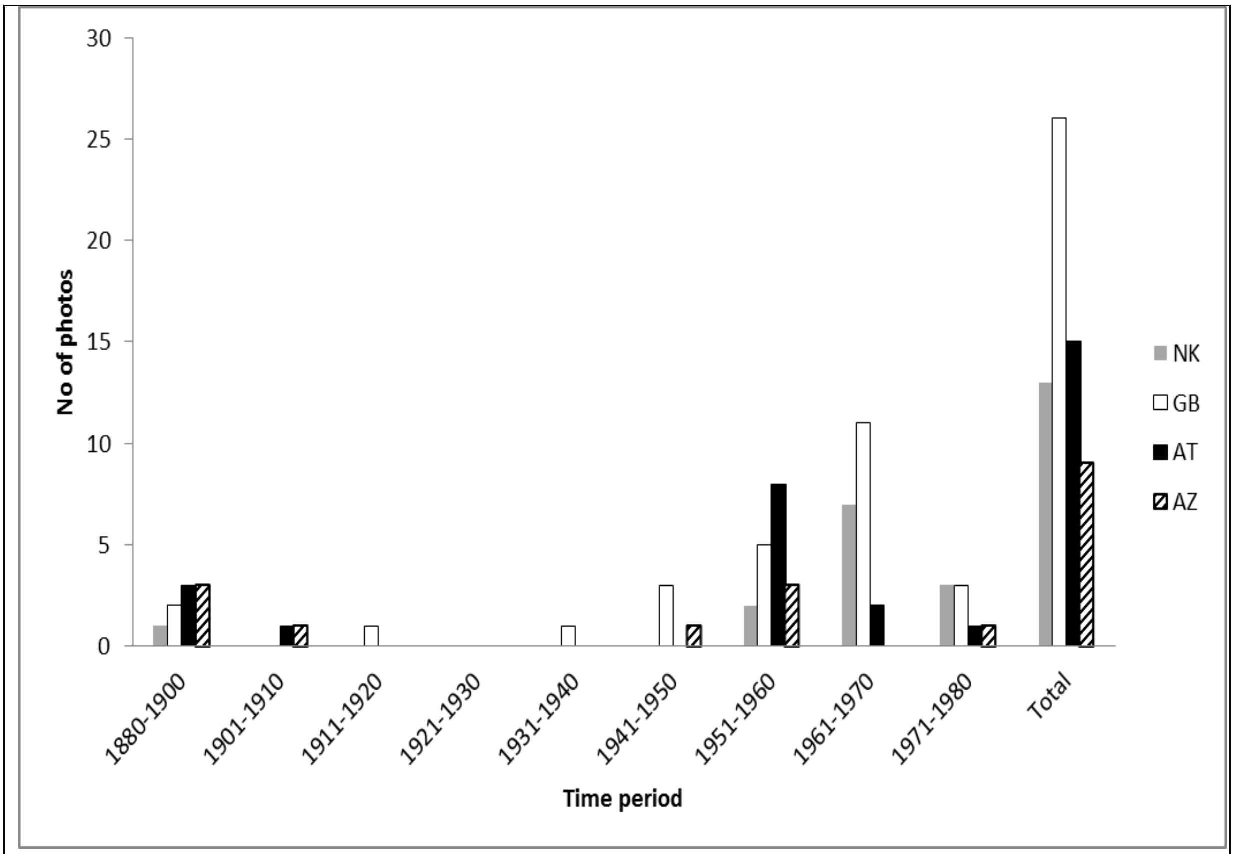


Figure 5.2: The number of historical photographs in the three biomes (Nama-karoo (NK), Grassland (GB), Albany Thicket (AT)) and Azonal vegetation (AZ) of the Karoo Midlands region grouped according to the decade in which they were originally taken. N=63.

5.4. Results

5.4.1. Decadal change in the cover of growth forms within the biomes of the Karoo Midlands

5.4.1.1. Grassland biome

While there was considerable variation between sites, grass cover increased on average by more than 3% per decade in the Grassland biome (Figure 5.3). The cover of dwarf shrubs declined by more than 3% per decade, while the cover of tall shrubs increased by about 2% per decade. Total cover increased by a similar amount (2% per decade) in this biome. Average cover values for the three growth forms differed between slopes and plains. However, these differences were not significant because of the high variation in cover change that existed between sites. Examples of the changes evident on the plains and slopes within most Grassland biome sites are shown in the matched photograph pairs of Figures 5.4 and 5.5 respectively.

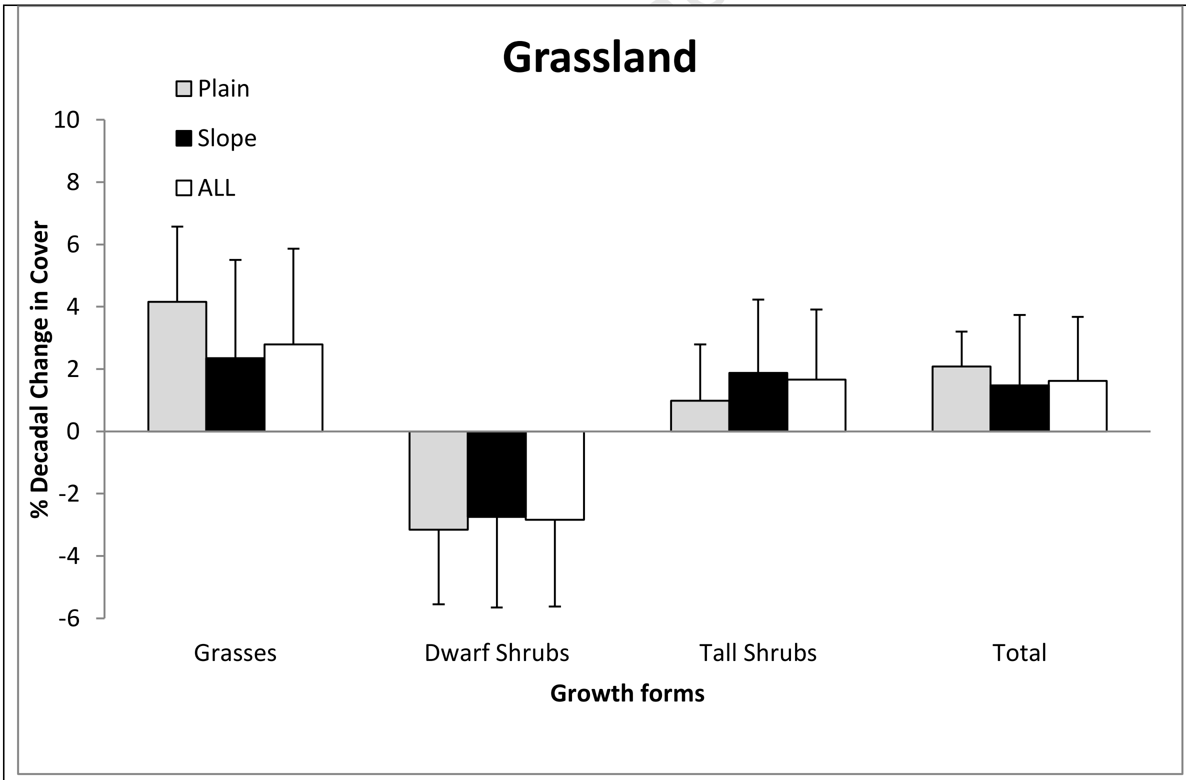


Figure 5.3: Percentage decadal change in cover (error bars are SD) of the main growth forms in the Grassland biome and as well as on slopes versus plains landforms in the biome. N=14 for plains, 43 for slopes and 43 for all.

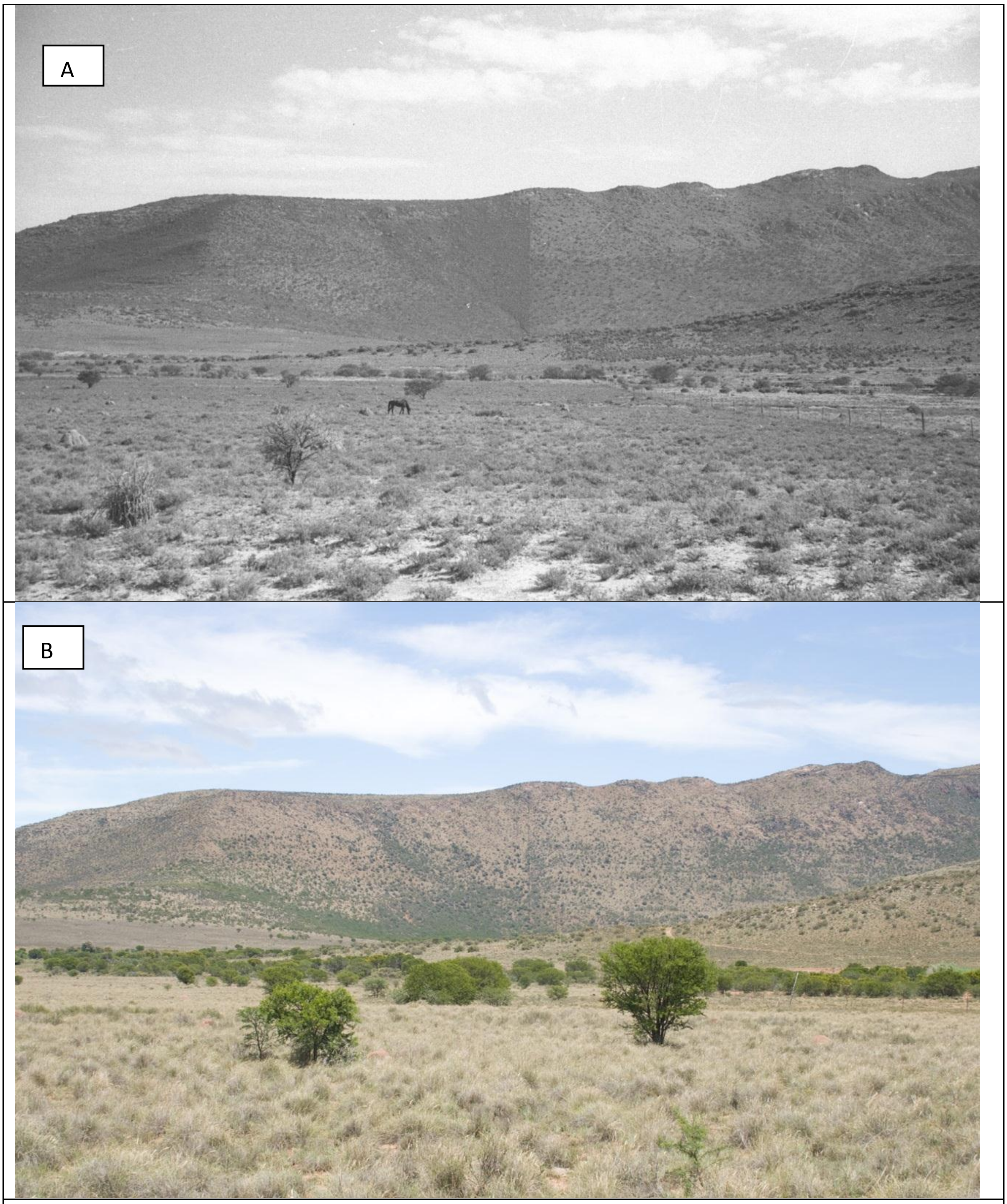


Figure 5.4: 541 Oudekraal
Location: S 32.10460, E 26.31957. Altitude (m): 1373
Original: A. 23 July 1946, J.P.H. Acocks
Repeat: B. 13 December 2009

The most significant change on the plains of the Grassland biome site shown in Figure 5.4 has been the replacement of karoo shrubs such as *Pentzia incana*, *Walafrida saxatalis*, *Eriocephalus ericoides* and *Felicia filifolia* by the long-lived, perennial C_3 grass, *Merxmuellera disticha*. There was very little grass cover evident in 1946 while the 2009 image, together with field survey data, suggests that *M. disticha* has a cover of 50%. Another significant change at this site has been the increase of *Acacia karroo* in the foreground plains. This expansion has been greatest in the drainage line in the middle distance.

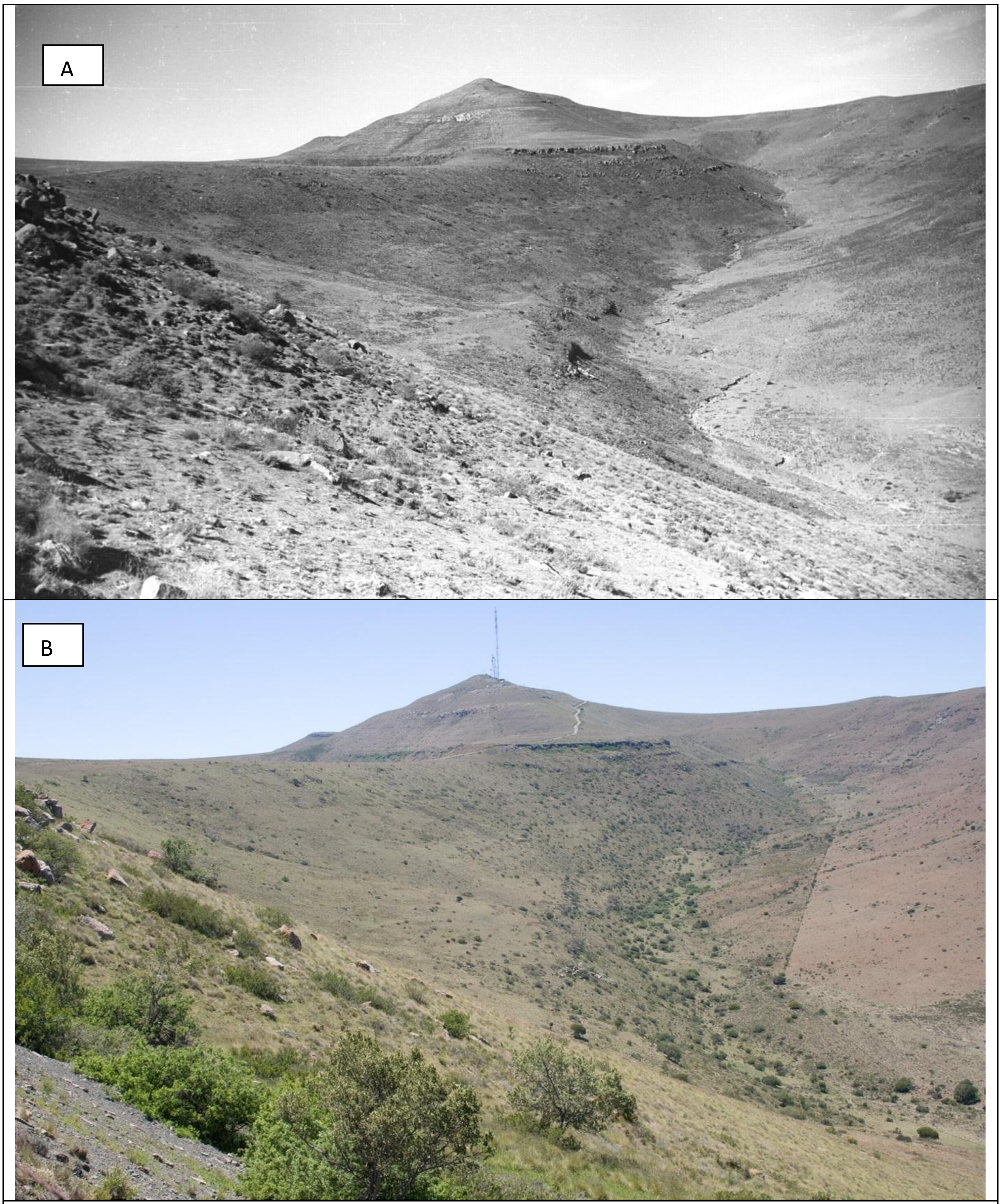


Figure 5.5: 536 Swaershoek 1
Location: S 32.29184, E 25.51054. Altitude (m): 1591
Original: A. 8 May 1953, J.P.H. Acocks
Repeat: B. 10 December 2009

An important change on the slopes of Grassland biome sites has been the increase in larger shrub and tree elements as well as an increase in grassiness at the expense of dwarf shrubs. Such changes are clearly seen the left foreground of Figure 5.5. Dwarf shrub elements that have declined include species such as *Chrysocoma ciliata*, *Felicia filifolia*, *Eriocephalus ericoides*, *Melolobium candicans* and *Walafrida saxatalis*. These species have generally been replaced by *Merxmuellera disticha* which now comprises almost 60% of the cover on the slope. Examples of tall shrubs that have increased in cover include *Searsia lucida*, *S. erosa* and *Diospyros austro-africana*.

5.4.1.2. Nama-karoo biome

This biome occurs predominantly on the plains of the Karoo Midlands region as the slopes generally support vegetation types with affinities either to the Grassland biome or Albany Thicket biome. Figure 5.6 shows that within the plains landform of the Nama-karoo biome grass cover (+4.5% per decade), tall shrub cover (+0.5% per decade) as well as total cover (+4% per decade) has increased over time while dwarf shrub cover (-1.5% per decade) has declined.

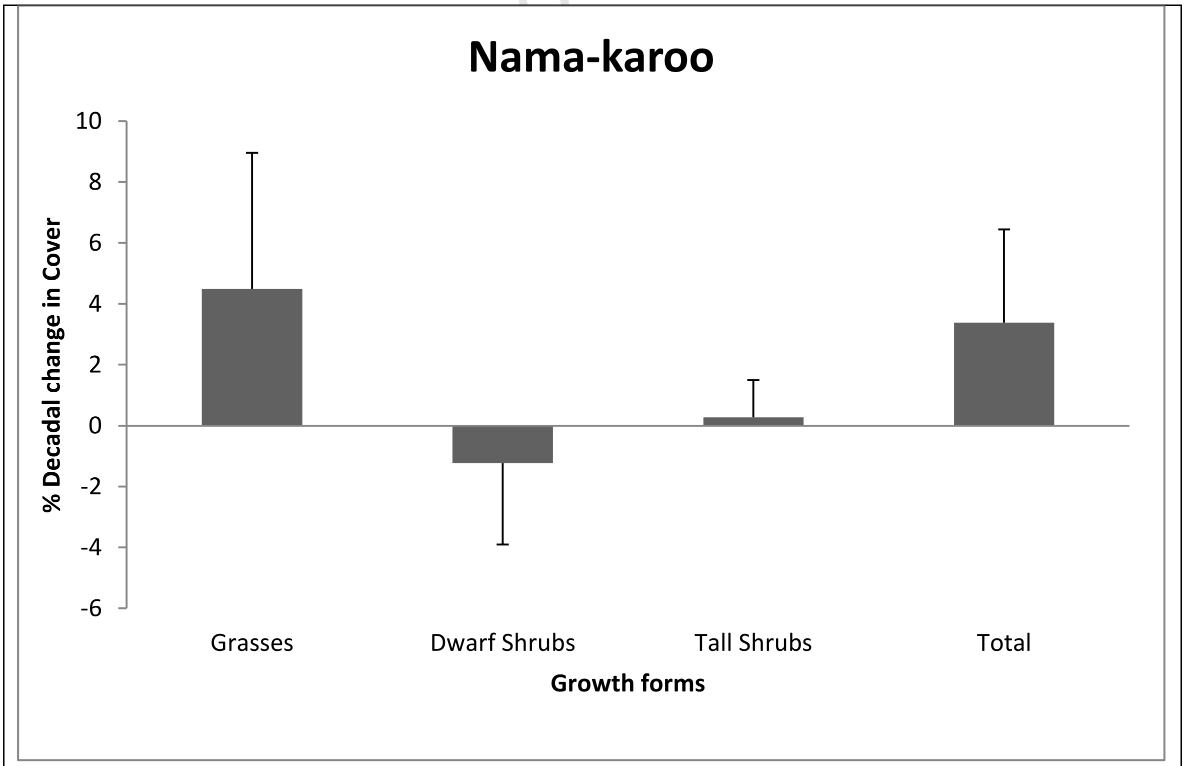


Figure 5.6: Percentage decadal change in the cover (error bars are SD) of the main growth forms on the plains landform of the Nama-karoo biome. N=20.

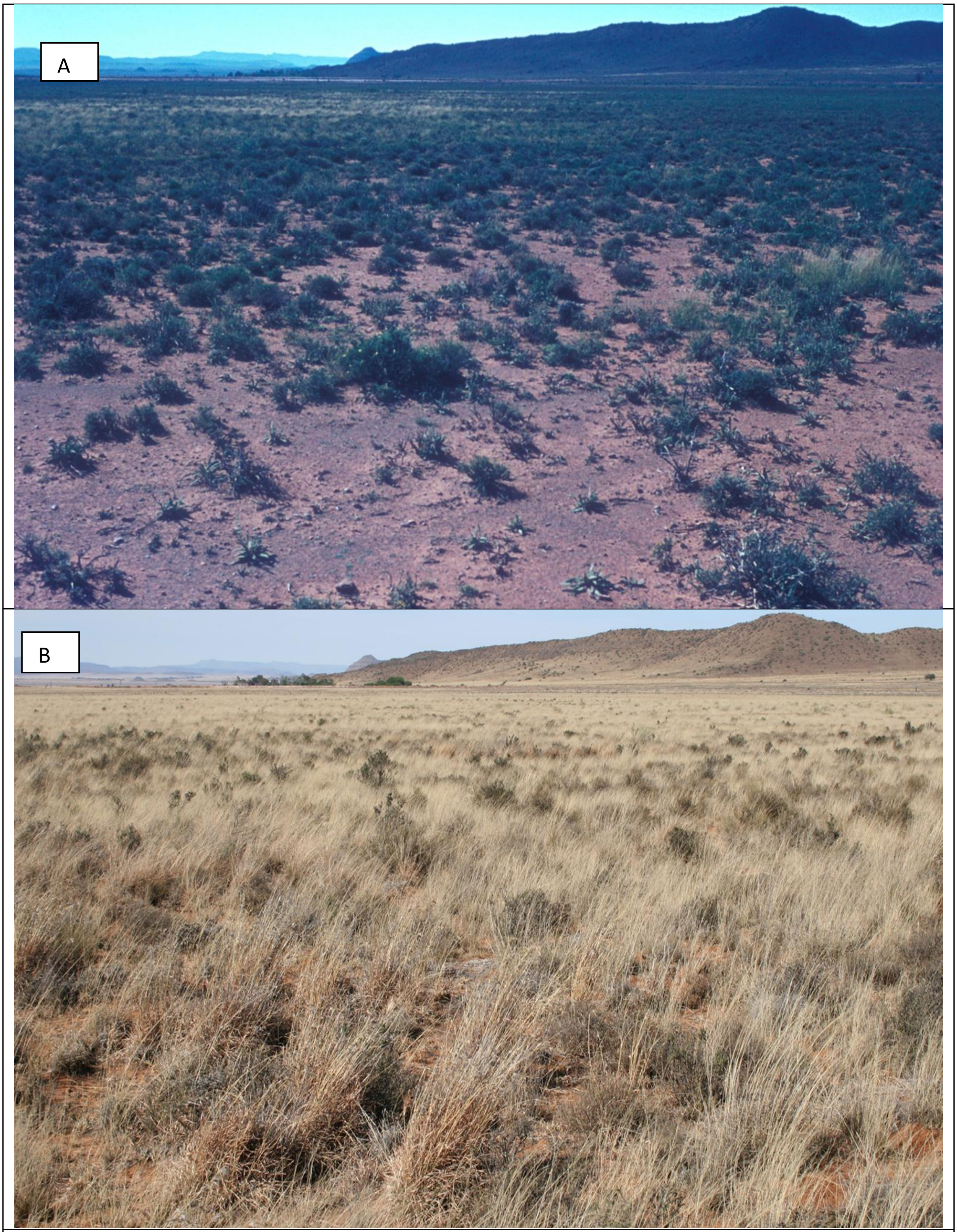


Figure 5.7: 583 Erin Renosteberg East
Location: S 31.60195, E 24.99808. Altitude (m): 1293
Original: A. 06 May 1971, J.P.H. Acocks
Repeat: B. 10 October 2010

Photographic evidence showing the increase in grass cover and decline in dwarf shrub cover within Nama-karoo biome sites is shown in Figure 5.7. In this matched photograph pair there has been a dramatic shift in cover from dwarf shrubs to C_4 grasses, particularly *Eragrostis curvula*, *E. lehmanniana* and *Enneapogon scoparius* with a few *Themeda triandra* and *Heteropogon contortus* patches also evident. The dwarf shrubs that have persisted in the landscape include *Pentzia incana*, *Chrysocoma ciliata* and *Rosenia humilis* with the former two species clearly more abundant in the past.

5.4.1.3. Albany Thicket biome

The % decadal change in cover of different growth forms on slopes of the Albany Thicket biome (Figure 5. 8) indicates that grass cover (+1%), tall shrubs (+1.5%), tall succulent shrubs (+0.25%) and total cover (+2%) have all increased while dwarf shrub cover has declined on average by 0.5% per decade.

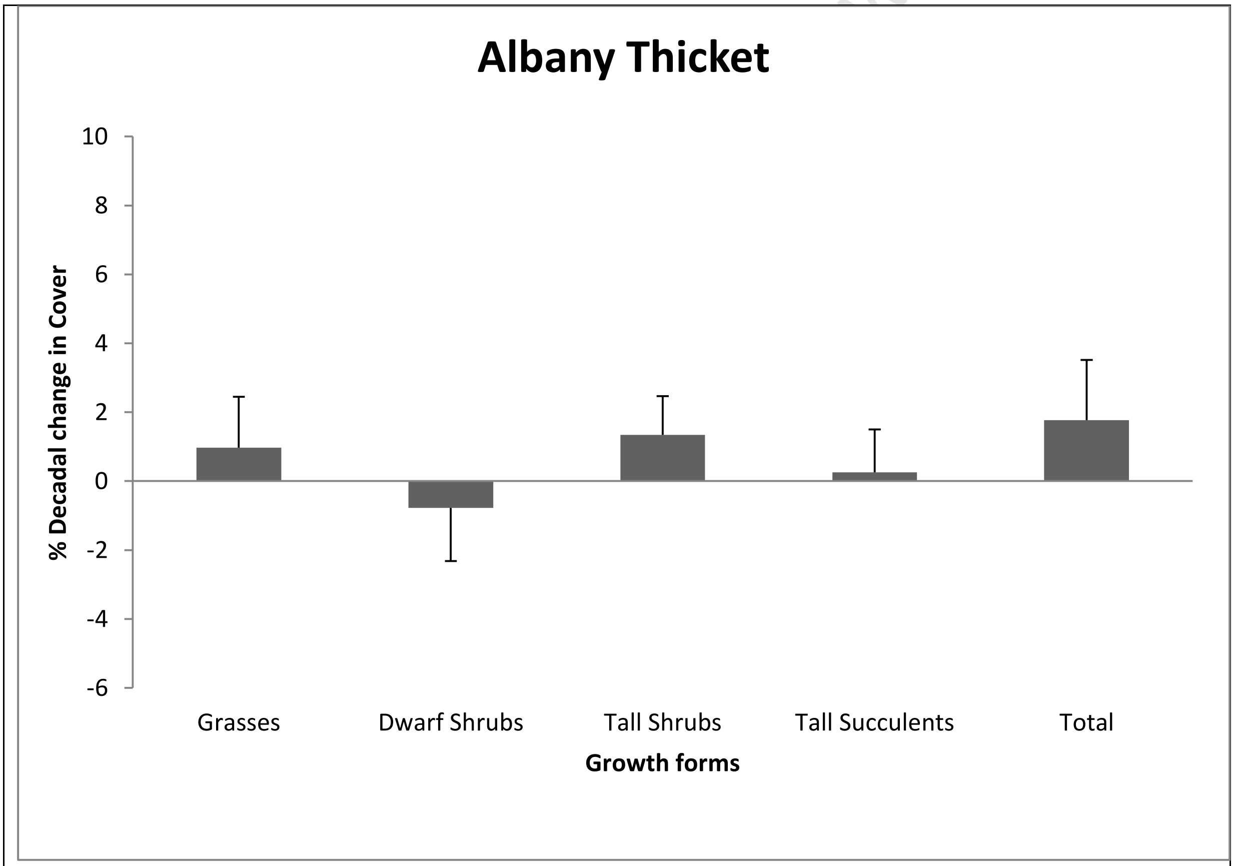


Figure 5.8: Percentage decadal change in cover (error bars are SD) of the main growth forms on the slopes of the Albany Thicket biome. N=30.

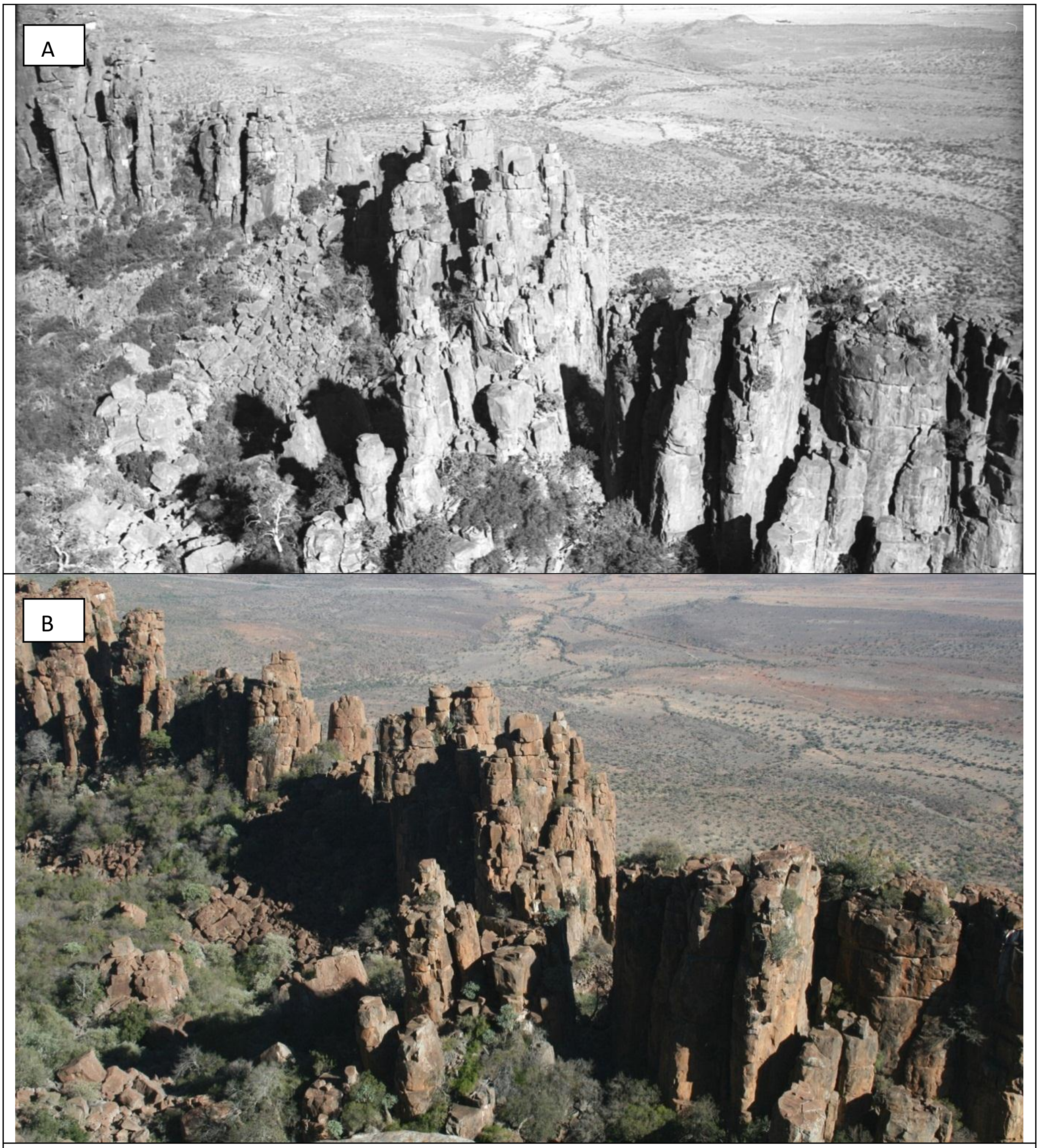


Figure 5.9: 518 Valley of Desolation viewpoint 2
Location: S 32.26509, E 24.48982. Altitude (m): 1370
Original: A. 9 May 1953, J.P.H Acocks
Repeat: B. 9 October 2009

Photographic evidence of such changes in the Albany Thicket biome is shown in Figure 5.9 and shows an increase in tall shrubs after 56 years, especially in well-protected areas such as relatively high-altitude dolerite ridges of the Valley of Desolation near Graaff-Reinet.

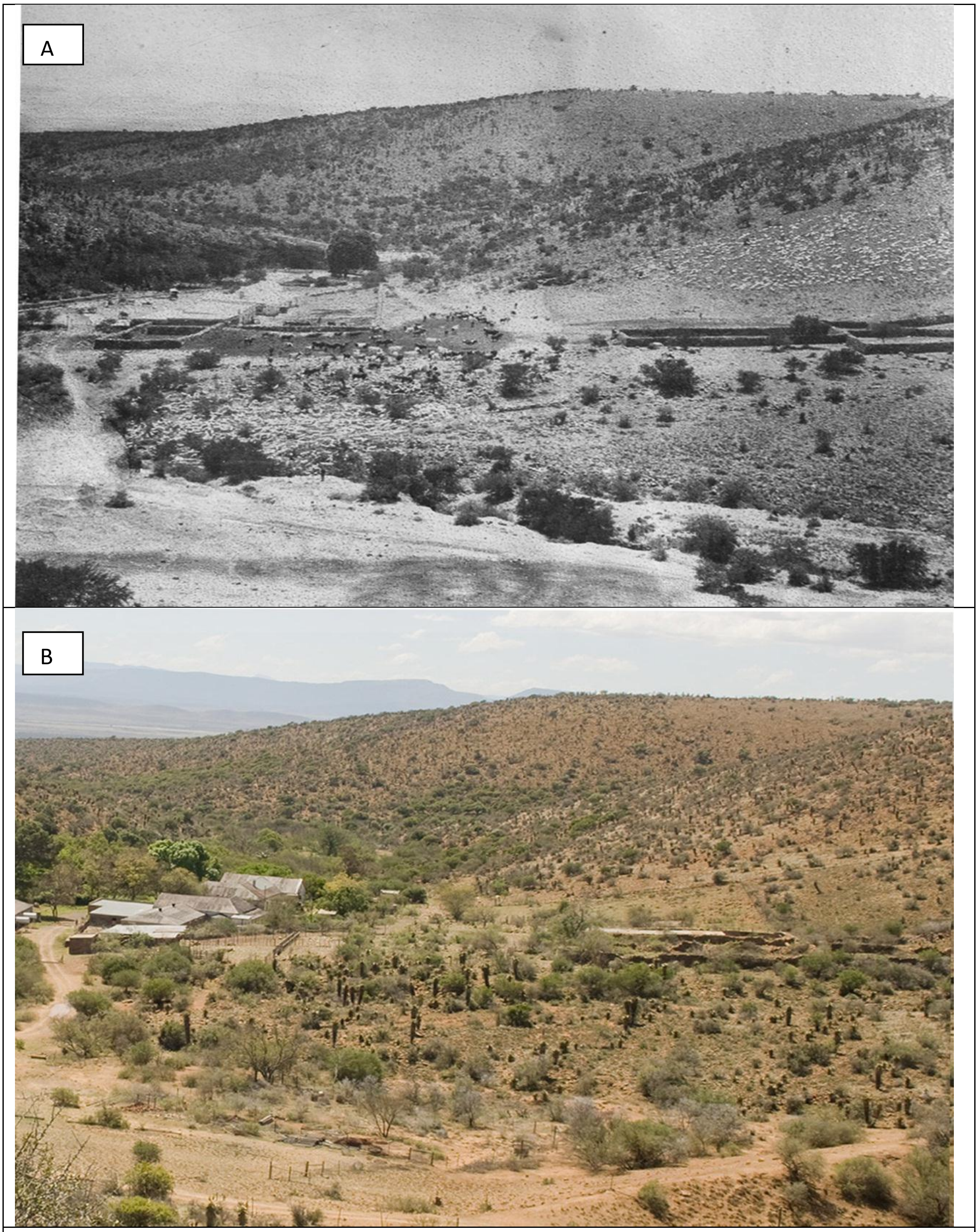


Figure 5.10: 522 Roodeberg Homestead Plate B
Location: S 32.52258, E 24.39033. Altitude (m): 897
Original: A. ca 1888
Repeat 1: B. 12 October 2009

Changes in different growth forms within the Albany Thicket biome are more substantial in Figure 5.10. This photograph pair reflects changes on heavily-utilized private land where livestock densities were high in the late 19th and early 20th centuries. Despite the grazing pressure, tall shrub and tall succulent shrub cover has increased substantially over time. Tall shrubs species that have contributed most to this increase include *Maytenus heterophylla*, *Grewia robusta*, *Carrisa haematocarpa* and *Diospyros lyciodes* while *Euclea undulata* and *Pappea capensis* have remained relatively stable in the landscape. The tall succulent shrub, *Aloe ferox*, has increased in cover over time. Dominant grass species at this site include several disturbance-adapted species such as *Aristida diffusa* and *A. congesta* while common dwarf shrubs include *Eriocephalus ericoides*, *Rhigozum obovatum* and *Felicia filifolia*.

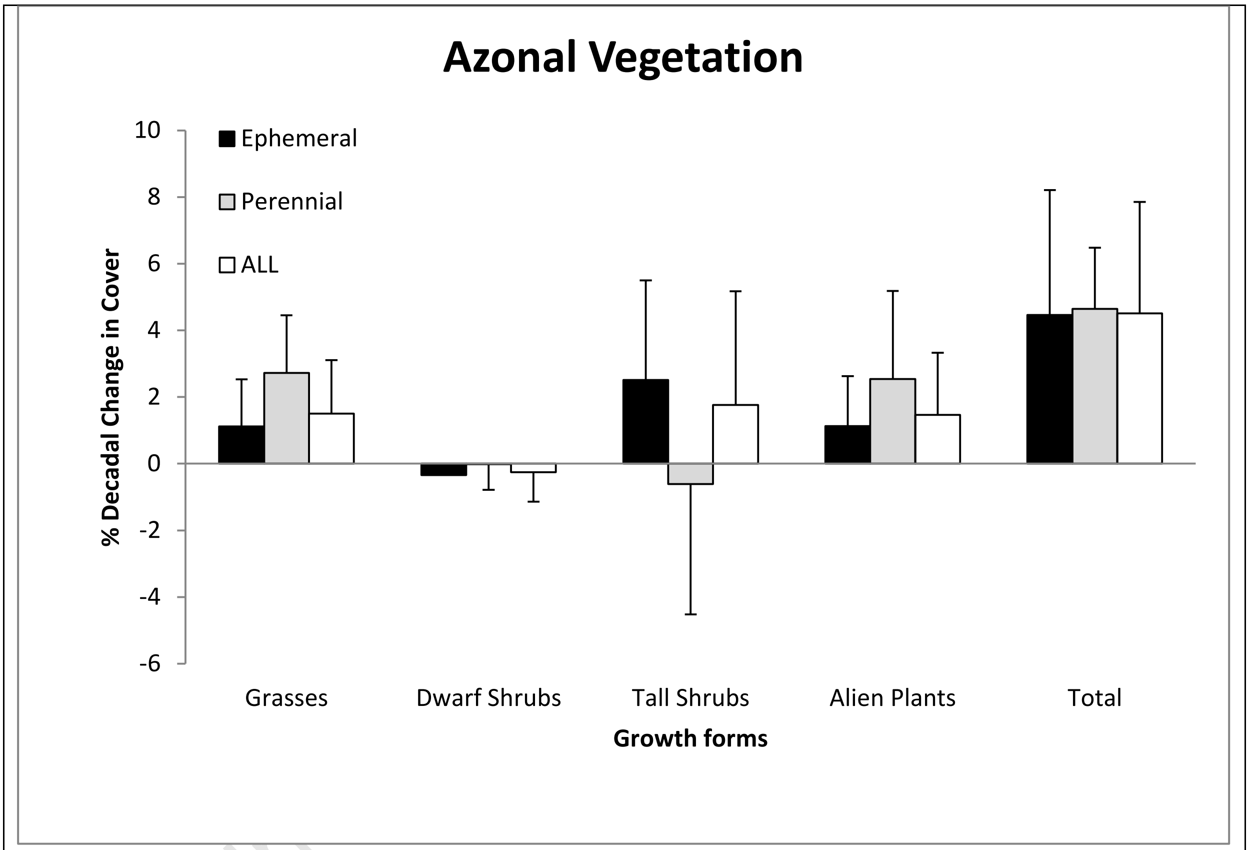


Figure 5.11: Percentage decadal change in cover (error bars are SD) of the main growth forms in ephemeral, perennial and combined Azonal habitats of the Karoo Midlands Region. N=16 for ephemeral rivers, 5 for perennial rivers and 21 for all.

5.4.1.4. Azonal vegetation

Within Azonal habitats in Figure 5.11 grass cover increased by more than 1.5% per decade while dwarf shrub cover was largely unchanged (-0.25%). The cover of tall shrubs increased by about 2% per decade although responses differed in sign between ephemeral and perennial river systems. In some of the perennial rivers, such as the Fish River, the continuous flow of water has reduced the cover of tall shrubs, particularly in the main river channel. This continuous flow of water, however, is a recent phenomenon (i.e. after the original photograph was taken) created by the development of several large-scale irrigation projects in the region. Alien plants have generally increased in azonal vegetation by 1.5% per decade while total vegetation cover has increased by an average of 4.5% per decade.

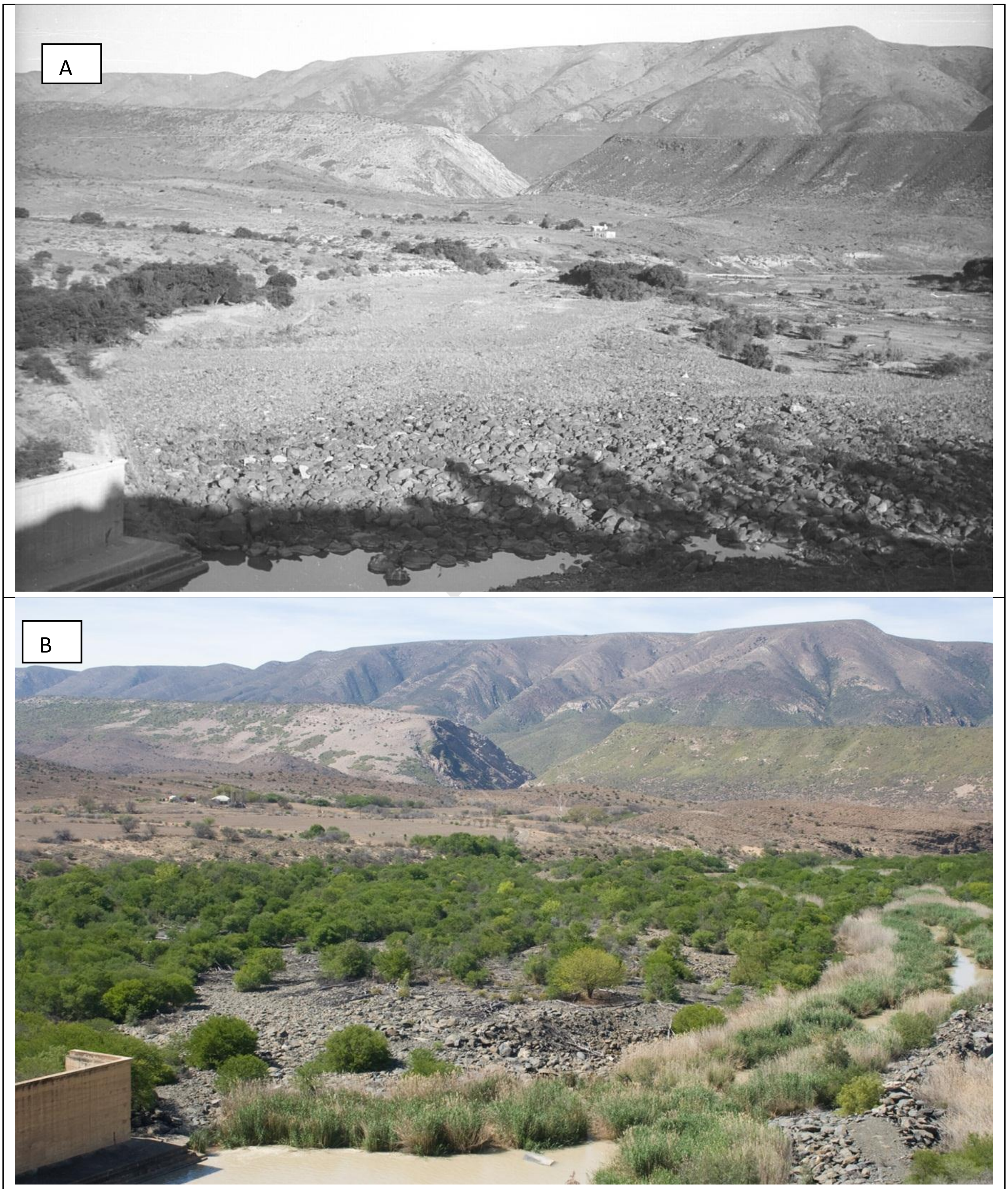


Figure 5.12: 525b Darlington Dam 2
Location: S 33.20623, E 25.14625. Altitude (m): 249
Original: A. 04 May 1953, J.P.H Acocks
Repeat: B. 14 October 2009

An example of the changes in Azonal vegetation is shown in Figure 5.12. Tall shrubs and tree species together with alien plants have increased significantly in the area below the Darlington Dam wall. There have been large increases in the density of alien plants, such as *Prosopis glandulosa*, *Tamarisk ramosissima* and *Schinus molle*, together with a few native species such as *Acacia karroo*, *Lycium oxycarpum* and *Searsia longispina*. Although alien trees were cleared in 2006 prior to the 2009 photograph being taken, alien plants have returned, requiring follow-up clearing by Working for Water alien-clearing task teams. *Phragmites australis* was also not present in 1953 when the original photograph was taken but now dominates the banks of the main water channel downstream of the dam wall on the right of the photograph.

5.4.2. Historical change in stocking rates within the Karoo Midlands

There has been a general decline in stocking rates of domestic livestock from 1911 until 1996 for all magisterial districts within the Karoo Midlands (Figure 5.13). The greatest decline (48%) has occurred in magisterial districts within the Nama-karoo biome followed by the Albany Thicket biome (40%). Stocking rates within magisterial districts of the Grassland biome declined by 36% between 1911 and 1996. The widespread impact of the 1969 drought on stocking rates in the region is evident in the trend lines for all biomes.

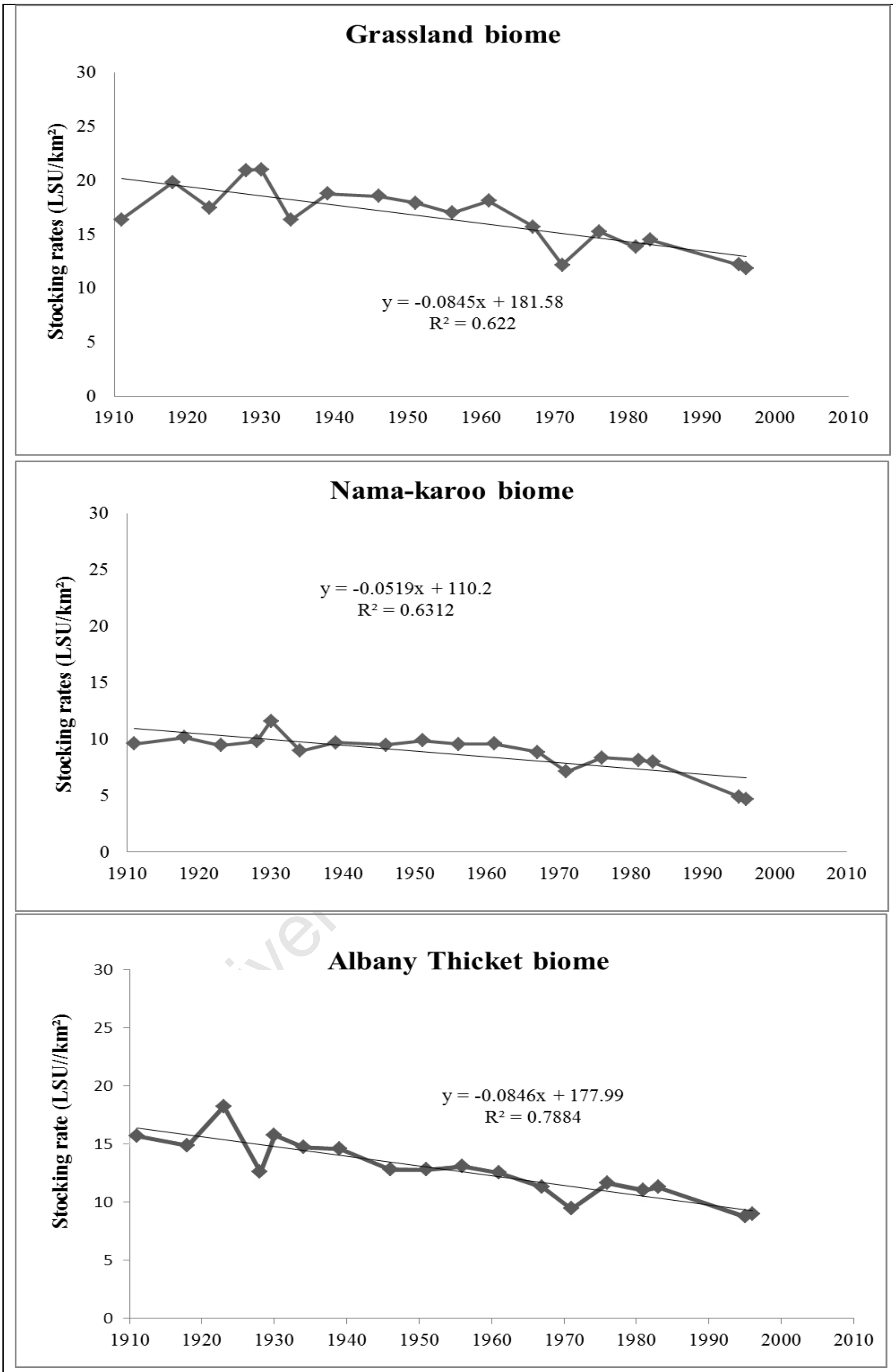


Figure 5.13: Average change in stocking rates within magisterial districts in the Grassland biome, Nama-karoo biome and Albany thicket biome in the Karoo Midlands region.

5.4.3. Historical change in climate of the Karoo Midlands

A full analysis of long-term changes in key climate variables in the Karoo Midlands is provided in Chapter 2. In summary, the results show that trends in annual rainfall and pan evaporation have not changed significantly over the last 100 years. There has, however, been an increase in large wet events and a shift to more early summer rain at some climate stations, particularly within the Nama-karoo biome. Average annual temperature values have generally increased in all biomes and there has been an increase in temperature range in the Albany Thicket biome.

5.4.4. Abiotic correlates of growth form change in the Karoo Midlands

Correlations between current climate descriptors, as derived from BIOCLIM and the % decadal change in growth form cover (Table 5.1) shows that in the Grassland biome, % decadal change in the cover of grasses increased with mean annual precipitation (MAP) on the plains but declined with altitude on slopes. The % decadal change in cover of dwarf shrubs on the other hand increased with mean annual temperature (MAT) and altitude on slopes but declined with MAP, potential evapotranspiration (PET) and a moisture index (MAP-PET) on both slopes and plains. Tall shrub cover was not significantly related to any of the BIOCLIM variables use in this analysis. The % decadal change in total cover in Grassland biome sites was significantly related to climate and altitude variables on the slopes only. Within this landform, the % decadal change in total cover increased with altitude, MAT and MAP-PET but decreased with MAP and PET.

In the Nama-karoo biome, the % decadal change in growth form cover was not significantly related to any of the climate variables. For sites within the Albany thicket biome the only significant correlation was for the % decadal change in grass cover which increased with MAP but declined with all other climate variables. Within Azonal vegetation, the % decadal change in dwarf shrub cover increased with altitude, MAT and MAP-PET but declined with MAP and PET.

Table 5.1: Correlation coefficients (r) for percentage decadal change in cover of different growth forms and climate variables within each biome. Climate variables were derived from BIOCLIM (MAP = mean annual precipitation, MAT = mean annual temperature, PET = potential evapotranspiration).

Biome	**MAP-PET**		**MAP**		**PET**		**MAT**		**Altitude**	
Grassland (N=57); P(14); S(43)	**Plain**	**Slope**	**Plain**	**Slope**	**Plain**	**Slope**	**Plain**	**Slope**	**Plain**	**Slope**
Grasses	-0.501	-0.199	**0.570***	0.144	0.522	0.193	-0.224	-0.266	-0.021	**-0.314***
Dwarf Shrubs	**0.691****	**0.405****	**-0.593***	**-0.376***	**-0.684****	**-0.403****	0.375	**0.377***	0.422	**0.436***
Tall shrubs	-0.231	0.148	0.082	-0.097	0.213	-0.143	0.044	0.252	-0.399	0.251
Total cover	-0.005	**0.361***	0.115	**-0.352***	0.020	**-0.361***	0.485	**0.335***	0.239	**0.341***
Nama-karoo (N=20)										
Grasses	0.099		-0.051		-0.095		0.068		0.099	
Dwarf Shrubs	0.017		-0.037		-0.019		0.088		0.017	
Tall shrubs	0.061		-0.012		0.053		-0.004		0.061	
Total cover	0.155		-0.117		-0.151		0.201		0.155	
Albany Thicket (N=30)										
Grasses		**-0.451***		**0.459***		**-0.453***		**-0.424***		-0.289
Dwarf Shrubs		0.269		-0.249		-0.267		0.206		0.113
Tall shrubs		-0.231		0.256		0.235		-0.245		-0.114
Tall succulents		0.189		-0.230		-0.194		0.146		0.081
Total cover		-0.159		0.140		0.157		-0.200		-0.210
Azonal Vegetation (N=21)	Rivers		Rivers		Rivers		Rivers		Rivers	
Grasses	-0.165		0.139		0.163		-0.261		-0.137	
Dwarf Shrubs	**0.565****		**-0.570****		**-0.566***		**0.509***		**0.539***	
Tall shrubs	-0.365		0.330		0.361		-0.192		-0.381	
Alien plants	0.114		-0.102		-0.113		0.207		0.180	
Total cover	-0.232		0.189		0.227		-0.071		-0.212	

*Significant differences are in bold with the level of significance as follows: *=p<0.05 and **=p<0.01*

Table 5.2: Correlation coefficients (r) for percentage decadal change in cover of different growth forms within each biome.

Biome			**Growth forms**			
Grassland Plains(14)	**Grasses**	**Dwarf Shrubs**	**Tall shrubs**	**Total cover**	**Tall Succulents**	**Alien plants**
Grasses		**-0.69****	-0.19	0.36		
Dwarf Shrubs	**-0.69****		-0.48	-0.12		
Tall shrubs	-0.19	-0.48		0.25		
Total cover	0.36	-0.12	0.25			
Grassland Slopes (43)						
Grasses		**-0.71*****	-0.19	0.30		
Dwarf Shrubs	**-0.71*****		-0.19	0.06		
Tall shrubs	-0.19	-0.19		**0.50*****		
Total cover	0.30	0.06	**0.50*****			
Nama-karoo (N=20)						
Grasses		**-0.69*****	**-0.49***	**0.75*****		
Dwarf shrubs	**-0.69*****		0.20	-0.14		
Tall shrubs	**-0.49***	0.20		-0.25		
Total cover	**0.75*****	-0.14	-0.25			
Albany Thicket (N=30)						
Grasses		**-0.69*****	**0.53****	**0.60*****	-0.05	
Dwarf Shrubs	**-0.69*****		**-0.54****	-0.34	-0.21	
Tall shrubs	**0.53****	**-0.54****		**0.55****	-0.09	
Tall Succulents	-0.05	-0.21	-0.09	0.50 **		
Total cover	0.60***	-0.34	0.55**		0.50**	
Azonal Vegetation (N=21)						
Grasses		-0.27	-0.07	**0.49***		0.29
Dwarf Shrubs	-0.27		-0.41	-0.23		0.12
Tall shrubs	-0.07	-0.41		**0.64****		-0.41
Alien plants	0.29	0.12	-0.41	0.31		
Total cover	**0.49***	-0.23	**0.64****			0.31

*Significant differences are in bold with the level of significance are as follows: *=p<0.05; **=p<0.01 and ***=p<0.001*

5.4.5. Inter-correlations between growth forms

Dwarf shrub cover was consistently negatively related to an increase in grass cover within all biomes except Azonal vegetation (Table 5.2). Tall shrub cover was negatively related to grass cover in the Nama-karoo biome but positively related to grass cover in the Albany Thicket biome. Tall shrub cover was also positively related to total cover in the Albany Thicket biome and Azonal vegetation. Alien plant cover was only recorded within Azonal vegetation and not related to any of the other growth forms.

5.5. Discussion

This study has quantified the nature, extent and rate of vegetation change within different landforms in the three most extensive biomes of the Karoo Midlands region. It has also related these changes to major climatic and land use drivers. Since land cover dynamics are connected to regional temperature and precipitation patterns (Feddema *et al*. 2005) it is valuable to quantify historical trajectories or trends of change and then relate them to those suggested by regional and even global climate change models. Repeat photos are important in the sense that historical trajectories of change can be used to complement and perhaps even assess model output concerning future trajectories (Clark & Hardegree 2005; Hendrick & Copenheaver 2009). However, determination of the cause of change is extremely challenging due to the lack of long-term data on the potential drivers of change. Furthermore, climate and land use drivers are often coupled and their combined influence may differ at a local scale (Turner *et al*. 2009). Here I first discuss the nature, extent and rate of vegetation change in the region before assessing the major influences on these changes. I address both climate and land use factors and explore the possible effect of competitive interactions between different growth forms in the region.

5.5.1. Nature, extent and rate of vegetation change

The results from the repeat photo analysis revealed that the direction of vegetation change was similar across both plains and slopes but varied considerably between different biomes in the study area. Rates of change in vegetation cover were greatest within Azonal habitats, somewhat less in the Grassland and Nama-karoo biomes and least in the Albany Thicket biome. Overall, results showed that there has been a general increase in vegetation cover in the Karoo Midlands region. The greatest contribution to the increase in total cover of the region was from grass cover, particularly in the Grassland and Nama-karoo biomes and to some extent from an increase in the cover of tall shrubs, particularly in the Albany Thicket and Grassland biomes. A relatively consistent result has been the decline in dwarf shrub cover, particularly within the Grassland biome. What is encouraging is that many of the dwarf shrubs that have declined are poor quality forage indicator species such as *Chrysocoma ciliata* and *Walafrida saxatalis* (Du Toit 2010b; Du Toit *et al*. 1995) which were on the increase prior to the 1970s (Acocks 1953; Roux 1968).

The decline in dwarf shrubs in the Grassland biome has been offset to some extent by an increase in tall shrubs, particularly in the more mesic sub-escarpment grasslands (Mucina & Rutherford 2006). Increases in tall shrub cover were dominated by only a few woody species, most of which belong to the genus *Searsia*. Tall shrub cover has also increased within ephemeral streams of Azonal vegetation. This is consistent with findings for the western part of arid southern African where a significant increase in tree and tall shrub cover, especially that of *Acacia karroo*, has been recorded along ephemeral and perennial streams (Hoffman & Rhode 2011; Rohde & Hoffman 2012). It is also consistent with recent changes documented in some semi-arid savanna environments immediately south east of the Karoo Midlands region (Buitenwerf *et al*. 2012). In most perennial rivers of the Karoo Midlands region, however, there has been a decline in tall shrub cover due largely to water catchment management and flooding particularly within the main river channel. An increase in alien plant cover is only evident in Azonal vegetation, and particularly along perennial streams in the study area. Other studies which investigated the hydrology of Azonal systems in Northern Ethopia, showed the dynamic nature of the river channel and gullies due to human influence (Frankl *et al*. 2012). Results suggest very little influence between 1860 and 1960 on river dynamics followed up by a large erosion cycle due to increased clearing of vegetation for rain-fed agriculture in the 1970s. Vegetation recovery apparently occurred from 2000 onwards with decreased run-off discharge, sediment load and flashiness of flows. Frankl *et al*. (2012) clearly demonstrated the value of repeat photography in terms of understanding hydrology, river channel and gully formation in riparian environments.

5.5.2. The influence of climate, land use and competition on vegetation change

A closer examination of the trends in potential drivers such as climate, land use and growth form competition should help to understand the permanency or otherwise of the changes observed in this study.

5.5.2.1. Climate

In arid regions, the variability of both temperature and precipitation together with extreme climate events associated with them are likely to have strong effects on biotic communities (Miranda *et al*. 2011; Jentsch *et al*. 2011; Jiguet *et al*. 2011; Thibault & Brown 2008; Rutherford 1980; Zhao & Running 2010). The % decadal change in the cover of different growth forms as well as the total cover in each biome varied along complex altitudinal, moisture and temperature gradients. Higher rainfall and cooler temperatures generally favoured an increase in grass cover change while the converse was true for dwarf shrub cover, particularly in the Grassland biome. Several studies have shown how rapidly grasses are able to respond to rain, particularly if it falls during the warmer summer months (Gelli *et al*. 2011; Hoffman *et al*. 1990; Muldavin *et al*. 2008; O'Connor & Roux 1995; Sala *et al*. 2000; Snyder & Tartowski 2006; Xu *et al*. 2010, 2011). Shrub cover, on the other hand appears better able to utilize moisture during the cooler autumn months (Roux 1968). The possible shift to early season summer rain in the study area (du Toit 2010a) as well as the increase in the number of wet events (Chapter 2) could be one reason why grass cover has increased in the Karoo Midlands. Other climatic factors that could contribute indirectly to this grass cover increase may be a combination of increased temperature and elevated CO_2 through increased soil moisture content (Morgan *et al*. 2011).

Dwarf shrubs in the region are projected to increase as a result of frequent drought and increased temperatures in the region (Midgley *et al*. 2008). In this study dwarf shrubs were negatively correlated with rainfall and moisture in the Grassland biome as well as in the Azonal vegetation but positively correlated to temperature and altitude. Other studies have shown a non-responsive behaviour of shrubs to growing season rainfall as well as the lower dependence of shrub cover on short-term, pulsed rainfall inputs in arid environments which only wet the upper soil layers (Katra *et al*. 2007; Moran *et al*. 2010; Muldavin *et al*. 2008; Pockman & Small 2010; Reynolds *et al*. 2004). It has been argued that because of the generally greater rooting depths of shrubs they are able to utilize moisture from larger rainfall events and which penetrate deeper soil layers (Carrick 2003; Golluscio *et al*. 1998; Moran *et al*. 2010). In this way they avoid competing directly with grasses for moisture in the upper soil layers.

Changes in tall shrub cover and alien plants appear unrelated to such gradients of moisture and temperature in the Karoo Midlands Region although findings from Wakeling *et al*. (2010) suggest that this is not everywhere the case. Tall shrub cover increase in the Grassland biome, the Albany Thicket biome and the ephemeral streams within Azonal environments may be promoted by CO_2 increase as suggested by Wigley *et al*. (2010), Bond & Midgley (2012), and Higgins & Scheiter (2012) for more mesic environments adjacent to the Karoo Midlands Region but also for riverine vegetation (Perry *et al*. 2012). *Acacia karroo*, the species that has increased most in the ephemeral streams and plains environments over time, appears particularly responsive to increases in CO_2 (Kgope *et al*. 2010).

5.5.2.2. Land use change and its impact on vegetation

Land use is a critical driver of land cover change in many parts of the world and can exert either a temporary influence on ecosystem structure and function or result in a permanent switch from one biome to another (Bond 2008; Opdam *et al*. 2009; Turner *et al*. 2007; Verburg *et al*. 2012). At local scales changes in land use practices can also have more of an impact on vegetation composition and cover than short-term changes in precipitation and temperature (Alkamande *et al*. 2011). For the Karoo Midlands region, changes in stocking rate appear most strongly related to the changes observed in the repeat photographs. It is likely that the steady decline in stock densities during the course of the 20th century has facilitated the recovery of vegetation within all biomes in the study area. Several long-term grazing trials carried out by the National Department of Agriculture in the region demonstrate the pivotal role that grazing has on the relative dominance of grasses and shrubs within landscapes of the Grassland and Nama-karoo biomes (Milton & Hoffman 1994; O'Connor & Roux 1995; Rutherford *et al.* 2012). Dwarf shrub cover appears to be associated with an increase in stocking density while continuous grazing and summer grazing only further promote an increase in this growth form. Grass cover, on the other hand, appears to be favoured by a reduction in stocking rate and is promoted by winter or rotational grazing at low stocking densities (Hoffman 1988).

In the first half of the 20th century, overgrazing and excessive browsing densities of domestic herbivores decimated large areas within the Albany Thicket biome (Kerley *et al*. 1999; Sigwela *et al*. 2009). This analysis of repeat photographs has showed that sites that have been protected from this high utilization impact, however, have changed very little compared with sites that have been heavily utilized, especially for goat farming. For example, sites within the Camdeboo National Park showed very little change in growth form cover compared with sites such as Roodeberg farm that continue to be utilized by domestic livestock. Other authors have reported a significant switch from livestock farming to ecotourism across the Karoo Midlands region (Smith & Wilson 2002; Powell 2009). Such large declines in stocking densities have also contributed to the general increase in cover in Albany Thicket biome of the region.

5.5.2.3. The role of competition between growth forms

Competition between different growth forms for water, nutrients and light also has an effect on the vegetation of a region. Grass dominance exerted a negative effect on dwarf shrubs in all of the biomes investigated in the Karoo Midlands Region (Hoffman *et al*. 1990; O'Connor & Roux 1995). It also affected tall shrub cover negatively at the more arid end of the gradient in the Nama-karoo biome but was positively associated with tall shrub cover at the more mesic end of the gradient in the Albany Thicket biome. Other studies in semi-arid southern Africa confirm the strong negative relationship between grass and dwarf shrub cover (Carrick 2003; Shiponeni *et al*. 2011). However, these results contrast with those for many other arid regions of the world where shrub-dominated environments have proven highly resilient to grass invasion (Turnbull *et al*. 2010). In the Karoo Midlands Region, the cover of long-lived perennial grasses such as *Merxmuellera disticha*, *Cymbopogon plurinoides* and *Themeda triandra* appears to have increased significantly over time with important negative consequences for dwarf shrub cover in particular. Therefore, discussions concerning the relative contribution of local and global drivers to vegetation change will also need to understand the affect that competitive interactions between growth forms have on this process.

5.5.3. Biome boundaries, climate change and land degradation

The dominance of major life forms such as grasses, shrubs, trees provides the most important criterion for distinguishing between different biomes in southern Africa (Rutherford & Westfall 1994). The results of this repeat photograph study suggest that if the current rates of change continue then boundaries between the major biomes in the Karoo Midlands Region might need to be re-considered. For example, the structural and physiognomic appearance of the eastern part of the Nama-karoo biome is now dominated by grasses and can no longer be described in the same was as it was in the 1950s (Acocks 1953). Evidence from this long-term perspective suggests that a sustained expansion of the Grassland biome into the semi-arid region of the Karoo Midlands has occurred in recent decades. While the expansion of tall shrubs into the Grassland biome at the more mesic end of the gradient might not reflect a shift in biome, the physiognomic profile of this region has also changed over time. Furthermore, much of the Albany Thicket biome, and in particular the riverine areas and previously open plains have also been transformed by an increase in tall shrubs and trees over the last 50 years.

Such switches in growth form dominance in the eastern Karoo reflect environments with generally improved range condition status (Milton & Hoffman 1994). These historical trajectories contrast with the anticipated deterioration of cover projected for the region in response to negative land use impacts such as overgrazing (Acocks 1953) as well as climate-induced aridification (Midgley & Thuiller 2011). They support, however, an earlier review of land degradation in South Africa based on the subjective views of agricultural extension officers and resource conservation technicians with experience in the region (Hoffman & Ashwell 2001). This review of land degradation suggested that the reduction in stocking rates, in particular, but also the improved management practices of the commercial livestock farmers in the region, have contributed significantly to the improvement in range condition over the last fifty years. However, the potential contribution of global drivers such as rainfall, temperature and CO_2 to these changes was not rigorously assessed in this review and more long-term, natural experiments (Wigley *et al*. 2010) and manipulated treatments (Buitenwerf *et al*. 2012) are urgently needed.

Chapter 6: Synthesis of the main findings related to vegetation change in the Karoo Midlands region in response to local and global drivers

This study investigated vegetation change in the Karoo Midlands region of South Africa at multiple spatial and temporal scales in relation to local and global drivers. This is important because changes in land cover have major implications for the conservation and management of biodiversity as well as for ecosystem services in the region (de Baan *et al*. 2012; Reyers *et al*. 2010). An understanding of the nature, extent and rate of change over time also helps to assess and refine projections anticipated under future climate change scenarios. Long term approaches are needed that cross disciplinary boundaries to include interactions and feedbacks at multiple spatial and temporal scales (Luo *et al*. 2011; Leuzinger *et al*. 2011). This enhances our ability to predict catastrophic events and develop strategies for minimizing their occurrence and impacts as we grapple with global change (Peters *et al*. 2004). It is only by integrating all aspects of landscape change through space and time that we can understand and disentangle these intricacies (Peters *et al*. 2006).

The main question addressed by this study was how the vegetation of the Karoo Midlands region has changed over the course of the 20th century in response to climate and land use at different spatial and temporal scales. I used historical climate and land use records in combination with repeat photography and long-term vegetation surveys to answer this question. Below, I provide a summary of the key findings from the study and discuss the implications of these findings for the broader research and natural resource management community.

6.1. Drivers of change: Climate

I first examined the historical climate record of the region and examined how temperature, rainfall, drought incidence and A-pan evaporation had changed over the course of the 20th century. This analysis provides a benchmark against which future climate changes can be assessed. I also evaluated these historical trajectories in terms of future climate change scenarios developed for the central parts of southern Africa.

6.1.1. Annual and seasonal rainfall patterns

For most climate stations within the Karoo Midlands region annual rainfall has not changed significantly in the last 100 years. This finding supports most long-term analyses of rainfall in southern Africa (Warburton *et al*. 2006; Hoffman *et al*. 2009; Nel 2009). However, when the climates stations were grouped according to their biome affinity several stations within the Nama-karoo biome showed an increasing trend in annual rainfall. Stations within the Grassland and Albany Thicket biomes generally showed no significant trend over time.

Future climate change projections promote a model of aridification with a decrease in rainfall over the next 100 years (Haensler *et al*. 2011; Sanderson *et al*. 2011). My analysis, however, found no evidence thus far for such a trend in the historical record. It is important that the network of climate stations is maintained and that appropriate statistical analyses are developed to identify changes in long-term trends. Interestingly, my analysis does report a change in rainfall seasonality with more early summer rain in the recent record (from 1990) than the earlier period. This supports the findings of Du Toit (2010) and may be an important driver of change in growth form dominance, particularly the switch from shrubs to grasses which has been observed in the eastern Karoo.

6.1.2. Extreme climate events (drought & flooding)

Climate extremes are a regular and important occurrence in arid and semi-arid environments (Easterling *et al*. 2000) and have a major influence on the vegetation (Fay *et al*. 2008; Godfree *et al*. 2011; Holmgren *et al*. 2006; Jentsch *et al*. 2009, 2011; Snyder & Tartowski 2006). There has been a recent increase in studies investigating the role that extreme climate events, such as drought or flooding, have on ecosystems throughout the world (Coumou & Rahmstorf 2012; Yang *et al*. 2011). While the majority of these studies have been carried out in forest ecosystems of North America and Europe (Eilmann & Rigling 2012), a few have occurred in several arid lands as well (Allen *et al*. 2010; McDowell 2011; McDowell *et al*. 2008; Sala *et al*. 2010; West *et al*. 2012). The main focus in these studies is generally concerned with the impact of drought and high temperature on tree and shrub mortality (Allen *et al*. 2010; Fensham *et al*. 2009; Ryan 2011). Some do, however, also explore the impact of these events on the dynamics between grass and shrubs (Alvarez *et al*. 2011; Godfree *et al*. 2010; Heisler-White *et al*. 2009; Munson *et al*. 2011b; Munson *et al*. 2012; Taylor *et al*. 2011).

Using a Standardized Precipitation Index (McKee *et al*. 1993) I found that there has not been an increase in the incidence and frequency of drought in the Karoo Midlands. This contrasts with the findings of Roualt *et al*. (2004) who reported a drying trend for some central Karoo stations. In contrast, my analysis provides some evidence that the frequency of wet periods has increased, particularly for climate stations located within the Nama-karoo biome. This finding should also be viewed in light of the aridification hypothesis suggested by some bioclimatic envelope model projections for the central parts of southern Africa (Midgley *et al.* 2008). Again, the maintenance of long-term records and the development of appropriate statistical techniques will be important if we are going to be able to detect such changes in the future. The identification and detection of threshold conditions is especially important in this regard.

6.1.3. Temperature

For most climate stations in the region there was a significant increase in maximum temperature over the historical period. However, values for minimum temperature generally increased more across the region although this was not the case for climate stations located within the Albany Thicket biome where they decreased. The general increase in temperature supports most analyses for the region (e.g. Engelbrecht *et. al*. 2009) although the impact of increasing temperature on the vegetation of the region is poorly understood. More experiments to address this issue are urgently needed. For example, the FACE experiments of Leakey *et al*. (2012) and Morgan *et al*. (2011) have helped to understand how temperature, in combination with the other climate factors such as increasing concentrations of atmospheric CO_2 influence the dynamics of key growth forms in a region.

6.1.4. Pan Evaporation

Investigations into the changes in pan evaporation values returned variable results for the Karoo Midlands region. Unlike the findings of Eamus and Palmer (2006) for the central Karoo or Hoffman *et al.* (2012) for the Western Cape, there were no consistent trends in pan evaporation values for the study area. However, there were only a few stations with long-term pan evaporation data and this renders any general finding problematic. It is a pity that because of the labour and management costs involved many government institutions responsible for the measurement of weather conditions across the world have replaced mechanical pan evaporation equipment with automated instruments (Roderick *et al.* 2009).

Theoretical measures of evaporation, derived from equations such as the Penman-Monteith algorithm do not provide the same measure of evaporative demand as one gets from a long-term pan evaporation record (Roderick *et al.* 2009; Hoffman *et al.* 2012).

6.2. Drivers of change: Land use

Land use change like climatic change exerts a major influence on the vegetation dynamics of a region (Alkemade *et al*. 2009; Verburg *et al*. 2012) and continues to affect biodiversity negatively at a global and regional scale (de Baan *et al*. 2012). It may also alleviate the effects of climate change Land use data for the Karoo Midlands shows that over the period 1911-1996 there was a consistent decline in stocking rates for the region as a whole as well as for each of the biomes investigated. Evidence suggests that the Nama-karoo and Albany Thicket biomes have experienced the greatest decline. This reduction in stocking densities appears to be a general phenomenon throughout privately-owned farms in South Africa (Hoffman & Ashwell 2001; Nel & Hill 2008). It coincides partly with the rise in state support for white commercial livestock producers in the period from 1960-1990 as well as better farming practices and the introduction of more appropriate animal breeds and grazing systems. The vegetation of the region today probably supports the lowest number of animals since the mid-18th century when settlers first moved into the eastern Karoo. The large-scale switch to wildlife farming and ecotourism in southern Africa over the last two decades (Smith & Wilson 2002; Powell 2009) is another contributing factor. This trend is likely to continue through the introduction of mega-reserves and the expansion of conservation corridor networks (Driver *et al*. 2012).

Such declines in stocking rate could be an important driver of grass cover increase and shrub cover decline especially in rangelands of the Nama-karoo and Grassland biomes (Hoffman & Cowling 1990; Milton & Hoffman 1994; Rutherford *et al.* 2012a). Within protected areas, however, such as in the Camdeboo National Park, the relatively low stocking densities appear to have had little impact on the dynamics of grasses and shrubs. These growth forms, together with trees appear more influenced by climatic events, particularly rainfall and flooding.

6.3. Patterns of vegetation change at different temporal and spatial scales

This study addressed growth form responses within three biomes (Grassland, Nama-karoo and Albany Thicket) in the Karoo Midlands region on different landforms (plains, slopes and rivers) at multiple spatial (local to regional) and temporal scales (1-100 years). Growth forms investigated included tall shrubs (or in some cases low trees), dwarf shrubs and grasses. They varied in abundance on different landforms within the different biomes and at different temporal scales. These growth forms provide the basis upon which the different biomes and vegetation types are classified in southern Africa (Mucina & Rutherford 2006). They have also been found to be dynamic in response to temperature and rainfall amount and seasonality (Archer *et al.*, 1995; D'Odoricko *et al*. 2010; Mayeux *et al.*, 1991; Midgley *et al.*, 2000; Parton *et al.*, 1994). The use of repeat photos which have proved valuable in this study can be improved by the use of satellite imagery to give a proper account of the extent of change in the biome boundary. Satellite imagery could also be used to develop a spatially explicit model of the full extent of the biome or regional scale changes (de Mûelenaere *et al*. 2012). Historical photos can be used to calibrate Landsat imagery from the early 1970s as shown in de Mûelenaere *et al*. (2012) as long as the number of historical ground photos spread across the region is sufficient.

6.3.1. Change in Growth forms

6.3.1.1. Grass cover change

The results at regional scale under longer (decadal) timeframes showed that grass cover has generally increased on plains and slopes particularly in the Grassland and Nama-karoo biomes. The ecotone study (Chapter 4) indicated that this increase is not a recent phenomenon but was evident in the 1989 photographs especially in the Nama-karoo sites (Hoffman & Cowling 1990). However, the shorter-term time series from the local study at the Camdeboo National Park (Chapter 3) showed that grass cover can vary in some vegetation types over annual to decadal cycles. Despite these short-term fluctuations evidence suggests that grass cover has increased at most locations in the Karoo Midlands region over the last half of the century. Other studies of vegetation change in the Karoo Midlands support this finding as they also show a sustained increase in tall, perennial grasses over time (Novelie & Bezuidenhout 1994; Kraaij & Milton 2006).

There are a few potential explanations for this increase in grassiness. Firstly, the reduction in stocking densities described above could be an important reason for the increase in grass cover in the study area. Several studies (O'Connor & Roux 1995) and models (Milton & Hoffman 1994) provide support for the relationship between stocking rate and grass cover. A second explanation for the increase in grass cover is that it coincides with a possible change in rainfall seasonality and amount as well as an increase in the concentration of CO_2 in the atmosphere. In the case of rainfall seasonality Du Toit (2010) (see also the comprehensive analysis provided in Chapter 2) finds support for a shift in rainfall to an earlier summer period especially for climate stations in the Nama-karoo biome. Several studies (Hoffman *et al*. 1990; Milton & Hoffman 1994; O'Connor & Roux 1995) emphasize the favourable response of grass cover to early summer rainfall. In other semi-arid areas inter-annual rainfall variability has been shown to be an important determinant of grass cover (Buiternwerf *et al*. 2011; Paurelo *et al*. 1999) particularly when soil conditions are favourable (Peters 2002). In more mesic areas, it is considered to have an even greater influence on grass cover than grazing (Paurelo *et al*. 2008) although grazing pressure is an important determinant of grass cover over much of semi-arid southern Africa (Hoffman & Cowling 1990; Cousins *et al*. 2003).

The influence of atmospheric CO_2 concentration on grass cover has recently been modelled by Higgins and Scheiter (2012) using an adaptive Dynamic Global Vegetation Model (aDGVM). They suggest that in the semi-arid regions of southern Africa, including the Karoo Midlands region, an increase in CO_2 together with temperature confers an advantage for grasses over shrubs. They support their model output using evidence from the FACE experiments of Leakey *et al*. (2012) and Morgan *et al*. (2011) in the US grasslands. These experiments show that improved soil moisture conditions, which arise as a result of a combination of increased temperature and CO_2, favours an increase in the cover of C_4 grasses, which is the dominant photosynthetic pathway for grasses in Africa (Bond 2008; Bond *et al*. 2005).

However, predictions based on Bioclimatic Envelope Models (BEM) for the region suggest that areas currently dominated by C_4 grasses will be replaced by C_3 shrubs later in the 21st century. This result is based on the suggestion that C_3 shrubs will be more competitive under the elevated CO_2 and more arid conditions projected for the future as a result of an increase in temperature and drought frequency (Ellery *et al*. 1991; Midgely & Thuiller 2011; Midgely *et al*. 2002, 2008). Notwithstanding the many problems of BEMs (Bellard *et al*. 2012; Leadly *et al*. 2010) there is also growing evidence from both field ecologists and modellers that the current plant functional type (PFT) classifications may also not adequately represent the observed variation in ecosystem function in response to global drivers of environmental change (Pavlick *et al*. 2012). Certainly this study finds more support for the recent output from Higgins and Scheiter's (2012) aDGVM than for the biome level projections reported for the Karoo Midlands region by the BEM analysis. However, more experimental work is needed to determine the relative roles of elevated atmospheric CO_2 concentration, temperature increase and drought on grass and shrub dynamics.

6.3.1.2. Change in cover of dwarf shrubs

The change in the cover of dwarf shrubs was generally found to be opposite in sign and extent to grass cover. Where grass cover increased, dwarf shrub cover declined by similar proportions. This was most noticeable in the Grassland and Nama-karoo biomes as dwarf shrub cover did not change significantly at sites in the Albany Thicket biome. Although there could be some concern that the reduction in dwarf shrub cover was simply an artefact of the photographic method used, repeated step-point transect surveys (Chapter 4) suggest that the reduction in dwarf shrubs cover is a real phenomenon measurable in the field. While tall grasses do obscure the field of view to some extent, the densities of several dwarf shrubs species have declined significantly at most Karoo Midland sites over time. John Acocks' earlier concern of a north-eastward expansion of karoo shrubs as a result of overgrazing (Acocks 1953) appears to no longer be a matter of consideration and the results of this thesis support the views expressed by Hoffman and Ashwell (2001) on this issue.

The state-and-transition model proposed by Milton and Hoffman (1994) as well as field observations in this study and models in other regions (Peters, 2002), together with experimental evidence by Shiponeni *et al*. (2011) suggest that grasses can outcompete dwarf shrubs, particularly when environmental conditions such as rainfall timing and stocking densities favour an increase in grass cover. Grass roots often occupy the uppermost soil layer and perennial grass tufts may at times grow considerably taller than their dwarf shrub neighbours. Under favourable conditions grasses are able to absorb much of the moisture (Walker & Noy-Meir 1982; Walter 1971) and are also able to shade out lower growing dwarf shrubs which utilize moisture in the deeper soil layer. Recent evidence from the western arid regions of southern Africa suggests that grasses may also have a greater competitive ability in the middle of the soil profile (February *et al*. 2011). Autumn and winter rainfall together with heavy grazing in summer, however, is thought to promote dwarf shrub dominance (Roux 1968; Milton and Hoffman, 1994). Elsewhere in similar environments it is generally reported that areas that have the highest densities of dwarf shrubs are not easily replaced by grasses (Turnbull *et al*. 2010) although these studies often occur over shorter time frames or are without adequate replication.

6.3.1.3. Change in Tall shrubs or Trees

Tall shrubs comprised an eclectic group of subtropical, Albany Thicket biome-related elements in the southern part of the study area as well as more temperate species of the high-lying southern African plateau region in the Grassland and Nama-karoo biomes. Despite this difference in biogeographic affinities, tall shrubs cover increased at most locations although less so at the more arid, Nama-karoo biome sites. Explanations for this general increase in tall shrubs relates mostly to a decline in heavy goat browsing that was evident in the first part of the 20th century particularly in the Albany Thicket biome (Hoffman & Cowling 1990; Kerley *et al*. 1995, 1999; Sigwela *et al*. 2009).

Many tall shrub and tree species have increased in abundance over time in southern Africa and it is anticipated that they will continue to do so in the future (Midgely & Thuiller 2011; Heubes *et al*. 2011). While not formally tested in this study, Wakeling *et al*. (2010) have highlighted the important role that rising temperature plays in promoting the growth rate of tall shrubs and trees. This may be an important driver for the increase in cover of the generally unpalatable tall shrub species in the high-lying cooler areas of the Grassland biome. Results from Higgins & Scheiter's (2012) aDGVM also show a general increase in tall shrub and tree cover, particularly in the more mesic eastern parts of southern Africa. Evidence from a repeat aerial photograph analysis provides further evidence of a widespread increase in tall woody plant cover with land use and elevated CO_2 concentration implicated as important drivers of this change (Wigley *et al*. 2010). The importance of CO_2 is further supported by Bond & Midgely (2012) as well as Buiternwerf *et al*. (2012) in manipulated experiments for the savanna region. For most regions, however, coordinated approaches that incorporate and quantify long term responses and dynamics of ecosystem processes to elevated CO_2 are still absent (Leuzinger *et al*. 2011; Luo *et al*. 2011) and the more arid Karoo Midlands region is no expetion.

6.3.2. Changes within different landforms

Because of the coarse resolution of most climate change projections little is known of how vegetation might change on different landforms within a biome. Some studies which model individual species suggest that they will respond differently within different landform units

(Loarie *et al*. 2009; Williams *et al*. 2007). Results from Chapter 5 confirmed that the extent, nature and rate of vegetation change varied depending on the landform. The low-lying plains were generally characterised by a decrease in dwarf shrub cover and an increase in grass cover especially at sites towards the mesic end of the rainfall gradient. This landform is also the most dynamic primarily because of the interaction between land use and climatic factors. However, since stocking rates have declined over the course of the 20th century, there has been a general improvement in the ecological condition and an increase in grass cover within the plains.

As is the case for the plains, dwarf shrub cover has declined and grass cover has also increased on slopes. However, this landform was also characterised by a general increase in the cover of tall shrubs. Aspect appeared to play an important role in determining the extent and nature of tall shrub increase and should be investigated further. Since human influence is generally lower on steep slopes than on the plains they might be more reflective of the relative role of climate-related changes on the vegetation of a region. However, it does not necessarily follow that land use impacts are unimportant. Previous studies within the region have shown how heavy goat browsing can affect species richness, even on steep slopes (Birch 2000; Hoffman & Cowling 1990a; Rutherford *et al*. 2012b). Results from my study confirmed that sustained heavy utilization by livestock can have a significant influence on the vegetation on slopes. For example, at Roodeberg farm in the Albany Thicket biome sustained heavily utilization of the slopes environments prior to 1970 resulted in major changes in growth form abundance. In contrast, low stocking densities at the Valley of Desolation sites within the Camdeboo National Park resulted in very little change in the vegetation. The experimental plots at Bergkamp near Middelburg also demonstrated the impact of both stocking density and season of utilization on the proportion of grasses, dwarf shrubs and tall shrubs on a slope.

Rivers were analysed as a distinct landform in the Karoo Midlands region. These environments are amongst the most threatened habitat types or ecosystems as a result of anthropogenic-related impacts (Frankl *et al*. 2012; Holland *et al*. 2012; Perry *et al*. 2012, Vörösmarty *et al*. 2010). Nel *et al*. (2007) maintain that diversity within South Africa’s main river systems are under more threat than adjacent terrestrial ecosystems. In Chapters 3 and 5 I explored the nature, extent and rate of vegetation change within two different azonal habitats differentiated primarily by the permanency of water. Results indicated that in the majority of ephemeral rivers and floodplains, there was an increase in grass and especially tall shrub cover while dwarf shrub cover did not change substantially over time. The dynamic nature of rivers and flood plains such as in the Camdeboo National Park also suggests that frequent monitoring is essential in order to capture the main changes within these ecosystems which can occur over relatively short time frames of years to decades.

In perennial river systems, on the other hand, there was a noticeable decrease in the cover of tall shrub and trees while alien plants appeared to have increased over time. This supports the suggestion of Driver *et al*. (2012) that ephemeral rivers are generally in better ecological condition than perennial river systems in South Africa. Furthermore, several river systems in the Karoo Midlands have been transformed by large-scale, inter-basin water transfer schemes. As a result rivers such as the Fish River which were ephemeral in the past have been transformed into perennial rivers. While some localized land use effects such as woodcutting and trampling by livestock are still evident at some sites, the regional impact of upstream development such as dam building and inter-basin water transfer can have a major influence on what happens downstream. For example, water flow, sedimentation, physical disturbance and river structure are all affected (Hoffman & Rhode 2012; Webb *et al*. 2011) with important implications for vegetation cover and composition. While these changes also interact with climatic drivers such as temperature and CO_2 increase, this study supports the view that anthropogenic impact remains the dominant driver of land cover change in riverine environments (Alkemade *et al*. 2009).

6.3.3. Changes within the three major biomes of the Karoo Midlands region

The major finding of the study in terms of vegetation patterns was that, contrary to a trajectory of deterioration in total cover in the region (Acocks 1953) and a contraction of the both the Nama-karoo and more mesic grassland biome as anticipated by Midgley & Thuiller (2010), I found a substantial increase in total cover within all biomes. Evidence shows that the increase in total cover was largely due to an increase in grass cover and tall shrubs or trees despite the fact that dwarf shrubs (mostly karoo shrubs) have declined in abundance across the region. The trajectory of increased grass cover was more pronounced in the Nama-karoo and Grassland biomes and usually occurred at the expense of dwarf shrubs. However, unlike in many shrublands and grasslands across the globe, where the trajectory is that of an increase in shrubby elements due to climate change and land use (Baez & Collins 2008; Beaumont *et al.* 2011; Bestelmeyer *et al.* 2007; Brown & Archer 1999; Chapin *et al*. 2007;

Gibbens *et al*. 2005; Frederickson *et al*. 1998; Midgley *et al*. 2002, 2008; Oesterheld *et al*. 1999; Okin *et al*. 2009; Snyder & Tartowski 2006; Van Auken 2009), this study found the opposite trajectory with grasses on the increase.

Studies in the region prior to 1970 reported shrub expansion from the Nama-karoo into the Grassland biome largely as a result of the effects of heavy grazing (Acocks 1953; Roux 1969) as well as drought in some instances or a combination of the two (O'Connor & Roux 1991). However, the set of repeat photographs and long-term vegetation surveys outlined in Chapter 4 explored this phenomenon at the ecotone between these two biomes. Results showed a general increase in grass cover and a decline in dwarf shrub cover over time. This investigation, which follows the earlier work of Hoffman & Cowling (1990) and Hoffman and Ashwell (2001) corroborates their pattern of an increase in grassiness and improved rangeland conditions at the ecotone between the Grassland and Nama-karoo biomes.

At the higher end of the rainfall gradient in the Grassland biome, the prediction of an increase in tall shrubs and trees by various models and field observations (Bond & Midgely 2012; Higgins & Scheiter 2012; Midgely & Thuiller 2011; Wigley *et al*. 2010; Puttick *et al*. 2011) was generally supported although results were a little more equivocal in the more arid Nama-karoo biome. A critical finding in this regard is that species with relatively strong subtropical biogeographic affinities such as *Rhus longispina, Acacia karroo* and even *Portulacaria afra* at some sites have also increased in the Albany Thicket biome despite the suggestion that this biome will contract under future climate change pressures (Robertson & Palmer 2002). Other studies in the Albany thicket biome have shown just how slow-growing some of the more common thicket species are (van Der Vyver *et al*. 2011) and the negligible change in tall shrub cover within the Albany Thicket biome of the Camdeboo National Park over 20 years (Chapter 3) supports this view. The role of *Portulacaria afra* as an ecosystem engineer with the Albany Thicket biome (van Der Vyver *et al*. 2012) appears central to the recovery of the tall shrub and tree component within this biome. It was, therefore, especially encouraging to record an increase in cover of this species at some of the locations studied.

Explanations for the changes observed between biomes over time are clearly very complex and have arisen from a combination of land use and climate drivers. The decline in stock numbers in the region is important as are the change in rainfall seasonality and the increase in temperature range in some parts of the region. Higher CO_2 levels have also probably played a role through its impact on the water use efficiency of rangeland plants. Many other factors, not investigated in this study might also have had an influence. For example, the increase in tall shrubs is clearly promoted by the presence of fences which allow birds to perch and deposit seeds of fruit-bearing shrubs and trees (e.g. *Rhus* spp.). Long lines of tall shrubs or trees, for example, are visible across the Karoo Midlands region in association with the many thousands of kilometres of fencing that have been erected in the area over the course of the 20th century. Further monitoring, together with carefully developed landscape-level experiments, is needed to discern the relative influences of land use and climate drivers on the extent, nature and rate of vegetation change in the region.

6.4. Broader implications of the study

The repeat photographs and vegetation surveys used in this study have been useful in understanding and documenting past changes and in evaluating potential future trends within the vegetation of the Karoo Midlands region. Using these techniques I was able to quantify the rate, nature and direction of vegetation change for the region at a range of spatial and temporal scales (Rogers *et al*. 1984). The findings of this study have created benchmark conditions for the different biomes and have provided an understanding of land cover change in one part of southern Africa over the last 100 years.

The risks are high across the globe that biodiversity protection and conservation in protected and unprotected areas will be jeopardized by inadequate capacity, planning and policy to deal with climate change (Araujo *et al*. 2011; Hannah *et al*. 2007). Future predictions of climate change and vegetation response, however, can also be informed by an understanding of the past (Costanza *et al*. 2012). Sustained shifts in dominant species and functional groups (e.g. grasses and shrubs), particularly at landscape and regional scales (Opdam *et al*. 2012), provide crucial evidence for the role of climate change impacts on biodiversity in our ecosystems. Important findings from this thesis will also contribute towards South Africa's Monitoring and Evaluation System outlined in the White Paper document entitled "*National Strategy on Climate Change Response*" (Anonymous 2011; DEA 2011). This initiative will benefit from an understanding of the historical trajectories of vegetation change in the Karoo Midlands region since a biome-based response is advocated in the strategy document. The increase in trees and grasses provides evidence for changes within several key biomes and presents appropriate and up-to-date benchmarks for the vulnerability and resilience planning component of the strategy.

Irrespective of such plans and policies, however, farmers and conservation managers can do little about managing the main climatic drivers such as rainfall, temperature and CO_2. This leaves them with fire and herbivory as the primary tools available for them to mitigate the impacts of climate change on biodiversity. How these tools are used will further influence the movement of species and the response of important ecosystem functions such as water movement and nutrient flow to climate change (Opdam *et al*. 2012).

In this study fire is an important management tool in the mesic grassland area to the northeast of the study area (Bond *et al*. 2003; Knapp *et al*. 2008). Its main use in these areas and similar environments is to reduce shrub cover and favour grasses (Trollope 1984; Ansley *et al*. 2010). The use of fire in the Nama-karoo biome, however, where it has been low to non-existent in the past might increase in future. This, in turn, will further promote grass dominance and lead to a switch from small stock to cattle farming (Nel 2008). The decline in karoo shrubs, which form an important part of the diet of sheep in the winter months in the Nama-karoo biome (Du Toit 1998; Brand 2000), has important negative implications for mutton and wool production outputs from the region (www.capewools.co.za).

Grazing by domestic livestock, and increasingly by indigenous ungulates, is the most important land use practice in the region. While there has been a long history of grazing-related research emanating from the universities and agricultural colleges in the region such as Glen and Grootfontein Agricultural College (Roux 1968) new research is needed on the impact of temperature and CO_2 increase. The interaction between local drivers and global drivers and the relative contribution of each to land cover change is an area of research which is also urgently needed. This thesis has demonstrated significant changes in the vegetation of the Karoo Midlands region over time and has made the case for continued long-term monitoring at these and other sites over the coming decades.

The protected area network managed by conservation agencies such as the South African National Parks will benefit from this study in terms of skills and knowledge transfer. Structured methodological and analytical techniques for assessing long-term vegetation change have been developed in this thesis and could be employed more widely for monitoring purposes. Within the SANParks network of conservation areas there are thousands of repeat photographs that have been taken but not analysed. In addition, these collections are rarely archived in a systematic way that will advance the knowledge and understanding of environmental history in the parks. For example, the extensive collection of repeat photos taken at the Camdeboo National Park (CNP) from 1988 had not been used as a management tool prior to this study. The updating and digitization of these images, together with analysis and proper archiving has provided the CNP management with an understanding of how the vegetation in the protected area has changed over time and in response to climate and herbivory. Other national parks such as Table Mountain National Park have also used photographic monitoring to document landscape-level vegetation changes. However, these collections need to be updated, analysed and archived for future monitoring purposes. A logical systematic standard for archiving the numerous repeat photography collections in all protected areas is urgently needed. The results from this study provide testimony to the important role of long-term monitoring in understanding land cover change in the region at a local scale.

At regional or national scale, important contributions of this research concern not only the knowledge about environmental change but also its relevance for policy. For example, the National Protected Areas Expansion Strategy of South Africa (2010) has some focus on the Camdeboo Escarpment, Karoo Escarpment and Upper Karoo regions. The proposal is to connect these areas with the Free State Highveld Grassland priority area as well as with the Amathole-Tarkastad region to the east. Such an expanded protected area network will potentially connect the Baviaans-Addo region along the coast with the Southern Berg priority area in the interior. This study documented and monitored a few localities within the planned expansion areas. The findings provide some evidence of the nature, extent and rate of vegetation that has occurred in the region. The geo-referenced and well-archived site data can also be used as a benchmark against which future changes in the region can be evaluated.

The thesis will also provide South African Environmental Observatory Network (SAEON), the national facility responsible for long-term ecological research in South Africa, with a properly-archived set of repeat photographs. Together with the associated metadata these repeat photographs can be used for on-going investigations of environmental change on the sub-continent. This will add to the developing knowledge base of long-term change and the relative influences that climate and humans have had on the region’s rangeland resources. It will also better equip natural resources managers to conserve South Africa’s rangelands for the benefit of future generations as stipulated in the country's Bill of Rights and the National Environmental Management Act (NEMA).

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