A geobotanical investigation of mountain ecosystems in Griqualand West, South Africa

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‘For you shall go out in joy and be led forth in peace; the mountains and the hills before you shall break forth into singing, and all the trees of the field shall clap their hands.’

Isaiah 55:12

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Declaration

I, Nanette van Staden, hereby declare that the work presented in PhD thesis, is my own. All sources that were used and/or quoted have been acknowledged by complete reference. The thesis has not been submitted for any other degree or examination at any other university. This PhD thesis is being submitted for the degree Doctor of Philosophy at the North-West University of the Potchefstroom Campus.

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Dedicated to Maria Wilman, John Acocks, William Burchell, Braam van Wyk,
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Abstract

The Griqualand West Centre (GWC) of plant endemism harbours a unique flora of which 24 species are endemic. Heterogeneous geology, climate and topography are considered drivers of the unique flora and local endemism. However, these drivers have not yet been investigated and our understanding of the effects thereof on vegetation dynamics remains poor. Four mountain ecosystems, each underlain by different rock types and with distinct climatic patterns, provided a setting to investigate the effects of ecological drivers shaping vegetation dynamics of this semi-arid area. Therefore, the primary aim of this study was to disentangle the effects of rainfall and geology, through soil properties related to the underlying geological parent material, as drivers of floristic patterns, plant diversity and structure, biomass production, and the relationship between diversity and biomass production. The objectives of this study were to (i) redefine the borders of GWC to establish which mountain ranges fall within the centre by using a MaxEnt spatial model based on geology, climate and topography in combination with distribution data of GWC endemics, (ii) describe the flora within the newly redefined borders of GWC based on dominant plant families and -species, indicator plant species, endemic species and species composition, (iii) compare soil properties, rainfall, plant diversity and structure between mountain ecosystems to test whether mountains, within the newly defined borders of GWC, differ significantly from each other, (iv) determine whether soil properties, rainfall or a combination thereof act as drivers of plant diversity and structural differences between mountains, (v) test for differences in total biomass production (above ground green plant material and debris), live biomass production (only live green above ground plant material) and respective plant functional group (PFG) biomass production between the four mountain rangelands, (vi) relate differences to specific soil properties and rainfall to identify the strongest drivers of biomass production, (vii) investigate diversity-biomass relationships for total plant species and for species representing different PFGs, and (viii) present an optimal range of biomass production at which herbaceous species diversity can be maintained at regional scale. Results obtained from this study revealed that each mountain plant community was characterised by unique herbaceous plant communities with specific indicator plant species, driven by soil properties and rainfall. Herbaceous plant composition, density, height, cover and shrub frequencies were related to a combination of soil properties and mean annual rainfall. However, plant diversity, and grass, lignified forb and tree frequencies, as well as woody plant height and canopy area, could only be related to soil properties. Grasses, lignified forbs and herbaceous forbs contributed to biomass production in descending order. At regional and local scales, diversity-productivity relationships followed non-linear trends. However, optimum biomass production was reached at highest diversity. Semi-arid mountain landscapes in GWC provide important ecosystem services through their unique plant diversity. It is necessary to follow a holistic, multi-disciplinary conservation and management approach to not only manage for species diversity, but to conserve the underlying environmental drivers in semi-arid mountain plant communities.

Key words: *banded ironstone; diversity-productivity relationships; dolomite; edaphic specialists; endemism; flora; plant-soil interactions; quartzite; rainfall; soil nutrients*

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Chapter 1

Introduction and general literature review

1.1. Background and rationale

Griqualand West (GW) is a distinct semi-arid region within the Savanna Biome of South Africa (Van Wyk & Smith, 2001; Mucina & Rutherford, 2006). The region is characterised by a high landscape diversity, which is considered to drive the distinctive flora, of which 24 species are endemic to the Griqualand West Centre of plant endemism (GWC) (Van Staden *et al.*, 2020). Despite its unique flora, vegetation dynamics of the region are understudied (Van Wyk & Smith, 2001; Frisby *et al.*, 2019). Drivers of plant species diversity remain uncertain in GWC. Yet, Frisby *et al.* (2019) divided GWC into four primary floristic regions that were linked to geology, topography and climate. Three of these regions were found to correspond to mountainous regions, i.e. the Ghaap Plateau, Kuruman- and Asbestos Hills (collectively called the ironstone hills), and the Langberg which differ in their underlying geology and climatic conditions. Soil fertility and –moisture availability are considered some of the most important determinants of savanna vegetation structure and productivity (Skarpe, 1992; Scholes, 1997). Considering its habitat heterogeneity and distinct climatic patterns, mountain ranges in GWC provided the setting to investigate how these ecological drivers shape floristic patterns, plant community structure and productivity.

Studies conducted in GW from 1967 to 2020 focused mainly on geology, drought and interannual rainfall variability (Tfwala *et al.*, 2018) and botany (Mostert, 1967; Tokura *et al.*, 2018; Frisby *et al.*, 2019; Van Munster *et al.*, 2019; Van Staden *et al.*, 2020). Additional literature (not indicated by Scopus) included the study of Ferreira (1927), Wilman (1946), Frisby (2015) and Ranwashe (2019). This brings the total of scientific botanical studies in GW to nine, excluding environmental impact assessments. However, scientific interest in GW is increasing since the South African Environmental Observation Network (SAEON) Arid Lands Node (J. Henschel personal communication, March 3, 2014) as well as the McGregor Museum (2007) identified the region as a priority research area. A meeting held with the Department of Environment and Nature Conservation (DENC) of the Northern Cape Province in 2017, revealed specific research needs that demand answers to ensure proper decision-making regarding management and conservation in GWC. The necessity for increased scientifically orientated botanical studies, is emphasised when considering major threats to GW which include mineral mining, hydraulic fracking, inappropriate rangeland management and climate change (Frisby, 2015).

Climate change poses serious threats to ecosystem intactness and plant diversity due to changes in rainfall, increasing temperatures and more frequent extreme events, such as floods, droughts and heat waves (Thuiller, 2007; Yates *et al.*, 2010; Mbokodo *et al.,* 2020). temperatures in South Africa have increased up to 2°C in the central interior regions in autumn between 1960-2010 (MacKellar *et al.*, 2014) and surface air temperatures more than 0.02°C per year during 1980-2014 (Jury, 2018). In contrast precipitation trends remain vague despite model simulations (MacKellar et al., 2014; Van Wilgen *et al.*, 2016). However, changes in rainfall patterns are a real threat, with more regions being susceptible to drought (Joubert, 2011; Stevens *et al.*, 2015; Van Wilgen *et al.*, 2016; Swemmer *et al.,* 2018; Smit & Bond, 2020). The Northern Cape Province was classified as a provincial disaster area due to the extreme drought of 2017/2018 (Tandwa, 2018). In January 2020, the province was still declared as a disaster area by the Northern Cape Premier (Kassen, 2020).

It is projected that the province will continue to experience drastic increases in annual average temperature, whereas rainfall anomalies are characterised by drying (DEA, 2013). Under these conditions, habitat plant specialists, which are adapted to specific soil and/-or environmental conditions associated within their habitats, may be threatened (Midgley *et al.*, 2002) since these plant species will be slow to adapt to changing environmental conditions (Rutherford *et al.*, 1999; Damschen *et al.*, 2010). Consequently, these species may become extinct or undergo range shifts (Rutherford *et al.*, 2000). A study on modelling by Harrison *et al.* (2009) suggested that edaphic floras, adapted to certain soil conditions, will only be threatened under wetter and warmer climate, since soil generalist plant species will outcompete edaphic specialists under such conditions. Under a drier and warmer climate, edaphic specialists will be less adversely affected and expand their distribution ranges to habitats with less harsh soils and outcompete generalists (Harrison *et al.*, 2009). In addition, Hoorn *et al.* (2013) stated that mountain plant species are specialised to a smaller area and hence may experience lower rates of extinction under climate change. This is ascribed to these species' requirements to move over shorter distances to reach their optimal temperature range in comparison to lowland species. Therefore, there is a higher likelihood of some of these species to disperse into other areas. Under this scenario, mountainous regions can then serve as a source of diversity under climate change. However, discrepancies prevail in the literature regarding whether edaphic specialists will be threatened or be adaptable to climate change (Damschen *et al.*, 2012).

Generally, increasing drought events and warmer temperatures cause loss of plant species and hence contribute to decreasing levels of above ground biomass production (Lohmann *et* *al.*, 2012). Consequently, carrying capacities of rangelands are expected to decline, which will lead to increased concerns among commercial and subsistence farmers due to the forced reduction of livestock numbers. Therefore, economic development in GW may be under pressure in the future.

To fully understand the potential negative effects of climate change on the ecosystem well-being of GW, an ecological and floristic investigation on top-down (climate) and bottom-up (geology, soil) controls, are needed. Such studies will provide baseline information for the establishment of long-term studies in GW, with the ultimate goal to aid management and conservation initiatives in the region.

1.2. Aim and objectives

The primary aim of this study was to disentangle the effects of geology, through soil properties, related to the underlying geological parent material, and rainfall as drivers of floristic patterns, plant diversity and structure, biomass production as well as relationships between diversity and biomass of four mountain ecosystems in GW.

Results chapters of the thesis were structurally designed to address three main research topics. These included (i) a floristic analysis of the mountain ecosystems in GW, (ii) analyses and comparison of plant species diversity and structure between GW mountain ranges, and (iii) assessments of biomass production and diversity-biomass relationships in response to rainfall and soil properties at regional and local scale.

Specific objectives were therefore to:

1. Redefine the borders of GWC to establish which main mountain ranges fall within the centre by using a MaxEnt spatial model based on geology, climate and topography in combination with distribution data of GWC endemics.
2. Describe flora within the newly redefined borders of GWC based on dominant plant families and -species, indicator plant species, endemic species and species composition.
3. Test whether mountain ecosystems within the newly defined borders of GWC differ from one another through comparing soil properties, rainfall, plant diversity and structure.
4. Determine whether soil properties, rainfall or a combination thereof act as drivers of plant diversity and -structural differences between mountains.
5. Test for differences in total biomass production (above ground green plant material and debris), live biomass production (only live green above ground plant material) and

respective plant functional group (PFG) biomass production between the four mountain rangelands.

6. Relate biomass differences between mountain rangelands to specific soil properties and rainfall to identify the strongest driver of biomass production.
7. Investigate diversity-biomass relationships for total plant species and for species representing different PFGs.
8. Present an optimal range of biomass production at which herbaceous species diversity can be maintained at regional scale.

1.3. Hypotheses

Hypothesis 1: Plant communities of the respective mountain ecosystems will be characterised by unique assemblages associated with particular indicator plant species.

From a biogeographical perspective, each mountain ecosystem can be considered as an edaphic island (Burke, 2001; Rajakaruna, 2004). Each island exhibits a specific microclimate and microhabitats (Kruckeberg, 1969). Over evolutionary time, plant species had the opportunity to undergo specialisation and adapt to edaphic and climatic conditions associated with the specific edaphic island (Rajakaruna, 2004; 2018). Consequently, certain plant species have gained a competitive edge and, are able to persist in a particular niche or developed tolerance to edaphic conditions (Mason, 1946a; Rajakaruna, 2004; 2018).

Hypothesis 2: A combination of soil properties and rainfall will act as drivers of herbaceous species composition, plant diversity and vegetation structure across mountain ecosystems.

Special edaphic floras with distinct climatic conditions are generally associated with distinct plant assemblages, suggesting plant-soil interactions in these unique plant communities. These results were observed for quartzite (Neely & Barkworth, 1984; Schmiedel & Jürgens, 1999; Curtis *et al.*, 2013), banded iron formation (Jacobi *et al.*, 2007; Jacobi & Do Carmo, 2008; Meissner *et al.*, 2009; Gibson *et al.*, 2012) as well as limestone (Henderson, 1939; Goldin, 1976; Zhu *et al.*, 1998; Clements *et al.*, 2006) and dolomitic habitats (Neely & Barkworth, 1984; Siebert & Siebert, 2005; Mota *et al.*, 2008). From this, it is hypothesised that each mountain ecosystem will be characterised by unique plant assemblages that correspond to the specific underlying geology due to plant-soil interactions. Additionally, it is expected that rainfall will contribute to these expected patterns. It is furthermore hypothesised that a combination of soil properties and rainfall will drive herbaceous plant assemblages in the mountain ecosystems of GWC.

Hypothesis 3: Relationships between plant species diversity and biomass will be unimodal at a regional scale but non-linear at a local scale.

The relationship between diversity and biomass is a highly debated subject in ecology, since these relationships may vary between being linear, non-linear and unimodal, while some studies also found no clear pattern (Guo & Berry, 1998; Mackey & Currie, 2001; Mittelbach *et al.*, 2001; Adler *et al.*, 2011; Fox, 2013; Fraser *et al.*, 2014; Koerner *et al.*, 2018; Zhu *et al.*, 2020). From these studies, some have identified linear relationships, suggesting that the productivity hypothesis of Connell and Orias (1964) is supported. According to this hypothesis, high species diversity will be accompanied by high levels of biomass production, producing a positive linear relationship. Yet, the most supported diversity relationship is the unimodal trend (Guo & Berry, 1998; Mittelbach *et al.*, 2001; Kershaw & Mallik, 2013; Fraser *et al.*, 2015; Van Coller & Siebert, 2015; Brun *et al.*, 2019; Xiao & Chen, 2019; Gao & Carmel, 2020) as initially proposed by Grime (1973). Certain factors are important to consider when investigating diversity-biomass relationships, especially habitat heterogeneity and limiting factors, since these variables contribute to the occurrence, co-existence and niches of plant species (Tilman *et al.*, 1997; Guo & Berry, 1998; Pausas & Austin, 2001; Lundholm & Larson, 2003). Hence, there are co-varying underlying factors and mechanisms that contribute to patterns when diversity-biomass relationships are investigated (Waide *et al.*, 1999; Graham & Duda, 2011). The multivariate productivity hypothesis (MPH) is considered more suitable to explain diversity-productivity relationships in natural plant communities (Cardinale *et al.*, 2006; Gross & Cardinale, 2007; Cardinale *et al.*, 2009). This hypothesis, as suggested by Cardinale *et al.* (2009), separates species richness components into colonists and competitors in the general species pool, since species are influenced by various environmental factors, especially with respect to resource supply. The MPH therefore suggests three primary pathways that generate diversity-productivity (in this study, above ground biomass collected for one year is used as a proxy of productivity). The first pathway considers resource supply as a direct limiting factor on aboveground biomass and/or productivity (rate of new production) by primary producers. Secondly, biomass levels are directly influenced by the species richness of local competitors of the species pool, and lastly, resource supply rates indirectly affect biomass levels through a certain number of colonising species that locally coexist in the species pool. From these three pathways, it is expected that geological formations that are known to harbour nutrient-rich soil and hence support possible high resource supply rates to the local species pool, will result in higher biomass production. Additionally, soil nutrients and rainfall will act as co-varying drivers of biomass production. It is expected that regional diversity-biomass relationships will follow a unimodal trend. At local scales, where each mountain ecosystem has distinct microclimates and underlying local heterogeneity, diversity-biomass relationships will respond more dynamically with diversity peaking at certain levels of biomass, resulting in non-linear trends.

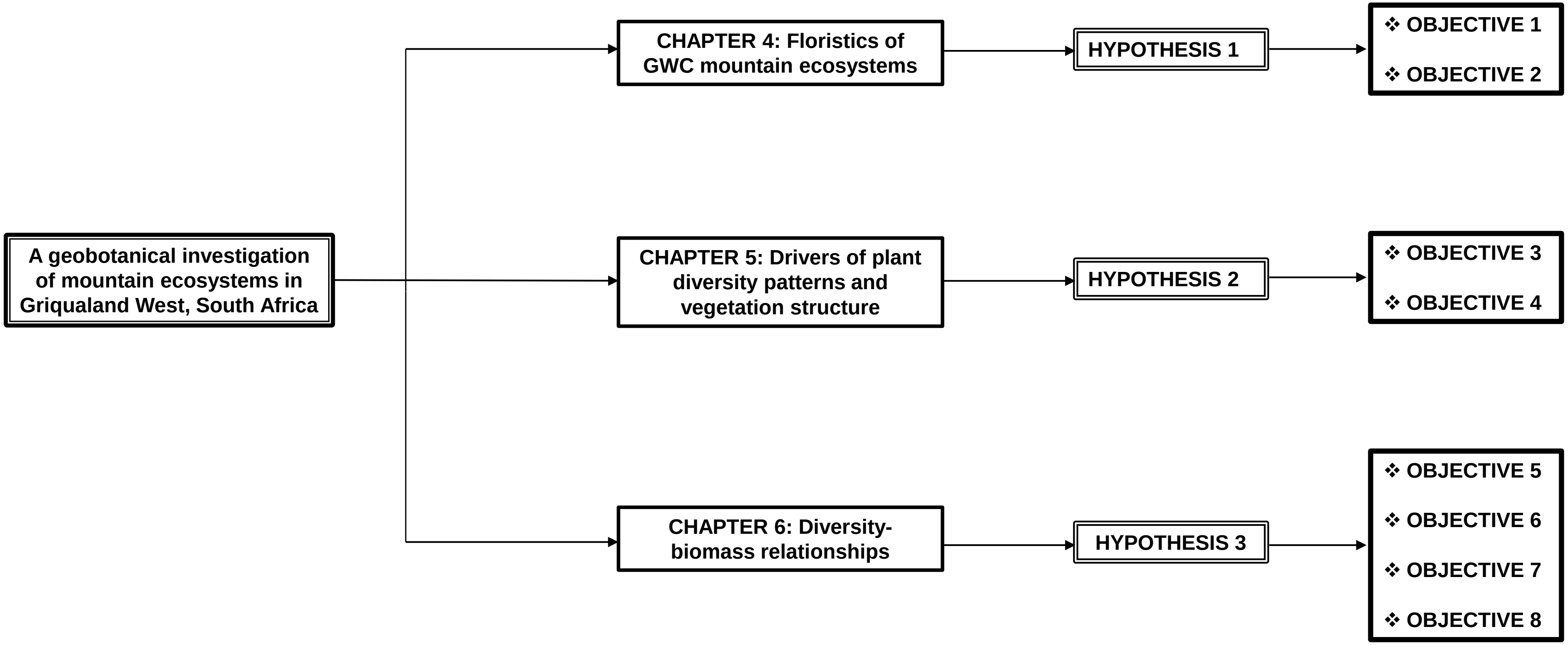

Figure 1.1. Summary of results chapters linked to specific hypotheses and objectives.

1.4. Structure of thesis

The thesis adheres to specific guidelines stipulated for a standard research thesis in the Manual for Post Graduate Studies of the North-West University (2016). This thesis comprises seven chapters. The format of results chapters follows a similar approach as associated with the preparation of manuscripts for submission to scientific journals for publication. As proposed by the DENC, recommendations are provided that directly address their conservation and management needs in a clear and comprehensible manner in Chapter 7.

Chapter 2: Overarching methodological approach

A detailed account of the study area is provided in this chapter. Comprehensive information presented on GW includes historical background and general characteristics of GW followed by detailed descriptions of each mountain ecosystem. Information regarding associated land use and land cover types in the GW region is provided. The general methodology is described and includes the experimental design, collection of field data, laboratory analysis as well as an overview of statistical analysis applied to obtain results associated with Chapters 3 to 6.

Chapter 3: Carbonate soils and ecosystems in Africa: A review

This chapter presents a focused literature review. The main aim of this chapter is to identify research gaps pertaining to edaphic specialists within centres of endemism on soils rich in magnesium (Mg) and calcium (Ca) in Africa. Ultimately, future research on these distinct substrates can be directed to ensure proper conservation and management of these unique plant species and their associated plant communities and habitats.

Chapter 4: Floristics of GWC mountain ecosystems

In this chapter, hypothesis 1 is tested through addressing objectives 1 and 2 (Figure 1.1). The chapter provides visual and tabular results regarding floristic analysis based on dominant plant families, herbaceous assemblages, common species, indicator plant species as well as numbers of endemic plant species. The chapter addresses conservation importance of each mountain ecosystem based on floristic analysis. This chapter has been published (Appendix E).

Chapter 5: Drivers of plant diversity patterns and vegetation structure

Results associated with the third and fourth objectives are presented and hypothesis 2 is tested (Figure 1.1). Statistical analysis, based on plant species abundances to generate species diversity measures, investigated effects of rainfall and soil properties, derived from the geological parent material, on plant species diversity and vegetation structure of each mountain plant community. Furthermore, together with chapter 4, this chapter indicates which mountain system should be considered a conservation priority area, not only based on floristic analysis, but also based on species diversity measures.

Chapter 6: Diversity-biomass relationships

This chapter focuses on the four mountain ecosystems as rangelands, since the primary ecosystem function of these landscapes are forage production to subsistence and commercial farmers. Therefore, hypothesis 3 and objectives 5-8 are addressed in this chapter (Figure 1.1). Diversity measures, generated in chapter 5, are used as a function of biomass production to determine diversity-biomass relationships at regional (for GW) and local (each mountain system) scale. Additionally, PFG specific diversity-biomass relationships are presented. It was revealed that herbaceous biomass production is driven by interactions between soil properties and rainfall. Diversity-biomass relationships, at regional and local scale, followed a non-linear trend. However, with regards to total herbaceous plant diversity, a positive linear relationship prevailed at regional scale. This suggested that plant diversity is thus maintained at high levels of biomass.

Chapter 7: Conclusions and recommendations

Major findings of this thesis are presented. Recommendations to guide future conservation and management practices for GWC mountain ecosystems are provided. Future research questions that need further investigation are also identified.

1.5. General literature review

1.5.1. Defining mountainous landscapes

Terrestrial mountains and/or mountainous landscapes are generally defined by local perceptions. These definitions are problematic since they are inadequate to provide a global perspective of mountains geographically (Kapos *et al.*, 2000). Altitude and slope were used by Kapos *et al.* (2000) to identify six classes of mountainous areas. In addition to their classification, the United Nations Environment Programme (UNEP) developed four main criteria to define mountain landscapes which are used to appropriately define mountains (Table 1.1). Considering these classes, the four mountains included in this study can be considered as mountains since their elevation ranged between 1 100-1 840 m and are associated with steep slopes (10-50º), with the exception of the Ghaap Plateau that is generally flat (0-1.5°) except for its steep escarpment (5-50º).

Table 1.1. The four criteria, as developed by United Nations Environment Programme (UNEP), to define terrestrial mountains. Adapted from Blyth (2002) and Chakraborty (2019).

Class	Definition
1	Regions with an altitude greater than 2 500 m
2	Regions with a minimum altitude of 1 500 m and a slope above 2º
3	Regions with a minimum altitude of 1 000 m and a slope above 5º
4	Regions with a minimum altitude of 300 m and local elevation range of 300 m

1.5.2. Why study mountains?

Biodiversity, in all its components, maintain and safeguard provision of ecosystem services, thereby insuring ecosystem stability (Tilman, 1999; Yachi & Loreau, 1999; Chapin *et al.*, 2000; Loreau *et al.*, 2001; Millennium Ecosystem Assessment, 2005; Balvanera *et al.*, 2006; Mace *et al.*, 2012; Tilman *et al.*, 2014; Turnbull *et al.*, 2016). Mountains are considered biodiversity reservoirs (Perrigo *et al.*, 2019) and biodiversity hotspots with high levels of endemism (Körner, 2004; Mittermeier *et al.*, 2011; Spehn *et al.*, 2011; Smyčka *et al.*, 2017; Noroozi *et al.*, 2018; Carbutt, 2019; Noroozi *et al.*, 2019; Rahbek *et al.*, 2019; Silveira *et al.*, 2019) that provide valuable ecosystem services, i.e. provisioning, regulating, cultural and supporting services, that maintain or contribute to human well-being (Blyth, 2002; Hamilton & McMillan, 2004; Thuiller, 2007; Grêt-Regamey *et al.*, 2012; Egan & Price, 2017). The most valuable provisioning services provided by mountains to humans include the provision of fresh water, medicinal plants, fodder for livestock, food, fibre and timber (Körner, 2004; Egan & Price, 2017).

Given increased human population growth as well as climate change, these diverse and unique landscapes are increasingly becoming vulnerable to land use, (Beniston, 2003; Körner, 2004; Gottfried *et al.*, 2012; Grêt-Regamey *et al.*, 2012; Platts *et al.*, 2013; Bentley *et al.*, 2019; Malanson *et al.*, 2019; Manish, 2019; Pringle, 2019; Tito *et al.*, 2020). Consequently, in the Anthropocene epoch these diverse landscapes may be prone to homogenisation resulting in biodiversity loss that will lead to declining provision of vital ecosystem services that will have socio-economic implications (Vitousek *et al.*, 1997; Chakraborty, 2019; Newbold *et al.*, 2019; Li *et al.*, 2020). The ecological study of mountains is therefore necessary to promote our understanding of underlying mechanisms which could act as drivers of diversity, as to insure human well-being through sustainable land use, proper land management strategies and conservation policies (Egan & Price, 2017). Additionally, mountains are natural laboratories where effects of climate change can be studied and explored along natural environmental gradients (Tito *et al.*, 2020). Thus, indirect and direct impacts of climate change can be identified to provide empirical evidence upon which recommendations can be made to mitigate effects of global change (Chakraborty, 2019; Silveira *et al.*, 2019; Tito *et al.*, 2020). However, considering the heterogeneous nature of mountains, future studies will require a multi-disciplinary approach (Chakraborty, 2019).

1.5.3. Mountain heterogeneity

Climate is generally considered the ultimate factor driving vegetation distribution patterns (Forseth, 2010). However, geological heterogeneity contributes a great deal to a flora of a region (Jenny, 1941; Cain, 1944; Kruckeberg, 1986; Rajakaruna, 2004). Geological heterogeneity acts as a driver of plant diversity, since edaphic factors generate diverse and unique habitats in which plant species and associated organisms live together, interact, reproduce and diverge over time, especially on unusual soils (Jenny, 1941; Cain, 1944; Kruckeberg, 1986; Rajakaruna & Boyd, 2008). Such unique habitats include mountainous landscapes.

Mountain landscapes differ in geology and climate compared to surrounding areas and are therefore perceived as island-like systems (Schmiedel & Jürgens, 1999; Barthlott & Porembski, 2000; Ogden, 2002; Rajakaruna, 2004; Rajakaruna & Boyd, 2008; Burke, 2019; Itescu, 2019). In these systems, microclimatic conditions driven by environmental factors such as topography and edaphic conditions produce various microhabitats (Porembski *et al.*, 2000; Szarzynski, 2000; Burke, 2003; Körner, 2004; Scherrer & Körner, 2011; Oke & Thompson, 2015). Each microhabitat is characterised by distinct plant communities adapted to thrive under associated microclimatic conditions (Wolf, 2001; Körner, 2004; Jacobi *et al.*, 2007; Bentley *et al.*, 2019). Hence, geological heterogeneity which contributes to fine scale environmental heterogeneity, can be considered as a major driver of mountain diversity (Jobbágy *et al.*, 1996; Körner, 2004; Chakraborty, 2019; Muellner-Riehl *et al.*, 2019; Perrigo *et al.*, 2019).

Geology and climate interacted as drivers of evolutionary speciation of plant species that resulted in the development of special edaphic floras due to environmental heterogeneity over time (Kruckeberg, 1969; Goldin, 1976; Körner, 2004; Damschen *et al.*, 2010; Gibson *et al.*, 2012; Hoorn *et al.*, 2013; Frisby *et al.*, 2019; Perrigo *et al.*, 2019). These edaphic floras consist of plant species that are habitat specialists, exclusively adapted to prevail under specific edaphic conditions and exploit their niche resources (Mason, 1946a; 1946b; Raven, 1964; Willis *et al.*, 1996; Schmiedel & Jürgens, 1999; Siebert *et al.*, 2001; Rajakaruna, 2018; Chakraborty, 2019).

Unique edaphic floras on mountains prevail in centres of plant endemism (Kruckeberg & Rabinowitz, 1985; Van Wyk & Smith, 2001; Jacobi *et al.*, 2007; Williamson & Balkwill, 2015; Noroozi *et al.*, 2018; Carbutt, 2019; Manish, 2019; Wang *et al.*, 2020). Mountains are associated with high speciation, low extinction rates (Hoorn *et al.*, 2013) and/or allopatric speciation driven by geographic isolation (Noroozi *et al.*, 2018), diversification and environmental filtering (Smyčka *et al.*, 2017). These processes contribute to sustaining unique, diverse, species rich and endemic mountain floras (Burke, 2001; Peñas *et al.*, 2005; Harrison *et al.*, 2009; Damschen *et al.*, 2012; Smyčka *et al.*, 2017).

1.5.4. Floras of unusual geologies

'Within a given climatic region, the growth of vegetation is mainly determined by the character of the parent material, whether limestone, igneous rock, sand deposit or clayey-shale'.

-Hans Jenny (Jenny, 1941)

Plant diversity, composition and community structure are shaped through plant-soil interactions (Robinson *et al.*, 1997; Harrison, 1999; Schmiedel & Jürgens, 1999; Dubbin *et al.*, 2006; Nunes *et al.*, 2015; Do Carmo & Jacobi, 2016; Burke, 2019). Three different geological types applicable to this study will be discussed focusing primarily on their unique soil properties and plant communities. This section will focus on mountains underlain by banded iron formation (BIF) and quartzites. In Chapter 3, Ccrbonate soils, such as those underlain by limestone and dolomite, will be extensively reviewed, with a specific focus on Africa.

1.5.4.1. Banded iron formation (BIF)

Banded iron formation is defined as a sedimentary rock type consisting of alternating layers of silicon dioxide (fine white quartz) and iron oxides (McCarthy & Rubidge, 2005; Trendall, 2013). It is classified as a chemical sediment formed through precipitation of iron oxide from seawater during the Precambrian era (Horstmann & Hälbich, 1995). Due to the high content of iron, these rock types vary in colour from red to black (McCarthy & Rubidge, 2005). Since this rock type is rich in iron and manganese ore, it is of high economic value (Trendall, 2013) and mined in South Africa (Horstmann & Hälbich, 1995; Eriksson *et al.*, 2006; Mining Weekly, 2018; Frisby *et al.*, 2019; Mining Technology, 2019), Brazil (Jacobi *et al.*, 2007;

Jacobi & Do Carmo, 2008; Nunes *et al.*, 2015; Do Carmo & Jacobi, 2016; Salles *et al.*, 2019) and Australia (Markey & Dillon, 2011a; Gibson *et al.*, 2015; Byrne, 2019; Miller *et al.*, 2019).

Mining therefore threatens these valuable ecosystems of BIF, necessitating research and conservation of such landscapes. A literature search in the Scientific Database Scopus (2020) revealed that Australia (45 studies) and Brazil (9 studies) are the leading countries with respect to research on ironstone plant communities, while South Africa is poorly represented by only one study (Frisby *et al.*, 2019). The publication by Van Staden *et al.* (2020), from this thesis, was not yet recognised by Scopus (2020) at the time of review. Thus, the latter already contributed to the literature gap associated with botanical research of BIF landscapes in South Africa.

Plant communities underlain by BIF are distinct in floristic composition (Meissner *et al.*, 2009; Meissner & Wright, 2010; Markey & Dillon, 2011a; Markey & Dillon, 2011b; Thompson & Sheehy 2011; Gibson *et al.*, 2015; Van Staden *et al.*, 2020), structure (Gibson *et al.*, 2010; Jacobi & Do Carmo, 2011; Do Carmo & Jacobi, 2016), are species rich and diverse (Jacobi *et al.*, 2007; Jacobi & Do Carmo, 2008; Gibson *et al.*, 2010; Do Carmo *et al.*, 2018) and harbour various endemic plant species (Gibson *et al.*, 2012; Millar *et al.*, 2014; Nistelberger *et al.*, 2015a; Nistelberger *et al.*, 2015b; Scatigna *et al.*, 2017; Turner *et al.*, 2018; Frisby *et al.*, 2019; Robinson *et al.*, 2019; Van Staden *et al.*, 2020). Many of these endemic species are habitat specialists that are restricted to ironstone (Yates *et al.*, 2011; Gibson *et al.*, 2012; Gibson *et al.*, 2015; Elliott *et al.*, 2019; De Barros Ruas *et al.*, 2020) and have conservation value (Gibson *et al.*, 2007; Meissner *et al.*, 2009; Meissner & Wright, 2010; Markey & Dillon, 2011a; 2011b; Do Carmo *et al.*, 2018; Byrne, 2019; Miller *et al.*, 2019; Salles *et al.*, 2019; Van Staden *et al.*, 2020).

The distinctiveness of ironstone plant communities is driven by a series of environmental factors. In arid and hot ironstone landscapes in western Australia, Gibson *et al.* (2015) reported that soil chemistry and climate, contributed to life history of especially perennial life forms and species richness in general. Ironstone specialists and richness thereof, were mostly driven by altitude, followed by Magnesium (Mg) and Calcium (Ca) soil content. Gibson *et al.* (2012) found that a high turnover of perennial plant species contributed to diversity between ironstone ranges in south western Australia. Variance in spatial scale and climate were drivers of variance in richness of perennial plants along an aridity gradient within this region (Gibson *et al.,* 2012). Ironstone plant communities occurring in dry climates were associated with lower species richness compared to more seasonally wet ironstone ranges. With increasing aridity, generalist plant species were more abundant suggesting physiological tolerance to the harsh environmental conditions (low rainfall, high soil temperatures). Consequently, specialists were exposed to extinction driven by stochastic processes in the drier systems (Gibson et al., 2012). Therefore, despite being on the same parent material, the climatic gradient contributed to the distribution of specialist taxa (Gibson *et al.,* 2012).

Soil chemistry was also revealed to be a major driver of these taxa in combination with broad scale spatial variation (Gibson *et al.*, 2012). In south western Australia, Gibson *et al.* (2010) related compositional changes and diversity patterns primarily to local scale heterogeneity in topography rather than geology and climate. Phytosociological investigations revealed that ironstone plant communities were distinct from one another and that differences were also related to geological substrate, soil chemistry and topography (slope position) (Meissner & Wright, 2010; Markey & Dillon, 2011a; 2011b; Thompson & Sheehy 2011), as well as rock cover and elevation (Meissner *et al.*, 2009). Evolutionary development of BIF flora is considered to be primarily constrained by geology that resulted in edaphic specialisation, however, long-term environmental stress and stochastic processes contributed to speciation (Gibson *et al.*, 2012; 2015), potentially through environmental filtering (Elliott *et al.*, 2019).

Similar to studies in Australia, a study conducted on an ironstone canga plateau, the Serra Sul in Brazil, revealed that vegetation types were distinguished based on life forms, i.e. herbaceous and shrubby campo rupestre (Nunes *et al.*, 2015). The distinction between life forms within vegetation types was related to environmental filters that included edaphic factors such as chemical and physical soil properties as well as hydrological characteristics. Nunes *et al.* (2015) concluded that edaphic factors, especially soil pH and depth, were the main edaphic filters that regulated plant species composition and community structure on ironstone islands. Fine-scale surface heterogeneity on ironstone outcrops contributed to composition of dominant functional groups that were adapted to persist in stressful bedrock habitats (Jacobi *et al.*, 2007; Do Carmo *et al.*, 2016). Plant species growing in these habitats must be able to persist under extreme drought conditions (Yates *et al.*, 2011) and their root systems are mechanically restricted due to underlying bedrock. Persistent species were mostly clonal and desiccation-tolerant (Do Carmo & Jacobi, 2016), and have adventitious root systems that provided them with rapid water uptake after a rainfall event which contributed to their survival during dry periods. Furthermore, these clonal plants can overcome problems associated with root anchorage since these species require fewer rooting places on smoother outcrops (Do Carmo *et al.*, 2016). Some plants were also leafless, a typical drought-tolerant trait (Yates *et al.*, 2011).

Surface habitat heterogeneity contributes to life form composition. Rare ironstone shrub species were found to be restricted to certain microhabitats such as fissures and cliffs (Yates *et al.*, 2011). In another study, where the microtopography was coarser, sclerophytes and graminoids were favoured (Do Carmo *et al.*, 2016). Sclerophyllous shrubs invest in their root biomass, enabling these plants to explore large surface areas (Poot & Lambers, 2003) to exploit the rocky and shallow soils for water access. Root systems may also be able to penetrate the underlying bedrock through fissures and/or crevices, forming large, columnar root structures underground and between rocks (Do Carmo & Jacobi, 2013). Geo-edaphic conditions were found to contribute to differences in life form groups that were characterised by specific dispersal and/or pollination syndromes (Jacobi & Do Carmo, 2011). Another factor that ironstone plant species must be adapted to is high concentrations of metals (Jacobi *et al.*, 2007). Species within the Velloziaceae have been found to be metal accumulators suggesting that certain plants may be metallophytes or be metal tolerant (Antonovics *et al.*, 1971; Jacobi *et al.*, 2007; Jacobi & Do Carmo, 2008; Do Carmo *et al.*, 2018). There is clearly an interaction between plants and soils derived from ironstone which contribute to their functional characteristics (Do Carmo & Jacobi, 2016).

1.5.4.2. Quartzite

Similar to BIF, quartzite is also a sedimentary rock type (McCarthy & Rubidge, 2005). However, it differs from BIF since the rock type is composed of sand grains, primarily mineral quartz, that was exposed to extreme heating processes that resulted in recrystallisation. Quartzite, a clastic sedimentary rock, is therefore a very hard and resistant rock type (McCarthy & Rubidge, 2005; King, 2020). Quartzites of the Olifantshoek Supergroup, applicable to this study, were deposited approximately 1 900 million years ago by means of deposition of marine sediments along the Western margin of the Kaapvaal Craton (McCarthy & Rubidge, 2005; Moen, 2006). Deposition of these marine sediments are indicators of geological change from deep-water conditions to a shallow continental shelf (McCarthy & Rubidge, 2005). As the inland sea became shallower, red coloured sandstones formed in the riverine settings (McCarthy & Rubidge, 2005). In contrast to BIF, the quartzites do not have high economic value with regards to mineral deposition (Moen, 2006). Yet, since it is a very hard and durable rock type, quartzite is usually used in architecture (i.e. counter tops, tiles), building material in construction and manufacturing of certain materials due to its high silica content (i.e. glass, silicon metals) (King, 2020).

A Scopus (2020) search revealed that botanical research on quartzite landscapes is well represented in South Africa (Bredenkamp & Deutschlander, 1995; Schmiedel & Jürgens, 1999; Schmiedel, 2002; 2004; Schmiedel & Jürgens, 2004; Schmiedel & Mucina, 2006; Haarmeyer *et al.*, 2010; Luther-Mosebach *et al.*, 2012; Schmiedel *et al.*, 2012; Curtis *et al.*, 2013; Van Tonder *et al.*, 2014; Klak *et al.*, 2015; Sieben *et al.*, 2017; Klak *et al.*, 2018; Frisby *et al.*, 2019; Van Staden *et al.*, 2020). Studies were also conducted in Zimbabwe (Wild *et al.*, 1963; Downes & Darbyshire, 2018), Mozambique (Downes & Darbyshire, 2018), Mexico (Bárcenas-Argüello *et al.*, 2010), Brazil (Conceição *et al.*, 2007; Messias *et al.*, 2013; Inglis & Cavalcanti, 2018; Mota *et al.*, 2018; Mucina, 2018; Silva *et al.*, 2019), Venezuela (Dezzeo *et al.*, 2004), Malaysia (Wong *et al.*, 2010), Spain (Rivero-Guerra, 2008), United States (Neely & Barkworth, 1984) and Turkey (Ozkan *et al.*, 2009). Quartzitic environments are vulnerable to climate change, biological invasion, and overexploitation of natural resources, land transformation, fragmentation, improper grazing practices, increased fire events and urbanisation (Dezzeo *et al.*, 2004; Schmiedel & Mucina, 2006; Benites *et al.*, 2007; Haarmeyer *et al.*, 2010; Wong *et al.*, 2010; Schmiedel *et al.*, 2012; Curtis *et al.*, 2013; Van Tonder *et al.*, 2014; Mota *et al.*, 2018). Therefore, these landscapes should be studied to promote their conservation and the implementation of proper land management strategies (Haarmeyer *et al.*, 2010; Wong *et al.*, 2010; Luther-Mosebach *et al.*, 2012; Schmiedel *et al.*, 2012; Curtis *et al.*, 2013; Van Tonder *et al.*, 2014).

Soils derived from quartzites are generally shallow, rocky, sandy, have poor water-holding capacity, low soil pH and nutrient content, high aluminium content, are deficient in soil phosphorous (P), and susceptible to nutrient leaching (Wild *et al.*, 1963; Neely & Barkworth, 1984; Benites *et al.*, 2007; Conceição *et al.*, 2007; Ozkan *et al.*, 2009; Wong *et al.*, 2010; Messias *et al.*, 2013; Schmiedel *et al.*, 2015; Mota *et al.*, 2018; Mucina, 2018; Teodoro *et al.*, 2019; Abrahão *et al.*, 2020). Since quartzites have a resistant nature to weathering, cover of rock and bare soil is characteristic to these ecosystems (Neely & Barkworth, 1984; Messias *et al.*, 2013). These soil conditions and additional harsh environmental conditions, acted as forces for speciation, that resulted in the development and evolution of endemic plant species (Wild *et al.*, 1963; Schmiedel & Jürgens, 1999; 2004; Conceição *et al.*, 2007; Rivero-Guerra, 2008; Wong *et al.*, 2010; Curtis *et al.*, 2013; Klak *et al.*, 2015; Sieben *et al.*, 2017; Inglis & Cavalcanti, 2018). Therefore, plant communities display high levels of endemism on quartzite inselbergs or mountains that are considered to function as edaphic islands (Wild *et al.*, 1963; Bárcenas-Argüello *et al.*, 2010; Wong *et al.*, 2010; Downes & Darbyshire, 2018; Inglis & Cavalcanti, 2018). Similar to these mountainous landscapes, quartz fields in South Africa are also island-like with harsh environmental conditions. Quartz fields are edaphically dry, azonal habitats with a high stone content (quartz debris) and low soil pH, that are found in various microclimatic environmental conditions (Schmiedel & Jürgens, 1999; Schmiedel, 2002; Luther-Mosebach *et al.*, 2012; Schmiedel *et al.*, 2012; Curtis *et al.*, 2013).

Edaphic conditions, together with local habitat heterogeneity and harsh environmental conditions exert a filtering effect on plant community composition and structure, favouring plant communities with certain trait sets (Bredenkamp & Deutschländer, 1995; Dezzeo *et al.*, 2004; Schmiedel & Mucina, 2006; Luther-Mosebach *et al.*, 2012; Sieben *et al.*, 2017; Inglis & Cavalcanti, 2018; Mucina, 2018; Abrahão *et al.*, 2020). Quartzitic landscapes then harbour distinct plant communities. Several studies reported that sclerophyllous plants are favoured by quartzitic substrates (Wild *et al.*, 1963; Messias *et al.*, 2013; Sieben *et al.*, 2017; Mota *et al.*, 2018; Mucina, 2018). In quartzite-sandstone plant communities (campo rupestre) in Brazil, Conceição *et al.* (2007), Messias *et al.* (2013) and Silva *et al.* (2019) found that floristics, community structure and life form spectra were primarily driven by edaphic factors as well as local habitat heterogeneity. In quartzitic grasslands in south eastern Brazil, floristic composition, vegetation structure and life forms varied across an altitudinal gradient and, plant communities at each altitude were characterised by specific indicator plant species. In combination with altitude, soil conditions contributed to habitat heterogeneity that contributed to distinct differences between plant communities (Mota *et al.*, 2018).

Neely and Barkworth (1984) found that certain plant species and life forms were favoured by quartzitic conditions. Favoured plant species were considered as calcifuges that are adapted to stressful environmental conditions (Neely & Barkworth, 1984). Additionally, Mota *et al.* (2018) found that dominant plant species are adapted to shallow soils, steep slopes, high temperatures, low soil moisture and soil infertility. Life forms are also driven by environmental conditions (Neely & Barkworth, 1984; Mota *et al.,* 2018). Neely and Barkworth (1984) found that shrubs, graminoids, chamaephytes, cryptophytes and therophytes were favoured. High cover of therophytes was an indication of harsh and xeric microclimatic conditions (Neely & Barkworth, 1984) while Mota *et al.* (2018) revealed that dominant life forms reflect the geomorphology underlying quartzitic grasslands.

Growth form composition is also influenced in quartzite landscapes. The combination of shallow, quartz debris covered and fine-grained soils with a gradient of decreasing stone content by volume and increasing salinity, is considered the determining factor for growth form composition in quartz-field landscapes (Schmiedel & Jürgens, 1999; 2004). Dwarfism is considered an adaptation to edaphic aridity (Schmiedel *et al.*, 2015). Since quartzite debris is white, heat from the sun is reflected resulting in cooler soil temperatures. Schmiedel and Jürgens (2004) found that quartz fields displayed lower maximum air temperatures compared to those of soil without quartz cover, and soil surface temperatures were cooler during hot summers whereas in winter times the soil surface was warmer. It is proposed that the importance of ‘dwarf’ ground-level growth forms associated with quartz fields is enabled by a decrease of thermal impact (Schmiedel & Jürgens, 1999; 2004). Dwarf shrub succulents of these landscapes also tend to have shallow rooting systems, enabling these plants with rapid water uptake abilities during rainfall events or dewfall (Schmiedel & Jürgens, 2004; Schmiedel *et al.*, 2015).

Life forms in quartz fields were found to be indicative of drought resistance since chamaephytes tended to respond less strongly to rainfall variability compared to geophytes and therophytes (Schmiedel *et al.*, 2012). Moisture availability also contributed to differences in vegetation cover in quartz fields, since vegetation cover increased with increasing moisture availability (i.e. fog, dewfall, rainfall) (Schmiedel *et al.*, 2012). Edaphic factors also had an effect on species richness of quartz fields. Species richness in acidic quartz fields was low compared to the more saline fields (Schmiedel *et al.*, 2015). Quartz fields located in the Overberg were more fertile and within a higher rainfall region than those in the Karoo and, hence had higher diversity than their drier western counterparts (Curtis *et al.*, 2013). Mediterranean mountain forests were also depauperate in species (Ozkan *et al.*, 2009).

On campos rupestres vegetation in Brazil, plant species in the Velloziaceae are adapted to quartzitic habitats and are able to colonise exposed rocks (Abrahão *et al.*, 2020). Teodoro *et al.* (2019) investigated root systems of these species and found their roots have specialised morphological and physiological traits, that are highly effective for resource acquisition, especially with regards to P. The roots have a mining strategy for P and release carboxylate that extract P from the rocks through their physical and chemical interactions with their rocky environment (Teodoro *et al.*, 2019; Abrahão *et al.*, 2020). Consequently, vellozoid plants contributed to the gradual weathering of rocks, with low P availability, and assisted soil formation by means of sand development from the “mined rocks” that resulted in substrate heterogeneity associated with campos rupestres landscapes (Teodoro *et al.*, 2019; Abrahão *et al.*, 2020). These species can therefore be considered environmental engineers since they can facilitate establishment of other plant species (Abrahão *et al.*, 2020). Nutrient impoverishment is thus considered as a significant environmental filter in campos rupestres landscapes that drives the spatial distribution patterns of rock dwelling species in the Velloziaceae (Abrahão *et al.*, 2020).

Quartz fields of the Knersvlakte, Little Karoo, Nama-Karoo and and Succulent Karoo are rich in endemic plant species as well as highly adapted habitat specialists (Schmiedel & Jürgens, 1999; 2004; Schmiedel & Mucina, 2006; Haarmeyer *et al.*, 2010; Luther-Mosebach *et al.*, 2012; Schmiedel *et al.*, 2012; Van Tonder *et al.*, 2014; Klak *et al.*, 2015; Schmiedel *et al.*, 2015; Klak *et al.*, 2018). These habitats are characterised by shallow soils with high salinity or acidity. Here indicator species and species richness were driven by abiotic factors such as soil pH and electrical conductivity (Schmiedel *et al.*, 2015). Furthermore, succulent plant species in the Mesembryanthemaceae are adapted to these edaphic factors and hence, lineages underwent diversification. Most of these plants are endemic succulent dwarf shrubs, usually slow growing, with reduced leaf numbers or contracted leaves (Schmiedel & Jürgens, 1999; 2004; Schmiedel *et al.*, 2012; Curtis *et al.*, 2013; Schmiedel *et al.*, 2015). Other dominating plant families included the Aizoaceae, Asteraceae and Crassulaceae (Schmiedel & Mucina, 2006; Schmiedel *et al.*, 2012; 2015). In the Overberg Quartzveld, species in the Fabaceae, Poaceae and shrubs in the Asteraceae were well represented (Curtis *et al.*, 2013).

1.5.5. Drivers of biomass production

In savanna landscapes herbaceous layers respond dynamically to environmental factors and/or disturbances and are therefore considered ‘event-driven’ ecosystems. Topography, herbivory, fire, soil nutrients and rainfall are considered major drivers of savanna vegetation dynamics (Westoby *et al.*, 1980; Skarpe, 1992; Augustine, 2003; House *et al.*, 2003; Siebert *et al.*, 2010; Buitenwerf *et al.*, 2011; Van Coller *et al.*, 2013; Van Coller & Siebert, 2015; Tietjen, 2016; Guo *et al.*, 2018; Koerner *et al.*, 2018; Van Coller *et al.*, 2018; Hannusch *et al.*, 2020; Siebert *et al.*, 2020). Consequently, these factors act as filters on species pools, which contribute to diversity and the production of above ground biomass (Gough *et al.*, 1994; Grace, 2001; Adler & Levine, 2007). Therefore, when edaphic and/or environmental factors, especially those associated with landscape heterogeneity, have a filtering effect on species pools and diversity, biomass production is also influenced (Loreau *et al.*, 2001; Kahmen *et al.*, 2005; YuKun *et al.*, 2009; Graham & Duda, 2011; Zuo *et al.*, 2012; Guo *et al.*, 2018).

Habitat heterogeneity and limiting factors (i.e. soil nutrients, light, water) shape response patterns of plant species and, hence determines occurrence of species, co-existence and niches (Waide *et al.*, 1999; Lundholm & Larson, 2003; Tylianakis *et al.*, 2008; Cardinale *et al.*, 2009; Ma *et al.*, 2010; Zuo *et al.*, 2012; Stein *et al.*, 2014; Grace *et al.*, 2016; Guo *et al.*, 2018; Pashirzad *et al.*, 2018; Qi *et al.*, 2018; Fayiah *et al.*, 2019; Palpurina *et al.*, 2019). Dominant species, adapted to heterogeneous conditions and limiting factors, were found to contribute the most to biomass production (Grime, 1998; Xu *et al.*, 2018).

A study conducted in temperate grasslands revealed that dominant tall growing herbaceous species contributed the most to biomass and that these species tended to increase across a soil moisture and nitrogen (N) gradient (Xu *et al.*, 2018). Furthermore, Grace *et al.* (2016) found that climate and soil fertility acted as divers of biomass. In nutrient-poor systems, biomass production was inhibited on quartzitic outcrops. Benites *et al.* (2007) related this finding to low carbon (C) stocks that were associated with quartzitic soils. As a result, stress-tolerant traits are favoured in infertile systems, compositional variability is reduced which in turn contributes to lower levels of biomass (Fernandez-Going *et al.*, 2012).

Fayiah *et al.* (2019) conducted a study in alpine grasslands and reported that soil N, C, P and Mg contributed to biomass yield. The authors concluded that soil nutrients were the primary regulator of biomass in these systems and not diversity as one would expect. In contrast, Niu *et al.* (2019a) found that biomass production in high elevation alpine meadows was significantly influenced by species richness. In combination with species richness, soil moisture also had an impact on biomass. Plant communities with lower soil moisture were characterised by lower biomass levels. This study also found that certain life forms such as perennial forbs and certain grass species are considered sensitive to climate change.

With increasing soil temperature abundances of grasses tended to increase whereas perennial forbs decreased resulting in shifts in plant communities (Niu *et al.*, 2019a). Plant species were also found to respond in specific manners to temperature as a result of their micro-environment, driven by evolution in alpine plants that enable plants to use solar energy to the maximum and produce organic matter (Niu *et al.*, 2019a). Another study in alpine meadows, identified topographical heterogeneity with respect to altitude and aspect, as drivers of plant cover, abundance of species, functional groups and biomass production (Niu *et al.*, 2019b). Of all these factors it was found that aspect, which regulates soil temperature, was the most important driver of vegetation distribution patterns on the studied hill landscapes. Aspect and altitude had a greater effect on functional groups than on species. Total biomass was mainly influenced by poales (graminoids and sedges) while forbs contributed to diversity. Therefore, results from this study suggested that functional groups should be conserved to insure maximum biomass production in alpine meadows. From these studies, biomass production is driven by a series of factors and therefore a multivariate approach is required to fully understand the underlying mechanisms that act as drivers (Waide *et al.*, 1999; Graham & Duda, 2011).

1.6. Summary

Mountains are diverse and unique landscapes that provide valuable ecosystem services for human well-being. Since these landscapes are threatened by land use practices and climate change, mountains require research and long-term monitoring which will contribute to knowledge and understanding of the processes and mechanisms that foster their distinctiveness. It is clear that geological heterogeneity followed by climate are the most important factors that should be included in research and that studies should follow a multi-disciplinary approach. This study provides the opportunity to investigate plant-plant, plant-soil as well as plant-soil-environment interactions between mountains on unusual soils across a rainfall gradient, following a multidisciplinary approach.

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Chapter 2

Study area and overarching methodological approach

2.1. Overview

This chapter provides a brief introduction on the history of Griqualand West (GW), followed by descriptions of the four mountain landscapes included in the study. Environmental characteristics based on vegetation, climate, geology and soil are discussed. Descriptions of general land uses and land cover types associated with GW are provided. The experimental design, survey methods and laboratory procedures for collecting and analysing vegetation- and soil data are given. Lastly, a brief overview of statistical analyses is provided.

2.2. Brief history

Griqualand West (GW) is a historical geographical region (Figure 2.1) and lies northwest of the confluence of the Orange and Vaal Rivers in the Northern Cape Province (Encyclopædia Britannica, 1998). The region is rich in history and heritage and is named after the semi-nomadic Griqua (Khoekhoe) people, a multi-racial group descending from European, Khoi, San and Tswana ancestry (Luscombe, 2018). The Griqua people were first to settle in the region during the late 18th century (Penn, 2005). Their early existence in GW is corroborated by rock art (Wilman, 1933; Frisby, 2015). Cornelius Kok, the son of Adam Kok (the founder and first chief of the Griqua people), decided to move out of the Cape Colony to the Orange River during the 1790's (South African History Online, 2016). Kok and his followers migrated in an eastern direction along the banks of the Orange River and established themselves at Klaarwater, currently known as Griekwastad (O'Connell, 2013; South African History Online, 2016). With the discovery of diamonds in GW during 1867, conflict arose between the Griqua people, the British Cape Colony and Boer republics. In 1871, GW was formally annexed by Britain (Figure 2.1), and the Griqua people were forced to sell their farms and relocate to Griqualand East (Encyclopædia Britannica, 1998) under the leadership of Adam Kok III (South African History Online, 2016). Today, the Griqua people are no longer semi-nomadic and active Griqua communities still reside in Campbell, Kimberley and Griekwastad (O'Connell, 2013; The Heritage Foundation, 2014).

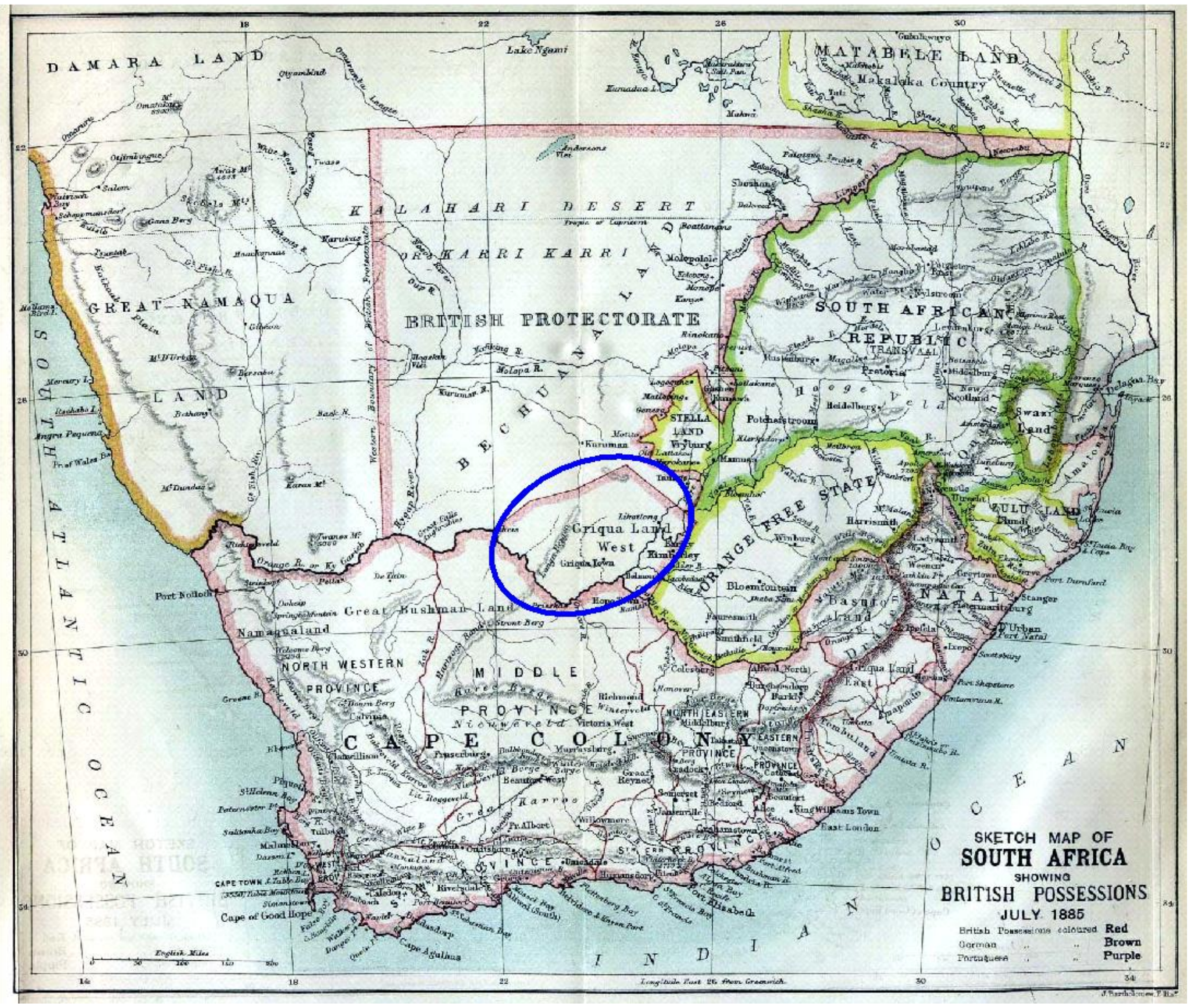

Figure 2.1. Historical sketch map of South Africa in the 18th century indicating the existence of Griqualand West, demarcated by the blue oval (Martholomew, 1885).

2.3. Floristic borders and core area

The Griqualand West Centre of Endemism (GWC), one of thirteen centres of plant endemism in southern Africa, was first proposed and mapped by Van Wyk and Van Wyk (1997). Van Wyk & Smith (2001) proposed that the core area of the GWC would be best described based on underlying geology with the Ghaap Group in the east and the Olifantshoek Supergroup to the west. Frisby (2015) redefined the borders of GWC with 218 quarter-degree grids (QDS) forming the greater Griqualand West. However, an ecological model based on historical occurrence records and environmental parameters (i.e. underlying geology and bioclimatic variables) allowed Van Staden *et al.* (2020) to redefine the borders of the core area proposed by Frisby *et al.* (2019) (see Figure 4.2, Chapter 4). The model revealed that the distribution of endemic plant species was restricted to four mountains that corresponded to the unique rock types of these landscapes (Chapter 4). These newly refined boundaries of GWC cover a surface area of 24 075 km² (Van Staden *et al*., 2020). This area is three times smaller than the core area of 75 172 km² as proposed by Frisby *et al.* (2019).

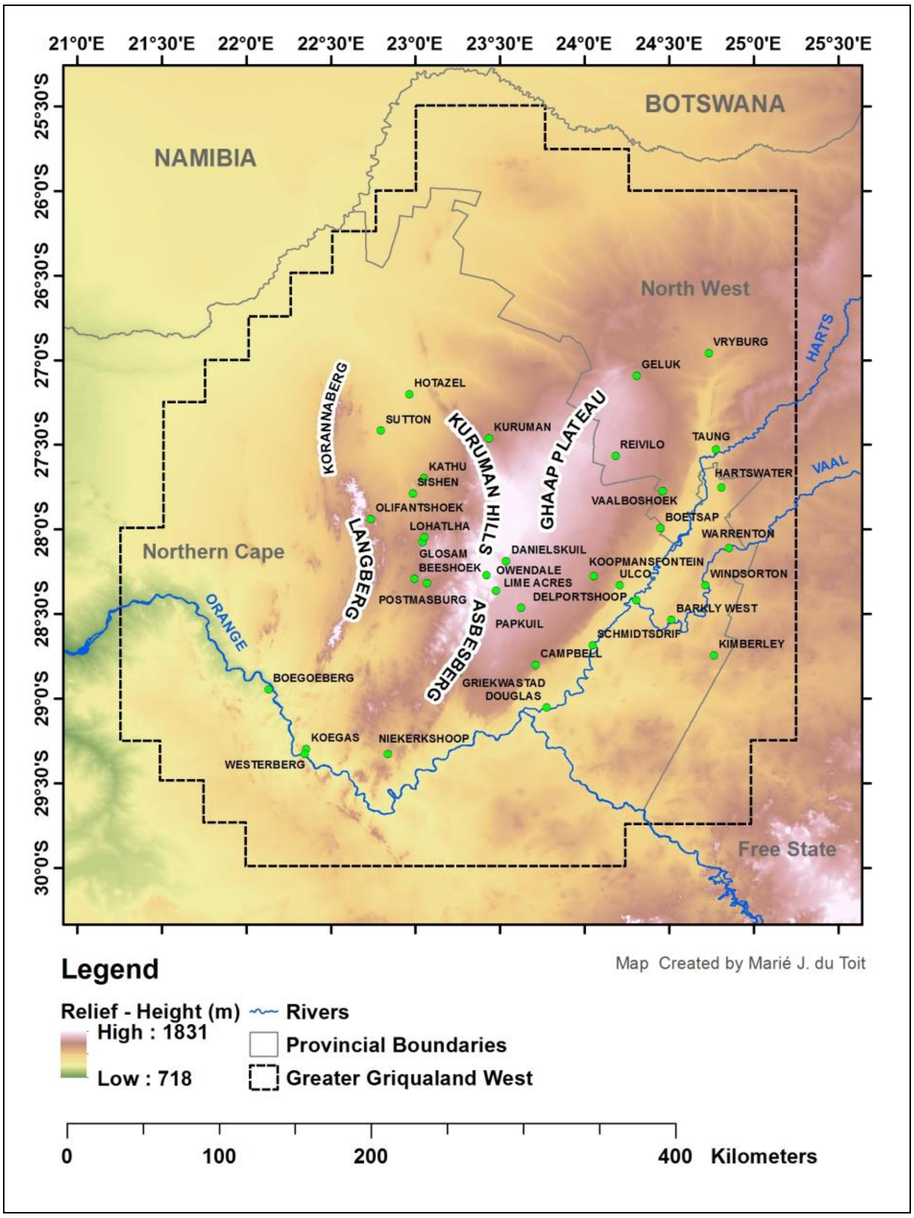

Figure 2.2. Greater Griqualand West includes parts of the Free State, North West and Northern Cape provinces.

2.3.1. General characteristics

2.3.1.1. Topography and geology

The topography and geology of GW is diverse and harbours majestic landscape features (Van Staden, 2019). Mountain ranges and/or ridges of GW are orientated from north to south with altitude ranging from 718 –1 850 m above sea level (a.s.l.) (Figure 2.2) (Frisby, 2015). In the east, GW consists of the Ghaap Plateau and an undulating landscape with sets of low hills, namely the Asbestos- and Kuruman Hills (Figure 2.2). The geology of the eastern region is associated with the Transvaal Supergroup which is divided into the Griqualand West Sequence or Ghaap Group and the Postmasburg Group (Van Wyk & Smith, 2001). Dominant rock types include dolomite and limestone on the Ghaap Plateau, whereas the Asbestos- and Kuruman Hills are underlain by the banded ironstone formation (BIF) (Keyser, 1997; Mucina & Rutherford, 2006). In the west, the landscape is mountainous, since the Langberg and Korannaberg are found in this region. The Olifantshoek Supergroup is mainly associated with the western region of GW (Van Wyk & Smith, 2001). Both these mountains are quartzitic (Keyser, 1997; Mucina & Rutherford, 2006).

2.3.1.2. Vegetation

The GW region is not only characterised by vegetation types of the Savanna Biome, but also of the Nama-Karoo Biome, which contribute to a high plant richness of approximately 2 100 species (Frisby, 2015). The mountainous western regions are dominated by Kalahari Mountain Bushveld, while the eastern plateau is covered by Kalahari Plateau Bushveld (Van Wyk & Smith, 2001). Eight vegetation units of the Eastern Kalahari Bushveld Bioregion are endemic to GW (Table 2.1; Mucina & Rutherford, 2006; Frisby, 2015).

Table 2.1. Summary of endemic vegetation units within Griqualand West.

Vegetation unit	MAP mm	MAT °C	MFD	Altitude m.a.s.l.	Conservation status
Stella Bushveld (SVk 2)	438	18.0	35	1 250-1 400	Vulnerable
Ghaap Plateau Vaalbosveld (SVk 7)	400	17.1	40	1 100-1 500	Least threatened
Kuruman Vaalbosveld (SVk 8)	422	17.1	31	1 300-1 500	Least threatened
Kuruman Thornveld (SVk 9)	368	17.5	36	1 100-1 500	Least threatened
Kuruman Mountain Bushveld (SVk 10)	371	16.8	40	1 100-1 800	Least threatened
Olifantshoek Plains Thornveld (SVk 13)	289	17.1	36	1 100-1 500	Least threatened
Postmasburg Thornveld (SVk 14)	306	17.0	38	1 180-1 440	Least threatened
Koranna-Langeberg Mountain Bushveld (SVk 15)	294	16.8	33	1 100-1 836	Least threatened

***MAP*, mean annual precipitation; *MAT*, mean annual temperature; *MFD*, mean number of frost days per annum; *m.a.s.l.*, meters above sea level. Conservation status of each is also indicated (Rutherford *et al.*, 2006).**

2.3.1.3. Flora

The GW region is rich in a unique and interesting flora (Van Staden, 2019). Wilman (1946) pioneered floristic surveys in GW and constructed a checklist for flowering plants and ferns. Acocks (1979) contributed extensive lists of taxa that were linked to vegetation types of the mountains in GW. In this rich floristic region, 24 endemic plant species and two near-endemic plant species (Frisby *et al.*, 2019; Van Staden *et al.*, 2020) are restricted to regions of diverse topography, climate and geological heterogeneity (Van Wyk & Smith, 2001). GWC endemic plant species are mainly present in SVk 7, SVk 10 and SVk 15 (Table 2.1). The distribution of some endemic species overlap, whereas others are narrow and restricted to certain vegetation units. SVk 7 on the Ghaap Plateau hosts 23 of the GWC endemic species, while SVk 10 (Asbestos- and Kuruman Hills combined) hosts 21 and SVk 15 (Langberg) 14 (Table 2.2). Confirmed endemic and near-endemic taxa are described in detail by Frisby *et al.* (2019) and discussed further in Chapter 4.

2.3.1.4. Climate

Griqualand West is characterised by a semi-arid climate with highly unpredictable rainfall events. The region receives the bulk of its rainfall in summer months. Mean annual precipitation (MAP) varies between 220 and 475 mm (Rutherford *et al.*, 2006). A rainfall gradient can be observed across mountain systems, based on recorded rainfall per actual sampling site (Figure 2.3). The mean annual temperature (MAT) is approximately 18°C. However, day temperatures can reach up to 42°C in summer months. The mountainous regions are slightly cooler than the lower lying areas (Frisby, 2015). Winters are dry with frost occurring frequently as night temperatures can drop below 0°C (Rutherford *et al.*, 2006). The mean annual frost days range between 27 and 43 days. Low soil moisture availability, confirmed by mean annual soil moisture stress of 81-86% (calculated as the percentage days when evaporation was more than double the soil moisture supply) (Rutherford *et al.*, 2006) may be stressful to plants in this ecosystem. Additionally, mean annual potential evaporation is 2 760 mm for the region (Rutherford *et al.*, 2006).

Table 2.2. Breakdown of the endemism within the Griqualand West Centre of Endemism (GWC) according to mountains. Adapted from (Frisby *et al.*, 2019).

Region	Number of GWC endemics	Restricted GWC endemics	Grasses (1)	Herbaceous forbs (7)	Succulents (6)	Lignified forbs* (7)	Shrubs (7)
Ghaap Plateau	23	3 herbaceous forbs	0	7	4	5	7
Ironstone Hills combined	21						
Kuruman Hills	17	0	0	4	3	4	7
Asbestos Hills	15	1 succulent	0	1	5	3	7
Langberg	14	1 succulent 1 grass	1	1	3	4	6

*Dwarf shrubs: In this study dwarf shrubs are considered lignified forbs, i.e. herbaceous plants displaying above-ground lignification with a basal diameter less than 5 cm.

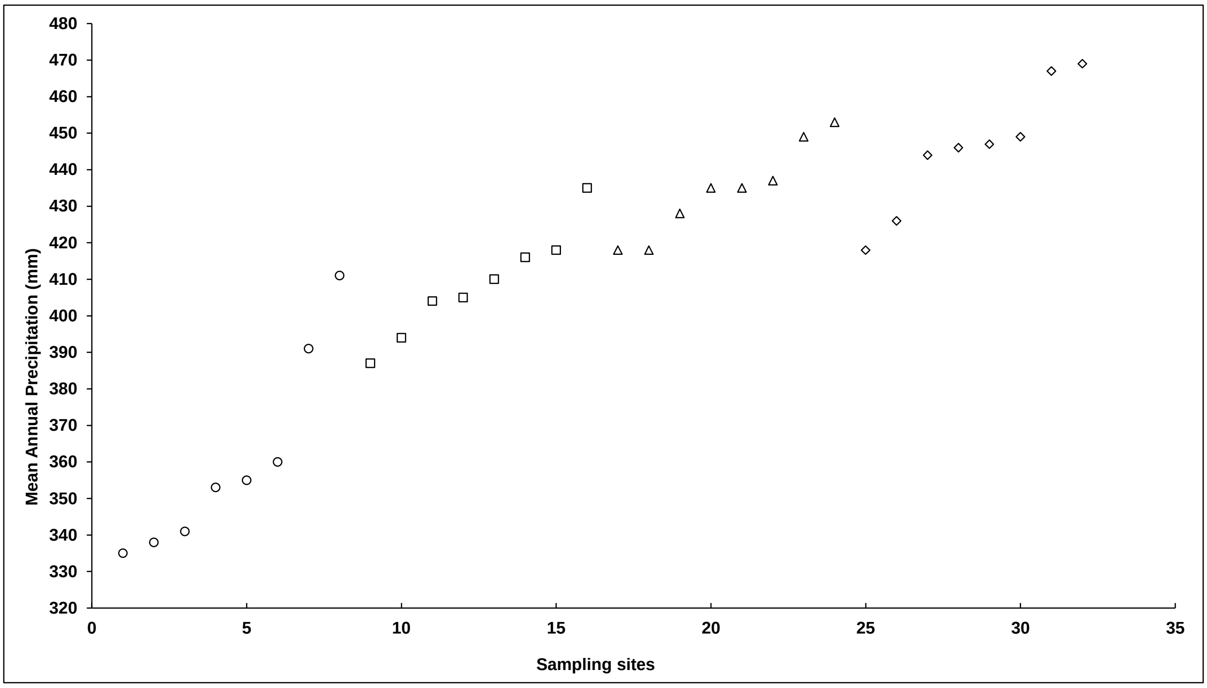

Figure 2.3. Mean annual precipitation per sampling site across mountains (Fick & Hijmans, 2017).

2.4. Mountains

2.4.1. Ghaap Plateau

The name Ghaap is derived from the Khoekhoen word, *#Hab*, meaning flat mountain or plateau (Raper, 1989). The plateau is 130 km wide and 280 km in length, covering areas of both the Northern Cape and North West provinces (Figure 2.2). The Ghaap Plateau extends from the confluence of the Orange and Vaal Rivers near Douglas northwards to Vryburg and is bounded by the Harts River in the east and the Asbestos- and Kuruman Hills in the west (Figure 2.2) (Van Wyk & Smith, 2001). The altitude ranges from 1 100-1 500 m a.s.l. (Mucina & Rutherford, 2006).

2.4.1.1. Vegetation

The Ghaap Plateau is located within the Vaalbosveld vegetation unit (SVk 7) (Figures 2.4 and 2.5). The shrub layer is well-developed with *Tarchonanthus camphoratus* L. and *Vachellia karroo* (Hayne) Banfi & Gallaso, while the open tree layer is characterised by *Olea europaea* L. subsp. *africana* (Mill.) P.S.Green, *Searsia lancea,* (L.f.) F.A.Barkley, *V. tortilis* (Forssk.) Gallaso & Banfi and *Ziziphus mucronata* Willd. (Mucina & Rutherford, 2006). However, some woody species are associated with specific regions. For instance, *O. europaea* subsp. *africana* is dominant towards the south, whereas *Senegalia mellifera* (Vahl)

Seigler & Ebinger, *V. hebeclada* (DC.) Kyal. & Boatwr. and *V. tortilis* are more prominent in northern and western regions (Mucina & Rutherford, 2006). South-central parts of the Plateau are dominated by *O. europaea* subsp. *africana, S. lancea* and *T. camphoratus*.

2.4.1.2. Climate

The mean annual temperature (MAT) of the Ghaap is 17.1°C, whilst mean annual precipitation (MAP) varies between 300 and 500 mm (Mucina & Rutherford, 2006). North-eastern parts are characterised by higher MAT and MAP (Figure 2.6a, b) when compared to the south-western parts. In the north, near Vryburg on the Armoedsvlakte, mean monthly maximum and minimum temperatures are 36.6°C and -5.5°C for December and July, respectively (Mucina & Rutherford, 2006). Mean maximum and minimum monthly temperatures in the south, near Griekwastad, range from 32°C in January and 0°C in July (SA Explorer, 2017). Given that maximum temperatures in the northern parts are higher than that of the southern parts, a temperature gradient can be observed (Figure 2.6c). Moreover, the southern region of the Ghaap Plateau is colder, reaching temperatures of -1.5°C whereas the north is slightly warmer (Figure 2.6d). Similarly, to temperature, a rainfall gradient can be seen from the north-eastern to south-eastern as well as the south-western parts for the month receiving the bulk of the rainfall (Figure 2.6e). During the driest month in winter, the northern parts are drier than the south (Figure 2.6f).

Figure 2.4. *Olea europaea* subsp. *africana* and *Tarchonantus camphoratus* observed in the Ghaap Plateau Vaalbosveld. Photo: N. van Staden.

2.4.1.3. Geology and soil

The Ghaap Plateau is associated with the Campbell Rand- and Schmidtsdrif subgroups (Figure 2.7) of the Ghaap Group (Griqualand West Basin) under the Transvaal Supergroup (Draper, 1894; Eriksson *et al.*, 2006). Since the landscape consists of a combination of dolomite, limestone and chert (Keyser, 1997), lime is present in the soil (Figure 2.8a). The geology is dominated by dolomite, a clastic sedimentary rock type rich in calcium magnesium carbonate [$CaMg(CO_3)_2$] (Figure 2.9a). Consequently, the soil is rich in magnesium (Mg) and calcium (Ca) (McCarthy & Rubidge, 2005). The soil is shallow (Figure 2.8b) since it is underlain by Hardpan Carbonate (MacVicar *et al.,* 1977; Land Type Survey Staff, 1972-2002; Land Type Survey Staff,1986; Rutherford *et al.*, 2006). Steep slopes are visible along the escarpment of the Ghaap Plateau (Figure 2.8c and 2.9b). Sampling sites are situated on three land types (Figure 2.10), namely Ae9, Fc4 and Fc6 (MacVicar *et al.,* 1977; Land Type Survey Staff, 1972-2002; Land Type Survey Staff, 1986;). Soils occurring on the Fc4 and Fc6 land types (Land Type Survey Staff,1986) are mostly of the Coega form (71%), which has a shallow topsoil (100-250 mm) on a hardpan carbonate subsoil (MacVicar *et al.,* 1977; Land Type Survey Staff, 1972-2002). On Ae9, shallow (200-450 mm) to deep (450-1 200 mm) soil of the Hutton form is found in combination with the Coega form (Soil Classification Working Group, 1991).

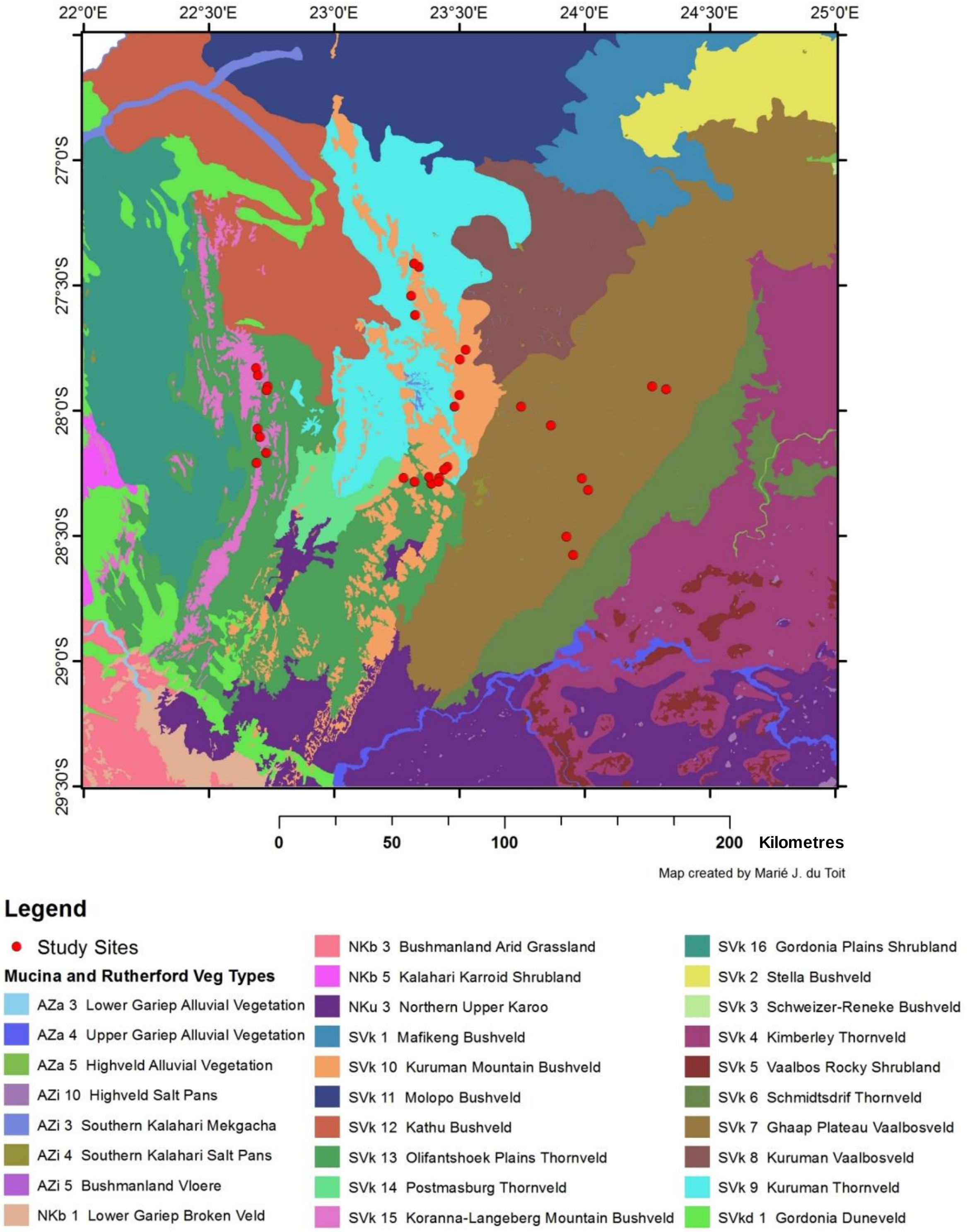

Figure 2.5. Localities of study sites within vegetation units of the study area (adapted from Mucina and Rutherford, 2006), which primarily includes the Ghaap Plateau (SVk 7), Asbestos- and Kuruman Hills (SVk 10) and the Langberg (SVk 15).

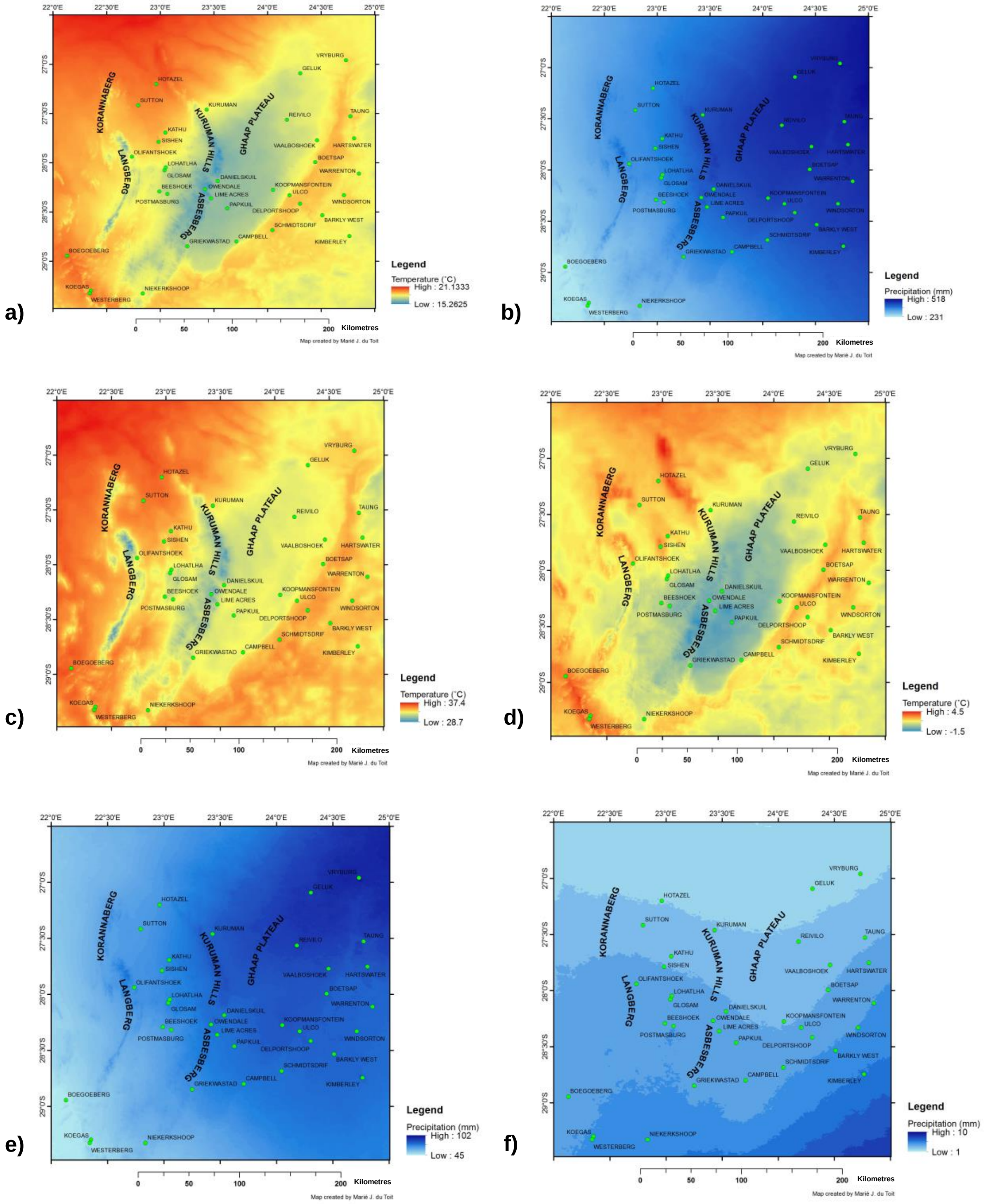

Figure 2.6. Climatic gradients for the mountains in the GW region. a) Mean annual temperature (MAT), b) Mean annual precipitation (MAP), c) Maximum temperature for the warmest month, d) Minimum temperature for coldest month, e) Mean precipitation of wettest month and f) Mean precipitation of driest month (Fick & Hijmans, 2017).

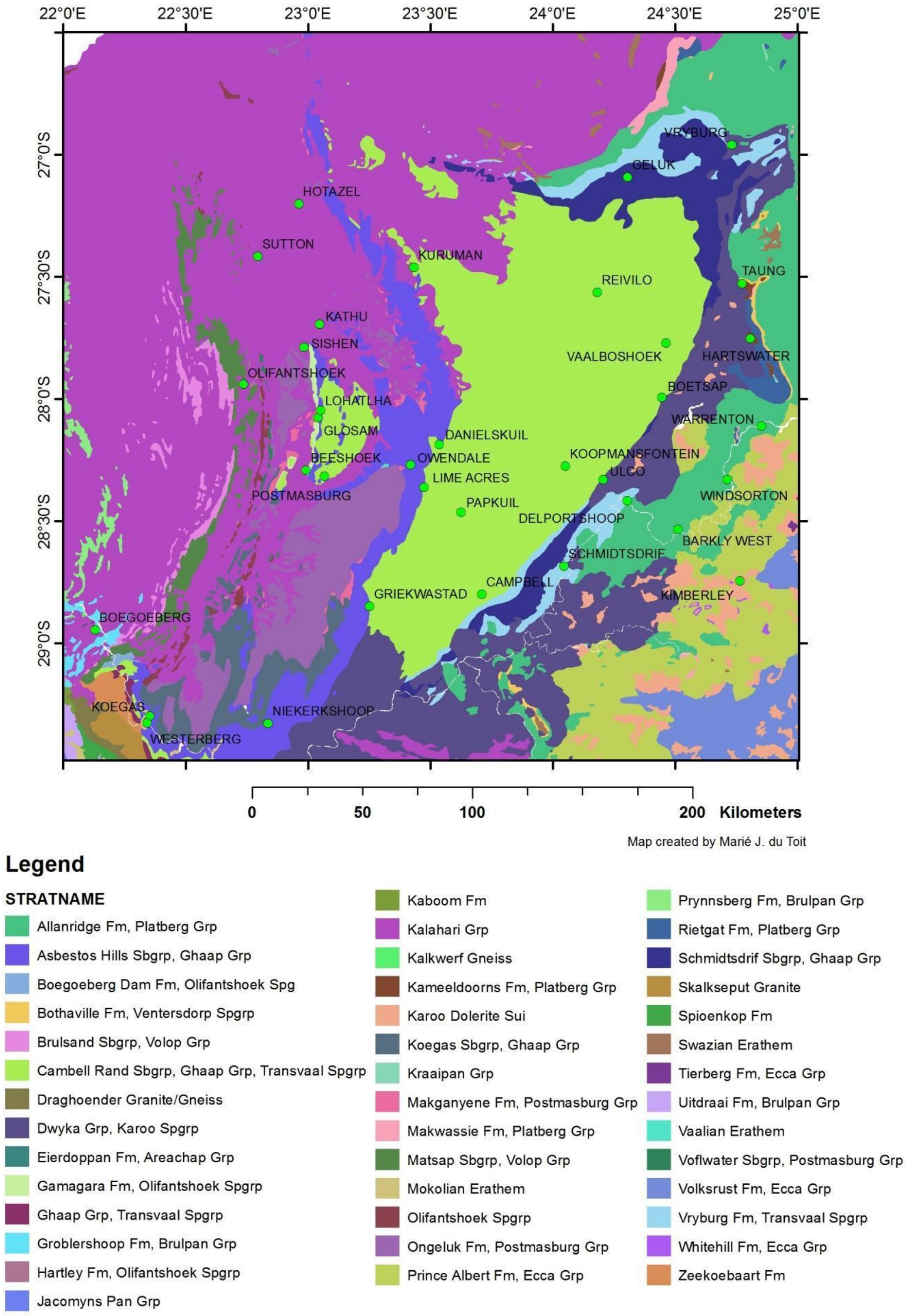

Figure 2.7. Geological map of the GW region (Council for Geosciences, 2008). Note that the Cambell Rand Subgroup as well as the Schmidtsdrif Subgroup, of the Ghaap Group, are within the Transvaal Supergroup. *Grp,* Group; *Sbgrp,* Subgroup; *Spgrp,* Supergroup.

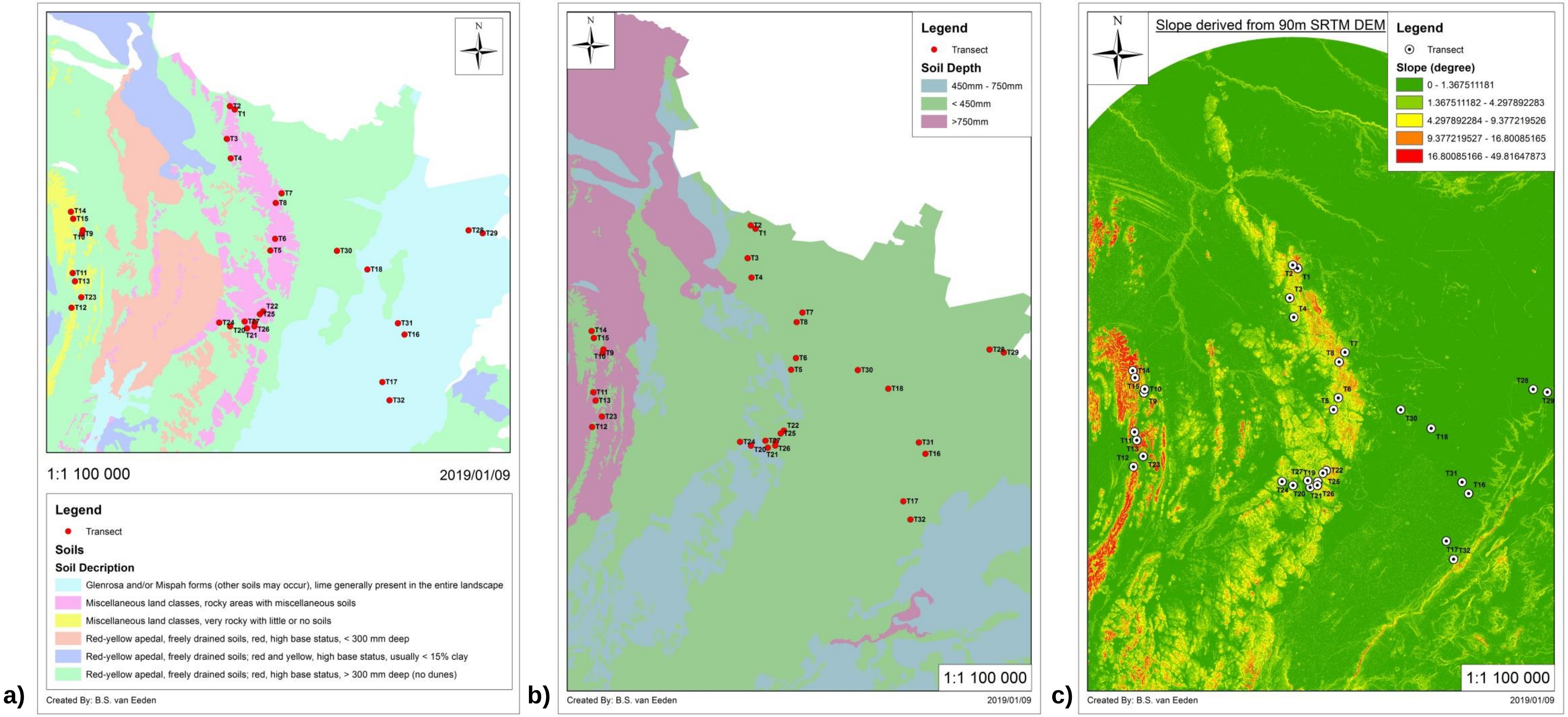

Figure 2.8. Maps of a) soil type, b) soil depth and c) slope for sampling sites (transects). *SRTM,* Shuttle Radar Topography Mission; *DEM,* Digital Elevation Model.

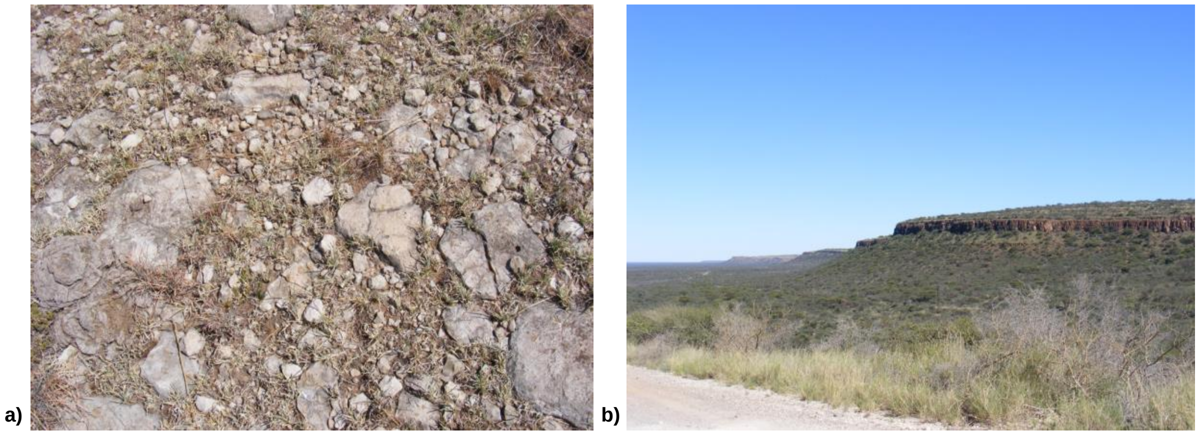

Figure 2.9. a) Exposed weathered dolomite of the Ghaap Plateau near Koopmansfontein and b) the escarpment slopes of the Ghaap Plateau beyond which a plateau develops. Photos: N. van Staden.

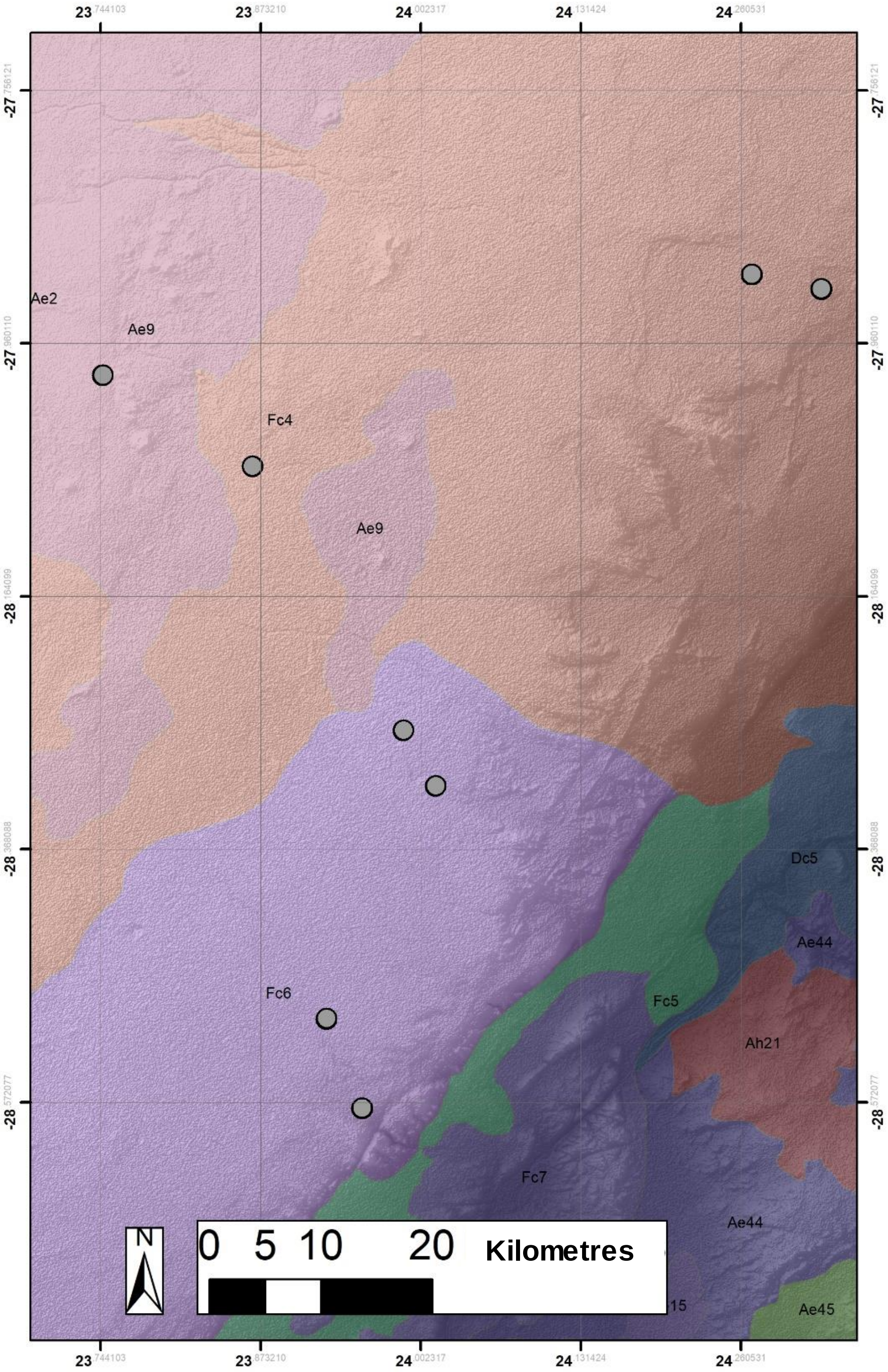

Figure 2.10. Sampled sites within land types (MacVicar *et al.,* 1977; Land Type Survey Staff, 1972-2002; Land Type Survey Staff, 1986) of the Ghaap Plateau. Map created by George M. van Zijl.

2.4.2. Asbestos- and Kuruman Hills

The Asbestos Hills, a southern extension of the Kuruman Hills, are located in a southern direction of Daniëlskuil, stretching west of Griekwastad, arching around Niekerkshoop towards the region of Koegas and Westerberg (Figure 2.2) (Keyser, 1997; Mucina & Rutherford, 2006). The Kuruman Hills extend between the towns of Kuruman and Daniëlskuil. Local farmers refer to the Kuruman Hills as the 'Red Hills' (from the Afrikaans name, *Rooirante*) due to the dominance of red grass (*Themeda triandra* Forssk.) and stab Grass (*Andropogon schirensis* Hochst. ex A.Rich.) that provide these hills with a characteristic red hue. The altitude of both landscapes varies between 1 100 and 1 800 m a.s.l. (Mucina & Rutherford, 2006).

2.4.2.1. Vegetation

The Kuruman- and Asbestos Hills are situated in the Kuruman Mountain Bushveld (SVk 10) (Figure 2.5) (Mucina & Rutherford, 2006). This vegetation unit is characterised by a high alpha diversity. During Acocks's (1953) botanical surveys for his publication on Veld types of South Africa, he produced a plant list consisting of 302 plant species in a single survey on the Asbestos Hills – the highest number of species to be recorded by him at a single site during his travels throughout South Africa. Acocks sampled more than 3 000 sites in South Africa, each site being ~13.8 km (north-south)-11.6 km (east-west) in size (Rutherford *et al.*, 2003).

The undulating landscape consists of an open shrub layer dominated by the tall shrub *Calobota cuspidosa* (Burch.) Boatwr. & B.-E.van Wyk, and a well-developed grass layer (Van Wyk & Smith, 2001). The physiognomy of the Asbestos and Kuruman Hills exhibit slight differences (Figure 2.11). For example, the grass layer of the Kuruman Hills is more conspicuous with increasing altitude, and woody species become extremely sparse (Figure 2.11a), whereas the woody layer on the Asbestos Hills is generally more prominent (Figure 2.11b).

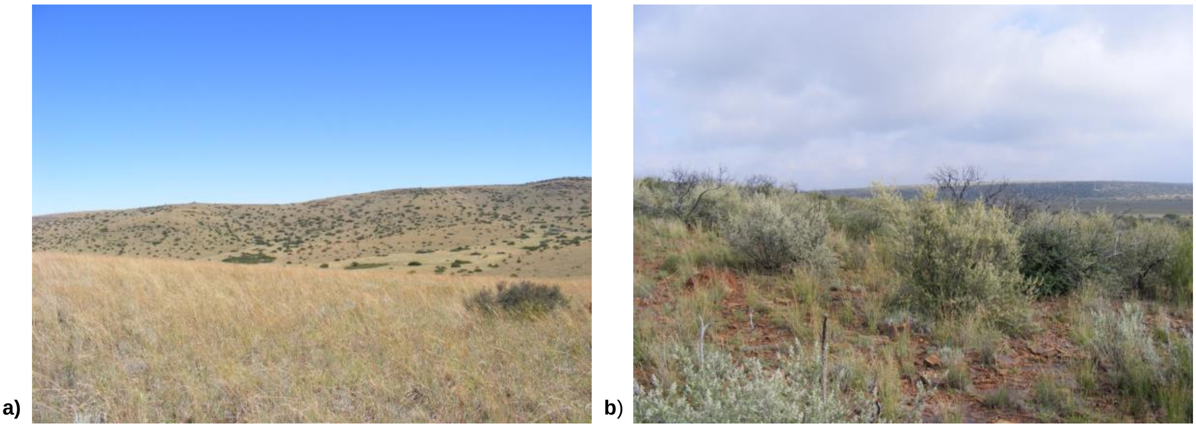

Figure 2.11. The Kuruman Mountain Bushveld (SVk 10) of the a) Kuruman Hills and b) Asbestos Hills. Photos: N. van Staden.

2.4.2.2. Climate

The Kuruman- and Asbestos Hills have a MAT and MAP of 16.8°C (Figure 2.6a) and 371 mm, respectively (Figure 2.6b) (Mucina & Rutherford, 2006). Mean maximum daily temperatures of the hottest month for towns near these hills vary between 31°C and 32°C for January. Mean minimum daily temperatures for the coldest month are below freezing point for July (Table 2.3). However, from the map for the hottest month (Figure 2.6c), the northern parts near Kuruman tend to be cooler than the far south near Niekerkshoop. For the coldest month (Figure 2.6d), northern parts of the Kuruman Hills and southern parts of the Asbestos Hills are warmer, whereas the central parts where these ranges join are colder. Similar to the Ghaap Plateau, a rainfall gradient prevails from north to south (Figure 2.6b). The northern Kuruman Hills receives higher MAP (500 mm) than the southern Asbestos Hills (250 mm) (Mucina & Rutherford, 2006). This gradient can also be observed in mean precipitation of the wettest month (Figure 2.6e), whereas mean precipitation for the driest month shows an opposite trend, tending to increase from north to south (Figure 2.6f) (Fick & Hijmans, 2017).

2.4.2.3. Geology and soil

The Asbestos Hills subgroup of the Ghaap Group dominates the geology of the Kuruman- and Asbestos Hills (Figure 2.7) (Eriksson *et al.*, 2006). The banded iron formation (BIF), a chemical sediment (Figure 2.12) (McCarthy & Rubidge, 2005), in combination with jaspilite, chert and riebeckite asbestos, are associated with these two mountain ecosystems (Land Type Survey Staff, 1972-2002; Keyser, 1997). The landscape consists of various land classes and soils (Figure 2.8a). Generally, the soil is sandy and shallow (Figure 2.8b) with rocks or boulders covering more than 60% of the surface (MacVicar *et al.,* 1977; Land Type Survey Staff, 1972-2002). Slopes can be very steep varying from 5 to 50 degrees (Figure

2.8c). The majority of sample sites of the Kuruman Hills were primarily located on the Ib236 land type (Figure 2.13) (Land Type Survey Staff, 1986). Soil forms occurring within this land type include soil-rock complex (71%), and shallow (50-300 mm) to deep (300-1200 mm) Hutton soils (MacVicar *et al.,* 1977; Land Type Survey Staff, 1972-2002). One survey site was located on land type Ae8 which is less rocky (4.2%) and consists primarily of medium (300-600 mm, 27%) to deep Hutton soil (600-1 200 mm, 50%). Four sampling sites of the Asbestos Hills was situated in land type Ib237, with three on Ib236 and one on Ag113 (Figure 2.14) (Land Type Survey Staff,1986). Land type Ib237 was dominated by soil-rock complex (60.6%) with shallow (50-300 mm) Hutton soils also occurring (MacVicar *et al.,* 1977; Land Type Survey Staff, 1972-2002). In contrast to Ib237, the soils of Ag113 are less rocky (42%), with shallow (100-300 mm), medium (300-750 mm) and deep (300-1200 mm) Hutton soils being more predominant (MacVicar *et al.,* 1977; Land Type Survey Staff, 1972-2002; Land Type Survey Staff,1986).

Table 2.3. Mean day temperatures of the warmest month and night temperatures of the coldest month for towns in the vicinity of the Kuruman- and Asbestos Hills (SA Explorer, 2017).

Town	Coldest month	Temperature (°C)	Warmest month	Temperature (°C)
Kuruman Hills				
Kuruman	June	0	January	32.6
Daniëlskuil	July	-0.2	January	31.8
Postmasburg	July	0	January	32
Asbestos Hills				
Lime Acres	June	-0.1	January	31.8
Griekwastad	July	0.3	January	32
Niekerkshoop	July	0.3	January	32

Figure 2.12. a) Banded iron formation of the Asbestos Hills, b) silicification of asbestos fibres during weathering periods, forming tiger eye depositions, and c) and d) banded iron formation of the Kuruman Hills. Photos: N. van Staden.

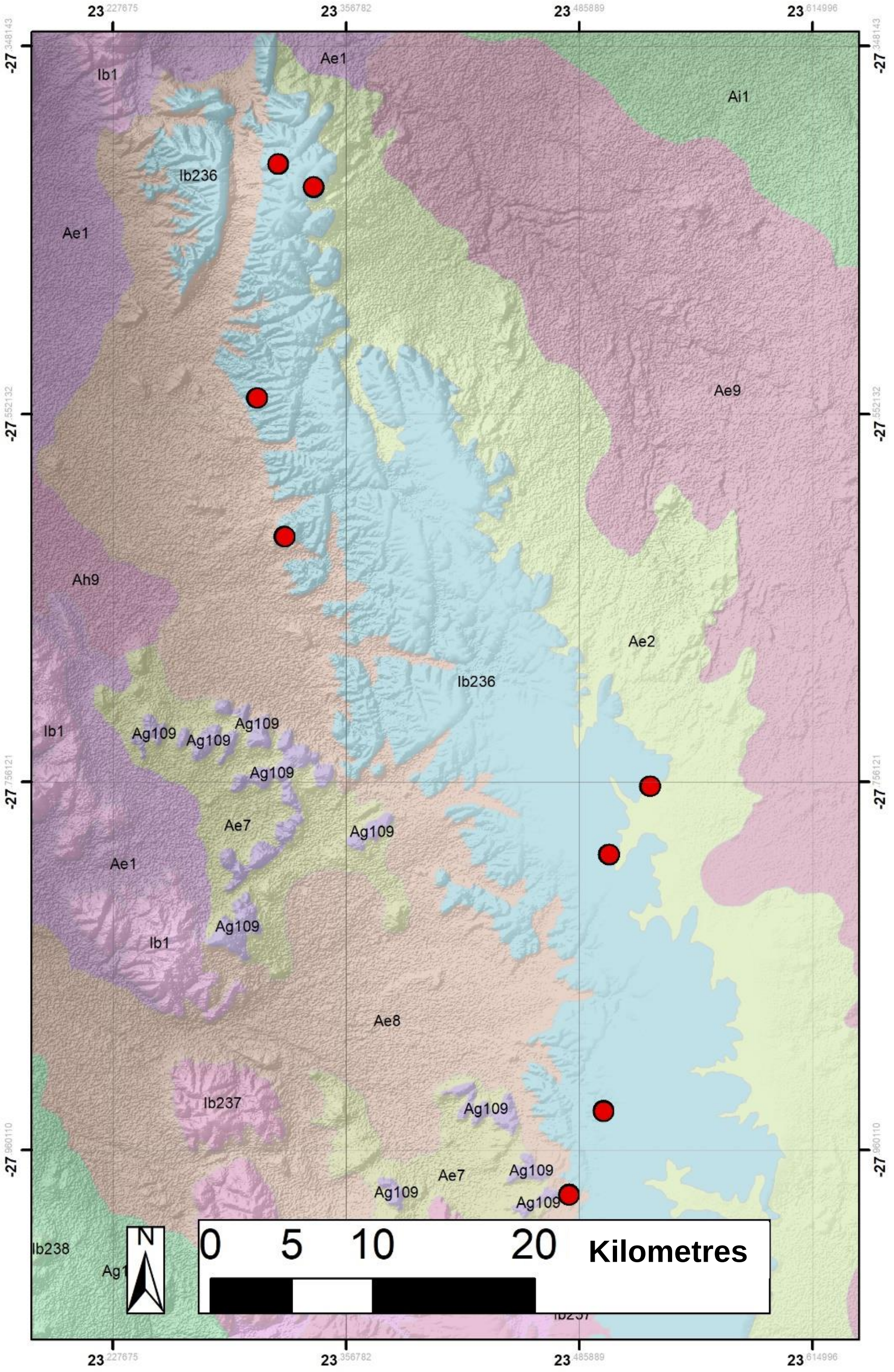

Figure 2.13. Land types associated with sampling sites of the Kuruman Hills (MacVicar *et al.,* 1977; Land Type Survey Staff, 1972-2002; Land Type Survey Staff, 1986). Map created by George M. van Zijl.

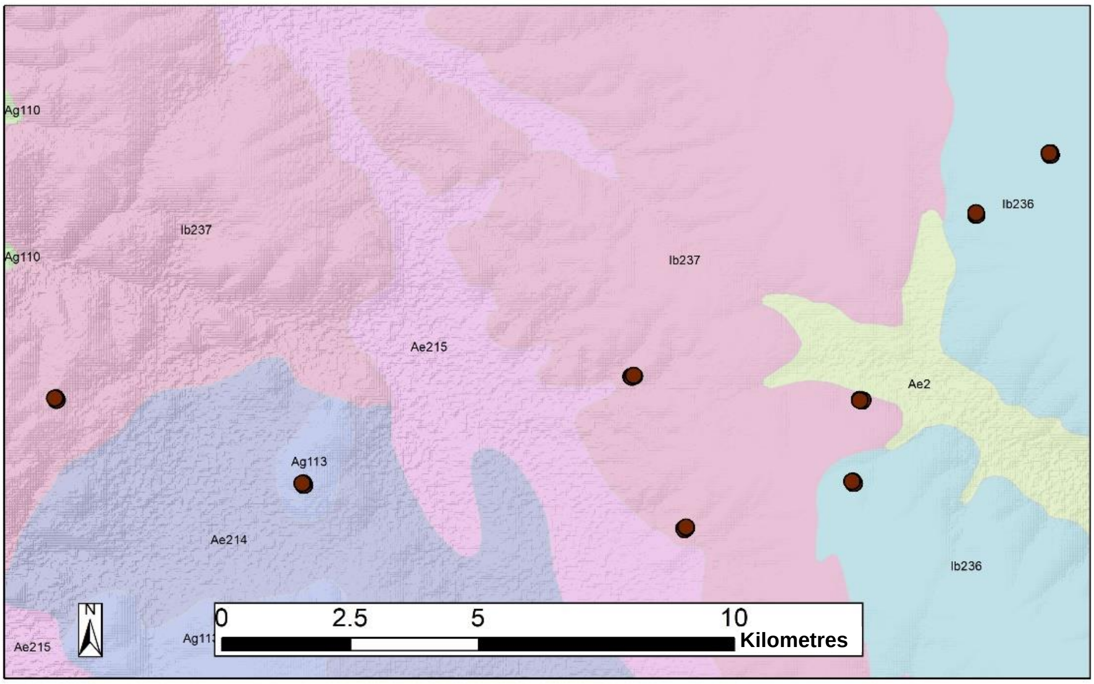

Figure 2.14. Land types (MacVicar *et al.,* 1977; Land Type Survey Staff, 1972-2002; Land Type Survey Staff, 1986) and the corresponding sample sites on the Asbestos Hills.

2.4.3. Langberg

The Langberg covers approximately 160 km as it stretches from Olifantshoek in the north, passing west of Postmasburg, to the area of Boegoeberg in the south (Keyser, 1997). North of Olifantshoek, the Langberg extends ultimately into the Korannaberg (Figure 2.2) which is of the same geology. Intermontane valleys filled with aeolian orange-red Kalahari sands and *V. erioloba* (E.Mey.) trees, form a distinct landscape feature (Figure 2.15). The altitude varies from 1 000 to 1 836 m a.s.l. (Mucina & Rutherford, 2006).

2.4.3.1. Vegetation

The Koranna-Langberg Mountain Bushveld (SVk 15) is associated with the Langberg (Figure 2.5). Open shrubland with a moderate open grass cover is a typical landscape feature dominated by the woody species, *Croton gratissimus* P.J.H.Hurter Burch. (Figure 2.15). Other dominant woody plant species include *Sarcostemma viminale* (L.) R. Br. as well as *S. mellifera* (Vahl) Seigler & Ebinger subsp. *detinens* (Burch.) Kyal. & Boatwr. (Mucina & Rutherford, 2006).

Figure 2.15. The Koranna-Langberg Mountain Bushveld on the Langberg approximately 16 km outside Olifantshoek. *Croton gratissimus* shrubs growing on rocky quartzite slopes can be seen in the foreground. The sand-filled intermontane valley with *Vachellia erioloba* can also be distinguished. The photo was taken during the drought of 2017/2018 by N. van Staden.

2.4.3.2. Climate

The Langberg is characterised by a MAT of 16.8°C (Figure 2.6a) and a MAP of 294 mm (Figure 2.6b) (Mucina & Rutherford, 2006). Mean daily maximum temperatures for Olifantshoek varies between 17°C in June and 32°C in January (SA Explorer, 2017). A temperature gradient is notable for the southern parts displaying slightly higher temperatures than the north for the warmest month (Figure 2.6c). During the coldest month, temperatures can drop below freezing point at night (SA Explorer, 2017), however the Langberg has the warmest minimum temperatures for the coldest month of all four mountain ranges (Figure 2.6d). MAP varies between 180 and 280 mm (Mucina & Rutherford, 2006), making it the driest mountain ecosystem in GW, with a notable increasing aridity gradient from north to south (Figure 2.6b). This gradient is also indicative of MAP for the wettest month (Figure 2.6e). Rainfall during the driest month is evenly distributed over the Langberg (Figure 2.6f) (Fick & Hijmans, 2017).

2.4.3.3. Geology and soil

The geology of the Langberg consists of clastic sediments such as quartzite (white, pink and green), greywacke, lavas, conglomerate and hematite of the Olifantshoek Supergroup (Keyser, 1997; McCarthy & Rubidge, 2005). Arenaceous rocks (derived from or containing sand) of the Volop Group are well exposed on the landscape with red-brown arenites of the Matsap Subgroup overlying the Hartley Formation (a layer of conglomerate material) (Figure 2.7) (Moen, 2006). Various land types occur on the Langberg (Figure 2.8a) and soils are mostly shallow (Figure 8b). Slopes are exceptionally steep (mostly between 10 and 50 degrees) (Figure 2.8c and 2.16). Sampling sites occurred on two land types (Figure 2.17), Ic2 in the higher lying areas and Ae6 covering the lower parts of the landscape (MacVicar *et al.,* 1977; Land Type Survey Staff, 1972-2002; Land Type Survey Staff, 1986). Ic2 consists mainly of rock (86%) with small proportions of Mispah (50-300 mm, 3%), and shallow (50-450 mm, 5%) to medium (300-780 mm, 4%) depth Hutton soils (MacVicar *et al.,* 1977; Land Type Survey Staff, 1972-2002). Soils are less rocky on Ae6, which is dominated by the deep Hutton land class (>1 200 mm, 93%) (MacVicar *et al.,* 1977; Land Type Survey Staff, 1972-2002; Land Type Survey Staff, 1986).

Figure 2.16. Rocky and steep quartz slopes characterise the landscape of the Langberg. Photo: N. van Staden.

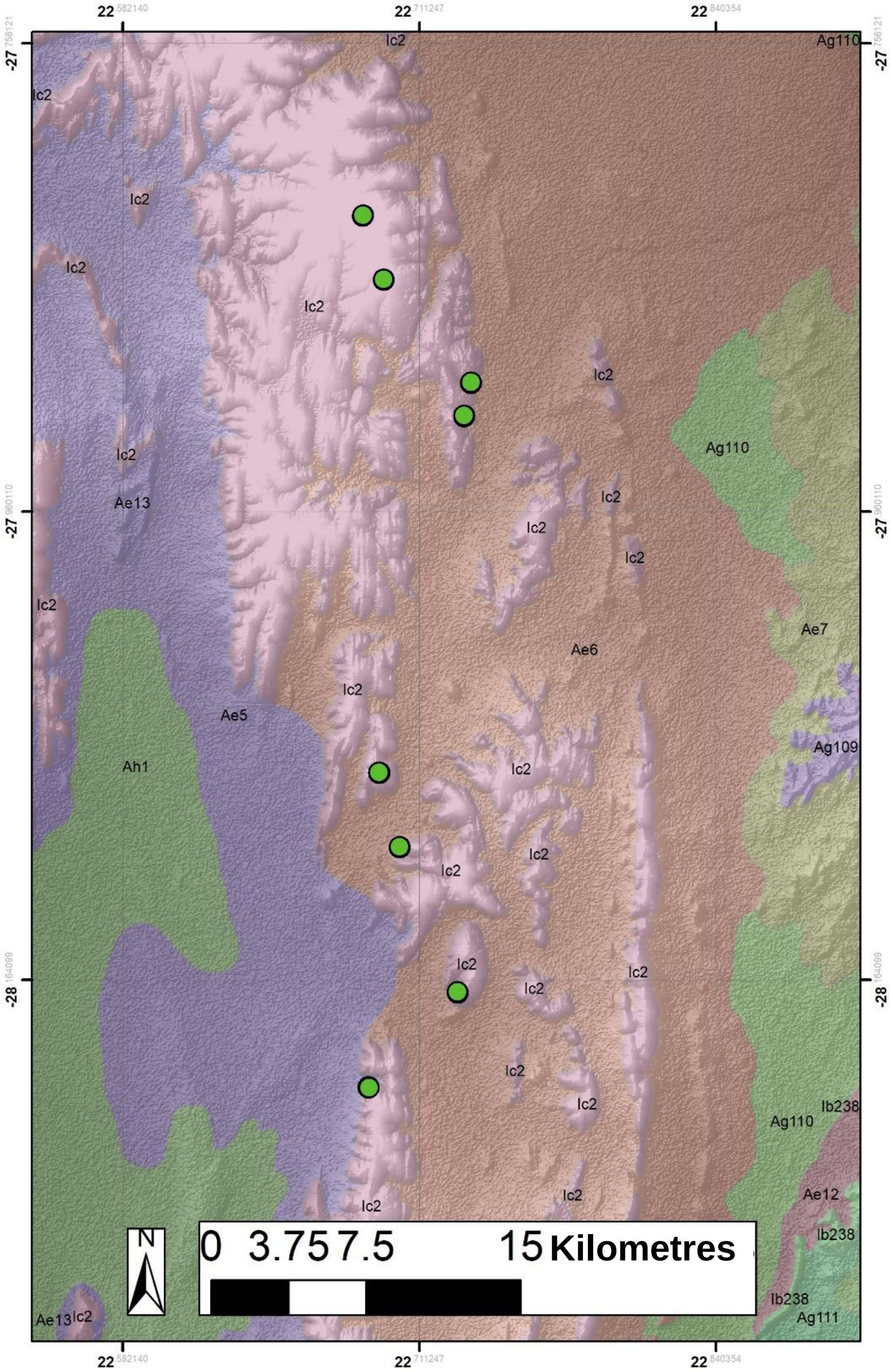

Figure 2.17. Langberg sites and the associated land types (MacVicar *et al.,* 1977; Land Type Survey Staff, 1972-2002; Land Type Survey Staff, 1986).

2.5. Land use and land cover

2.5.1. Green energy

Development of renewable energy sources has increased remarkably in the Northern Cape over the past seven years (Young, 2017). Several solar- and wind farms, as well as one hydro-electric plant, are already operational while planning for additional projects continues (Theobald, 2016). More specifically relevant to the study area, the Lesedi and Jasper photovoltaic solar projects near Postmasburg (Figure 2.18) are completed and fully operational (Theobald, 2016; De Villiers, 2018). In addition, the Redstone Solar Thermal Power Tower will be constructed next to these projects and will supply approximately 200 000 households with green energy. This tower will be the second highest concrete structure (after the Hillbrow tower) in South Africa, reaching a height of 250 m (De Villiers, 2018). Further developments including two wind energy facilities on the Kuruman Hills, south-west of Kuruman, are also proposed (CSIR, 2018a). The environmental impact assessment for these facilities has already been submitted to the Department of Environment Forestry and Fisheries (DEFF) and awaits a final decision (CSIR, 2018b). The region is also subjected to exploration for natural gas (Petroleum Agency SA, 2018).

Figure 2.18. The Lesedi and Jasper solar power projects visible from a site on the Asbestos Hills. Photo: N. van Staden.

2.5.2. Mining

Mining is one of two industries that carries the economy of the Northern Cape (Young, 2017). The extent of these mines can be observed (black areas) on the National Land Cover

Map (Figure 2.19). Various minerals are mined in GW. Limestone is mined at Lime Acres, Daniëlskuil and Ulco (Altermann & Wotherspoon, 1995). Crocidolite asbestos used to be mined near Kuruman and Owendale, but production ceased due to health risks and consumer resistance (Snyman, 1988; Abratt *et al.*, 2004; Selby, 2020). Iron ore is mined at Sishen Mine, Kolomela Mine (Anglo American, 2019), Beeshoek Mine (Assmang, 2016a), Khumani Mine (Assmang, 2016b), Sedibeng (Sedibeng Iron Ore, 2018) and Autumn Skies (Mining Weekly, 2018). Most of these mines are situated near Postmasburg and Kathu. In the region of Hotazel, manganese ore is mined at the Mamatwan and Wessels Mines (South 32, 2017), Black Rock (Assmang, 2016c) and Glosam (Lanham, 2004). Diamonds are mined south-west of Lime Acres at the Finsch Mine (Petra Diamonds, 2019).

2.5.3. Agriculture

Together with mining, agriculture is the other major economic pillar of the province (Young, 2017). In the study area, maize, wheat, lucerne and pecan nuts are mainly cultivated under irrigation from the Vaal River at Hartswater (Figure 2.19). In the mountainous areas, cropping practices are limited due to the unavailability of a potential water source, and rocky and shallow soils. The Ghaap Plateau, Kuruman- and Asbestos Hills are covered by low shrubland as well as grasslands on high-lying areas (Figure 2.19). The Langberg is mainly covered by thicket and/or dense bush as well as woodland and/or open bush (Figure 2.19). These vegetation types favour livestock farming with cattle, sheep, goats and horses, as well as game farming. The Northern parts of the Kuruman Hills are especially heavily utilised for grazing (Mucina & Rutherford, 2006).

2.5.4. Protected areas

The GW region is poorly conserved with only three protected areas. These are Mokala National Park which falls under South African National Parks (South African National Parks, 2020), Witsand Nature Reserve, a provincial nature reserve, administered by the DENC (DENC, 2019) and the privately owned Tswalu Kalahari Reserve (Tswalu, 2020). The Koranna-Langeberg Mountain Bushveld is the only vegetation unit of the four mountain ecosystems that is protected as it is conserved within Tswalu Kalahari Reserve (Mucina & Rutherford, 2006). Each of the vegetation units (Koranna-Langeberg Mountain Bushveld, Kuruman Mountain Bushveld and Ghaap Plateau Vaalbosveld) have a conservation target of 16% and is generally considered untransformed (Mucina & Rutherford, 2006). Yet, studies are required to ensure these vegetation types are conserved and possibly re-evaluated for new conservation targets.

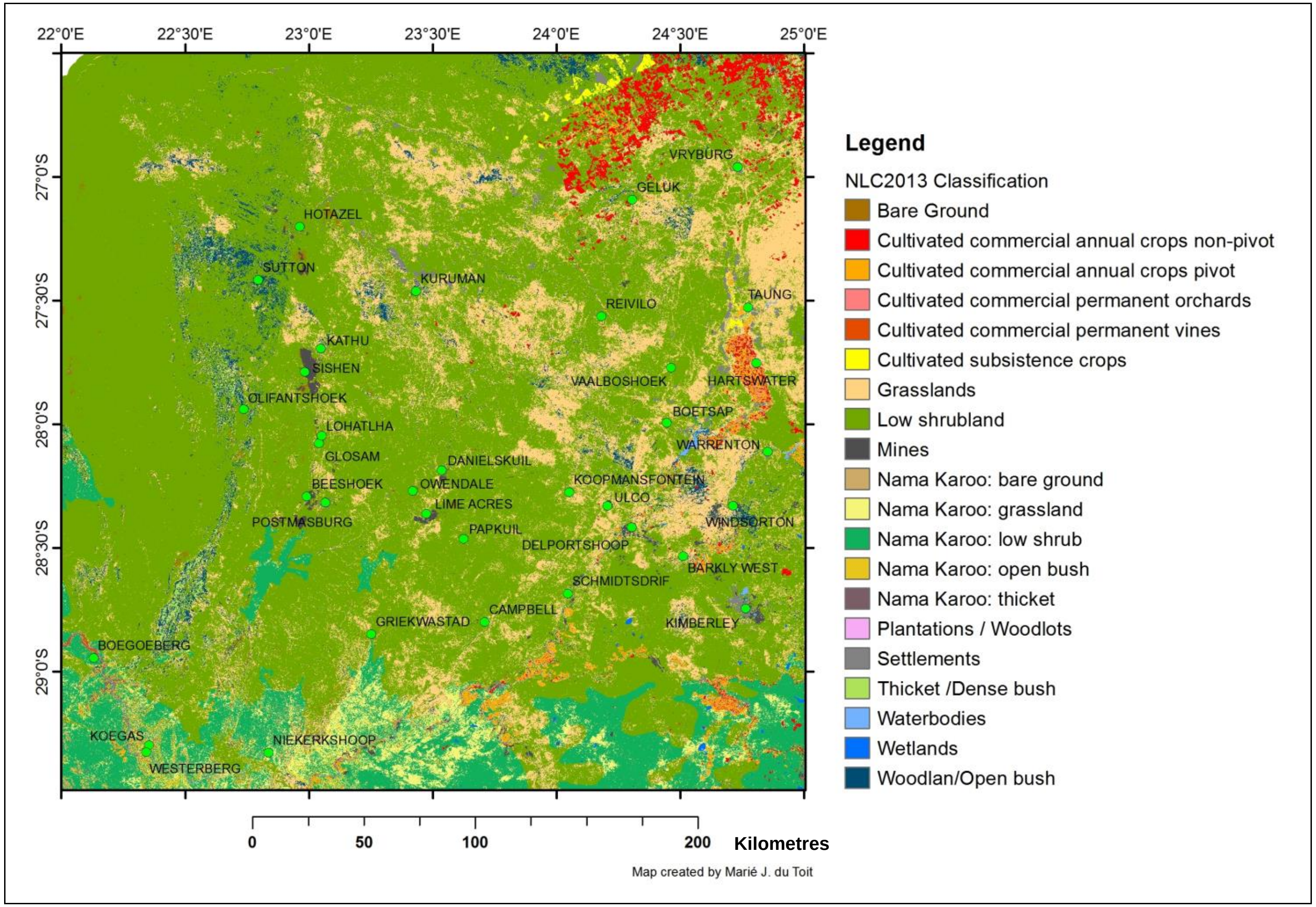

Figure 2.19. National Land Cover map according to the 2013 classification (Geoterraimage, 2015). Note that towns are represented by the green filled circles.

2.6. Experimental design and survey methods

Vegetation sampling was conducted during the peak growing season from 19 March to 6 May 2018. An extensive drought event in 2017/2018 preceded the plant surveys. Eastern and/or western slopes were sampled in areas where one could stand firmly on the slope. Modified-Whittaker (MW) plots (Stohlgren *et al.,* 1995) were mainly chosen based on accessibility (e.g. where one could drive with a vehicle up onto the mountains) and were situated more than 50 m from the nearest disturbance (e.g. road, micro-wave towers, watering points). Additionally, sites were chosen where the veld was allowed to rest and recover after drought and grazing, as well as where it was known that no fire occurred within the two years prior to sampling.

The experimental design (Figure 2.20) was based on the MW nested vegetation sampling approach (Stohlgren *et al.*, 1995). Recommendations by Schweiger *et al.* (2016) were followed to optimize the sampling effort along the studied environmental gradients, across four mountain ecosystems. A total of eight 50 x 20 m MW plots were sampled per mountain ecosystem (Table 2.4). The longest side (i.e. 50 m) of the plot was placed parallel to the mountain range, along the environmental gradient with the shorter 20 m side perpendicular to the longer side. Two MW plots of 1 000 m² each, were sampled per farm and situated approximately 5 km from one another. Global Positioning System (GPS) coordinates were taken at each corner of the MW plot. Each sampled MW plot consisted of two 1 m² subplots in the corners (Figure 2.20, A and B, Table 2.4). Within these subplots, all rooted individuals in the herbaceous layer were identified up to species level and counted (Figure 2.21). All above-ground rooted clonal structures were counted as individuals. Plant height was randomly measured for a maximum of three individuals per species inside each subplot. In instances where less than two individuals were present in a subplot, additional individuals were measured inside the MW plot. Cover estimates for herbaceous forbs, grasses, lignified forbs, bare soil, rock and debris were visually estimated in a frame consisting of 16 divisions of 25 x 25 cm each. Standing herbaceous aboveground biomass (biomass production) was collected and split in brown paper bags labelled for grasses, herbaceous forbs, lignified forbs and debris (Figure 2.22). Phytomass was dried at 30°C for approximately a week after returning from the field.

At each MW plot, two point-intercept transects of 50 m each (Figure 2.20, C and D, Table 2.4) were sampled to collect frequency values (Hill *et al.*, 2005) for the purpose of gathering community structure data. These transects were situated 3 m from the 1 m² subplots, towards the centre of the MW plot. Nearest grass, herbaceous forb, lignified forb, shrub and tree species were identified at each 2 m interval along these transects (Figure 2.23). Canopy height and two canopy diameters (perpendicular to one another) were measured for lignified forbs, shrubs and trees.

Five soil samples were randomly collected at a depth of 0-10 cm, depending on soil depth and rockiness at each MW plot (Figure 2.24a). These samples were collected in a honey jar, emptied in a Ziplock bag and thoroughly mixed to make up one composite sample per MW plot.

Table 2.4. Summary of the total sample size for this study.

Mountain	MW plots	Subplots	Point intercept transects	Data points
Ghaap Plateau	8	16	16	400
Kuruman Hills	8	16	16	400
Asbestos Hills	8	16	16	400
Langberg	8	16	16	400
Total	**32**	**64**	**64**	**1 600**

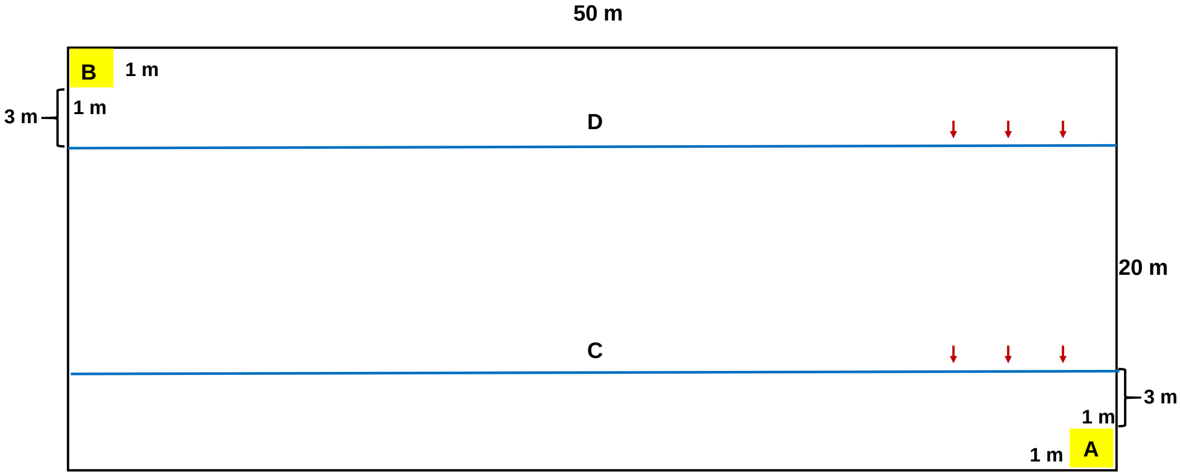

Figure 2.20. Experimental layout of a Modified-Whittaker plot (Hill *et al.*, 2005). A and B are the 1 m² subplots, C and D (blue lines), the two point-intercept transects of 50 m each. Red arrows indicate the 2 m intervals at which frequency values were collected.

2.7. Laboratory procedures

Soil samples were dried at room temperature (25°C) until they appeared visibly dry. After drying, composite samples were sieved through a 2 mm sieve to remove organic debris and rocks. Macro- and micro-nutrients of soil samples were analysed using a handheld X-ray fluorescence (XRF) analyser (Koch *et al.*, 2017) (Figure 2.24b). Three XRF-readings were taken per sample and the mean calculated for each element. Particle size distribution, pH (water), electrical conductivity (EC) and Cation Exchange Capacity (CEC) were analysed according to procedures prescribed by the Non-Affiliated Soil Analysis Work Committee (1990). These analyses were conducted byt the Eco Analytica Laboratory of the North-West University.

Figure 2.21. A 1 m² subplot nested within the Modified-Whittaker plot. Photo: N. van Staden.

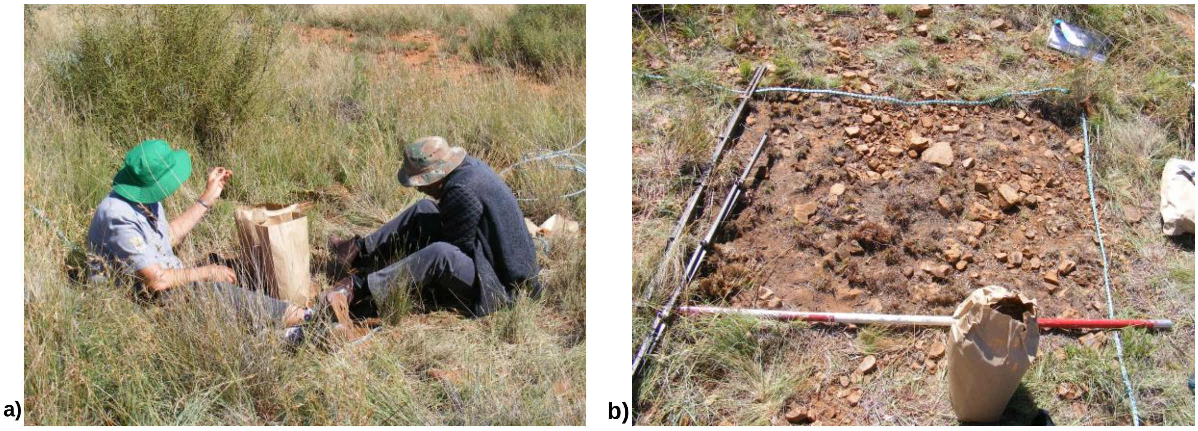

Figure 2.22. a) Phytomass collection within a 1 m² subplot, and b) subplot after phytomass removal. Photos: N. van Staden.

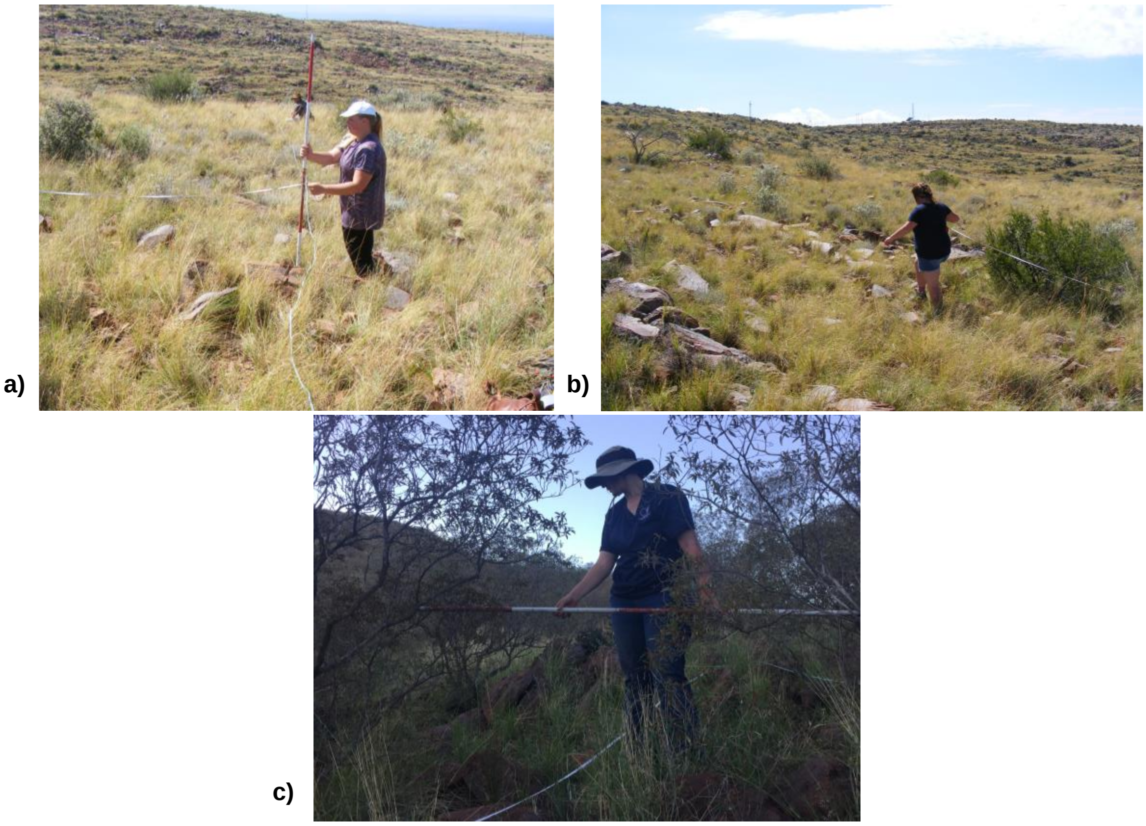

Figure 2.23. In a) and b) a point-intercept transect is laid out within the Modified Whittaker plot. Photos: N. van Staden. In c) canopy height and two canopy diameters measured along a point-intercept transect for the nearest dwarf shrub, shrub and tree. Photo: C. Small.

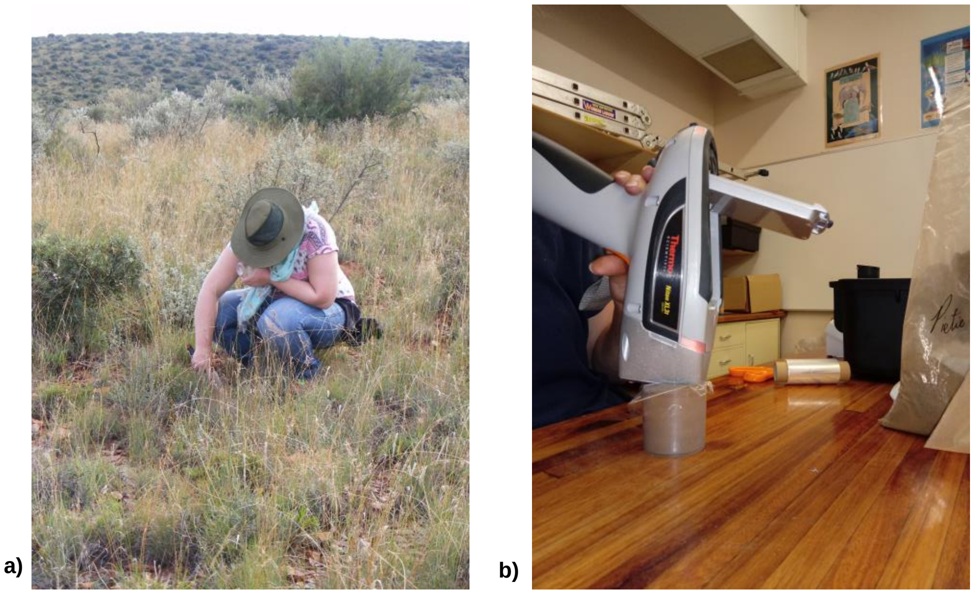

Figure 2.24. a) Soil sample collection in the field, and b) macro- and micro-nutrients are being measured with a handheld X-ray fluorescence analyser in a laboratory. Photos: N. van Staden.

2.8. Overview of statistical analyses

A brief overview of statistical analyses is provided for each chapter. Statistical analysis, research questions, aims and objectives and further detailed descriptions for each of the respective results chapters will be discussed in more detail under each of these chapters.

2.8.1. Chapter 3: Carbonate soils and ecosystems in Africa: A review

A review of peer-reviewed scientific literature was conducted in August 2019 using the electronic database Scopus with four main search strings. Language and document type were limited to English articles and only studies conducted in Africa were included. Furthermore, subject areas were limited to Environmental, and Agricultural and Biological Sciences. A total of 105 studies were individually screened based on the title and abstract. Papers that (1) did not focus on plant communities, (2) followed a non-ecological approach and (3) did not evaluate aspects of plant-soil relationships, were discarded. After screening, 39 papers were considered relevant and were further inspected. Each relevant paper was given scores under various topics to eventually establish broad themes and conduct metrics on the scored topics. Metrics included the number of studies in bioregions, geographical regions and time period in which studies were conducted. Furthermore, studies in world biomes and South African biomes were established and compared. Floristic information was primarily extracted for the number of studies that were conducted in centres of endemism in South Africa and also in which centres. Lastly, specific information of species that were studied were gathered, e.g. which were edaphic specialists, had a conservation status or how many of these species were newly described. Graphs were constructed in Microsoft Excel.

2.8.2. Chapter 4: Floristics of GWC mountains

MaxEnt software (Elith *et al.*, 2011; Phillips *et al.*, 2019) was used to develop an ecological niche model based on bioclimatic variables, geology and occurrence records of the 24 endemic plant species. This model was used to refine and redefine the borders of GWC. Floristic analyses based on historical and field collected data, was then conducted within these refined borders. The largest plant families associated with each mountain ecosystem were identified and ranked using Spearman's rank correlation in STATISTICA version 13.3 (TIBCO Software Inc., 2017). To determine the degree of similarity between mountain ecosystems on species level, Jaccard similarity coefficients were performed in PAST (Hammer *et al.*, 2001). Plant species were ranked according to their overall abundances to identify common plant species. Herbaceous species composition between mountains was assessed by constructing a Non-metric Multi-Dimensional Scaling (NMDS) scatterplot followed by Permutational Multivariate Analysis of Variance (PERMANOVA) to test whether clustering was significant in PRIMER 6 (2012). Indicator species, unique to each mountain, were identified by performing indicator species analysis in RStudio (Roberts, 2016) where after these species were correlated with environmental variables with Canonical Correspondence Analysis (CCA) in CANOCO 5 (Šmilauer & Lepš, 2014).

2.8.3. Chapter 5: Drivers of plant diversity patterns and vegetation structure

Differences in soil characteristics and herbaceous composition between mountain habitats were investigated using PERMANOVA (Anderson, 2001) in PRIMER 6 (2012) followed by homogeneity of multivariate dispersions (PERMDISP) to test for homogeneity of dispersion. These results were then visualised in a NMDS plot. Normality of soil variables was investigated and where necessary, variables were log transformed [log(x+1)]. One-way Analysis of Variance (ANOVA) was performed to test for significant variance between soil variables among the four mountain systems. Tukey's post-hoc Honesty Significant Difference (HSD) tests were conducted on normally distributed variables to determine which mountains differed significantly. If variables violated assumptions of normality, non-parametric Kruskal-Wallis post-hoc tests for two-tailed multiple comparisons of mean ranks for all groups were performed. All these analyses were conducted in STATISTICA version 13.3 (TIBCO Software Inc., 2017).

The relationship between plant community composition and soil parameters was examined using PERMANOVA, PERMDISP and distance linear modelling (DistLM) analysis in PRIMER 6 (2012) under the PERMANOVA add on (Anderson *et al.*, 2008). Results of the DistLM model were visualised by performing distance-based redundancy analysis (dbRDA) (Legendre & Anderson, 1999; Anderson & Walsh, 2013).

Diversity indices were calculated in PRIMER 6 (2012). Similarly, to the analysis described for the soil characteristics, species diversity indices, herbaceous- and woody structure variables, were tested for normality using STATISTICA version 13.3 (TIBCO Software Inc., 2017). Normal distributed data were subjected to ANOVAs to test for significant variance among mountain ranges. To test for significant differences in variables between mountain ranges, Tukey's post-hoc Honestly Significant Difference (HSD) test was performed. When assumptions of normality were still violated despite transformations, non-parametric Kruskal-Wallis ANOVA by Ranks followed by post-hoc tests for two-tailed multiple comparisons of mean ranks for multiple independent groups were performed.

Soil characteristics acting as drivers of species diversity measures and community structure were identified by performing multiple linear regression models in STATISTICA version 13.3 (TIBCO Software Inc., 2017). Results of multiple regression models were then visualized using redundancy analysis (RDA) in CANOCO version 5 (Šmilauer & Lepš, 2014).

2.8.4. Chapter 6: Diversity-biomass relationships

Diversity indices, calculated in Chapter 5, were used to investigate diversity-biomass relationships at regional and local scale. In addition, diversity measures were also calculated for plant functional groups (PFGs) in PRIMER 6 (2012). Relationships between biomass, species- and PFG diversity measures were analysed using linear correlation matrices, followed by locally weighted scatterplot smoothing (LOWESS) in STATISTICA version 13.3 (TIBCO Software Inc., 2017). To establish the contribution of each PFG to biomass and diversity measures, values of variables were calculated separately for each respective PFG. Diversity measures (for species and PFGs), biomass data and environmental data were subjected to normality tests, followed by ANOVAs and by Tukey's post-hoc HSD tests and/or non-parametric Kruskal-Wallis post-hoc tests for two-tailed multiple comparisons of mean ranks for multiple independent groups. Where necessary, variables were log(x+1) transformed. These analyses were conducted to detect significance in variance in measured variables between the four mountains.

Multiple linear regression models were performed on biomass, soil characteristics and rainfall to determine relationships between variables. Relationships between significant environmental variables and biomass were visualised using RDA in CANOCO version 5 (Šmilauer & Lepš, 2014).

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Chapter 3

Carbonate soils and ecosystems in Africa: A review

3.1. Introduction

Calcareous soils cover more than 30% of the Earth's surface and are widely distributed across various climates (FAO, 2019; Taalab *et al*., 2019) and ecosystem types ranging from tropical (Henderson, 1939; Furley & Newey, 1979; Zhu *et al*., 2003; Clements *et al*., 2006) to Mediterranean (Cerdà, 1997; Goldblatt, 1997; Mota *et al*., 2008; Filibeck *et al*., 2019) and dryland areas (Scholz, 1971; Ward *et al*., 1993; Miller *et al*., 2006; Brock-Hon & Morgenthaler, 2019). In dryland areas, these soils occur on geological parent material (Holmes, 2012) generally rich in calcium (Ca) such as dolomite ($CaMg(CO_3)_2$) and limestone ($MgCO_3{\cdot}CaCO_3$) (Soil Classification Working Group, 2018). Other calcareous soils include those on calcrete. Wright (2007) defines calcrete as an accumulation of calcium carbonate ($CaCO_3$) near the soil surface through cementation (i.e. displacive and replacive introduction of $CaCO_3$ into the soil profile, sediments or bedrock). This usually occurs in regions where vadose and shallow phreatic groundwater becomes saturated with $CaCO_3$ (Wright, 2007). It is also known as hardpan which is a Ca-rich duricrust that becomes hardened in soil profiles as a result of climatic fluctuations, especially in semi-arid and arid regions (Encyclopaedia Britannica, 2008). Calcite is a mineral consisting purely of $CaCO_3$ (McCarthy & Rubidge, 2005) and is easily dissolved in groundwater. When dried, water evaporates and the mineral precipitates on the surface (Encyclopaedia Britannica, 2008). After precipitation, carbon dioxide (CO_2) saturated rainwater acts as an acid that dissolves the calcite. Consequently, the mineral is redeposited on to soil particle surfaces and as the interstitial soil spaces are filled, an impermeable crust is formed (Encyclopaedia Britannica, 2008). Despite Ca-rich substrates developing differently through geological and sedimentation processes, they have one specific factor in common, namely high levels of $CaCO_3$, and are hence referred to as carbonate soils (Glasauer *et al*., 2013; Taalab *et al*., 2019).

Carbonate soils are alkaline (pH values above 7) and rich in various elements such as potassium (K), magnesium (Mg) and Ca, with higher concentrations of exchangeable cations compared to acid soils, and lower fine sand content compared to soils derived from quartzite (Bredenkamp & Theron, 1991; Matthews *et al*., 1993; Cowling & Witkowski, 1994; Cowling *et al*., 1994; Abd El-Ghani & El-Sawaf, 2005; Abd El-Ghani & Marei, 2007; Weil & Brady, 2017; FAO, 2019). These soils tend to be deficient of a high organic matter content, nitrogen (N), phosphorous (P), and micronutrients, especially zinc (Zn) and iron (Fe) (Matthews *et al*., 1993; Abd El-Ghani & Marei, 2007; FAO, 2019). It is widely accepted that unusual or nutrient-poor soil types provide edaphic niches to plant species which can tolerate such conditions, serving as a selective force for plant speciation (Raven, 1964; Kruckeberg & Rabinowitz, 1985; Kruckeberg, 1986; Rajakaruna, 2004; Clarke & Moran, 2016). Mason (1946) was the first to propose links between edaphic factors as drivers of endemism, including carbonate soils. Consequently, through the process of speciation and natural selection, carbonate soils harbour unique plant communities with variable levels of endemism (Kruckeberg, 1969; Kruckeberg & Rabinowitz, 1985; Kruckeberg, 1986; Willis *et al*., 1996a; Cowling & Hilton-Taylor, 1997; Zhu *et al*., 2003; Qin *et al*., 2012; Smyčka *et al*., 2017). Endemic plant species on unusual soils are generally referred to as edaphic endemics, edaphic specialists or habitat specialists (Cowling & Holmes, 1992; Van Wyk *et al*., 2010; Magee *et al*., 2011; Goldblatt & Manning, 2012). Plants that are adapted to occupy Ca-rich habitats are referred to as calcicoles, calcicolous plants, calciphiles or calcicolous flora (Tansley, 1917; De Silva, 1934; Reinhardt *et al*., 2013; Rogers *et al*., 2018).

Plant communities growing on carbonate soils are characterised by distinct species assemblages, high species richness and contribute significantly to regional as well as global plant diversity (Kruckeberg, 1969; Cowling, 1990; Zhu *et al*., 1998; Pärtel, 2002; Abd El-Ghani & El-Sawaf, 2005; Clements *et al*., 2006; Harrison *et al*., 2009; Damschen *et al*., 2012; Reinhardt *et al*., 2013; Smyčka *et al*., 2017). Moreover, many species included in the Red Data List are associated with these communities (Zietsman & Bredenkamp, 2007; Magee *et al*., 2011; Friis *et al*., 2017; Dülgeroğlu & Aksoy, 2019; Frisby *et al*., 2019; Karlík & Poschlod, 2019). Despite its distinctiveness and contribution to biodiversity, plant communities associated with carbonate soils remain understudied and poorly conserved in some regions of Africa (Zhu *et al*., 2003; Clements *et al*., 2006; Frisby *et al*., 2019). The aim of this review was therefore to document our current understanding of the calcicolous flora and ecology of carbonate soils (i.e. limestone, dolomite, calcrete) in Africa. The first objective was to summarise the extent to which carbonate soils are considered and valued, directly and/or indirectly, in ecological and floristic research on the African continent.

Calcicolous floras are threatened by acid pollution (Pärtel, 2002), climate change (Harrison *et al*., 2009; Damschen *et al*., 2012; Basto *et al*., 2018; Dülgeroğlu & Aksoy, 2019), mining (Clements *et al*., 2006; Goldblatt & Manning, 2013), alien invasion (Rouget *et al*., 2003; Zietsman & Bredenkamp, 2007) and habitat loss (Willis *et al*., 1996a; Van Buren & Harper, 2003; Lu *et al*., 2016). Conservation of calcicolous floras remains challenging in Africa, due to restricted geographical plant distribution ranges and specific habitat preferences (Loehle, 2006; Retief *et al*., 2008; Van Wyk *et al*., 2010; Goldblatt & Manning, 2013). Thus, the second objective was to identify knowledge gaps and provide new perspectives by asking significant questions that may contribute to future botanical research or guide conservation and management efforts of calcicolous plant communities in Africa.

3.2. Materials and methods

3.2.1. Literature search and applied criteria

A search of peer-reviewed scientific literature was conducted in October 2018 and August 2019 using the electronic database Scopus with the following four search strings: (1) Africa* AND dolo* AND plant* OR vegetation OR flor*, (2) Africa* AND calcareous* AND plant* OR vegetation OR flor*, (3) Africa* AND calcrete AND plant* OR vegetation OR flor* and (4) limestone AND endemic AND species (to gain more information regarding endemic species-specific to limestone, since some studies on this topic were not retrieved from the first search) in the title, keywords or abstract (Table A1; Appendix A). Language and document type were limited to English scientific articles. Grey literature was not considered in the search. Additionally, affiliation countries in Africa were selected. Research areas outside the African continent were excluded. Subject areas were limited to Environmental, Agricultural and Biological Sciences (Tables A1, A2 and A3). A total of 111 studies were individually screened based on the title and abstract (Figure A1). Papers that (1) did not focus on plant communities, (2) followed a non-ecological approach and (3) did not evaluate aspects of plant-soil relationships, were discarded. After screening, 41 papers were considered relevant and were further examined (Figure A1). Two publications were omitted since one study could not be retrieved in full-text through library services and/or through internet sources, whilst the other was a duplicate study that was published under different titles in different journals but with similar results. Finally, a total of 39 research articles were included in the review.

3.2.2. Research context

A hierarchical approach was followed to structure the review (Figure 3.1). Firstly, keywords derived from article titles and keywords, as well as the general topic of literature were sorted using Microsoft Excel. Some words were omitted which were considered irrelevant or changed to be grouped under broader keywords or topics. Initially, 223 keywords were screened of which 48 were omitted, 78 changed while 60 were related to climate and biomes. Finally, 117 keywords were used to construct a word cloud in WordItOut (2020) (Figure 3.2) to reveal general topics that were researched in Africa. The default setting for constructing a Word Cloud in WordItOut (2020) allows for the assumption that word size and width would reflect the weight of a particular research topic in the selected literature sources. Seven main themes were distinguished from the word cloud (Figure 3.3). From these main themes, research topics were identified that were directly linked to general overarching themes of this study to address the specific aim and objectives of this review (Figure 3.1). Five overarching themes with their sub-themes were differentiated, namely (1) speciation and functional organisation, (2) plant community characteristics and vegetation dynamics, (3) ecosystem services of calcicolous floras, (4) calcicolous floras and the Anthropocene, and (5) conservation and management.

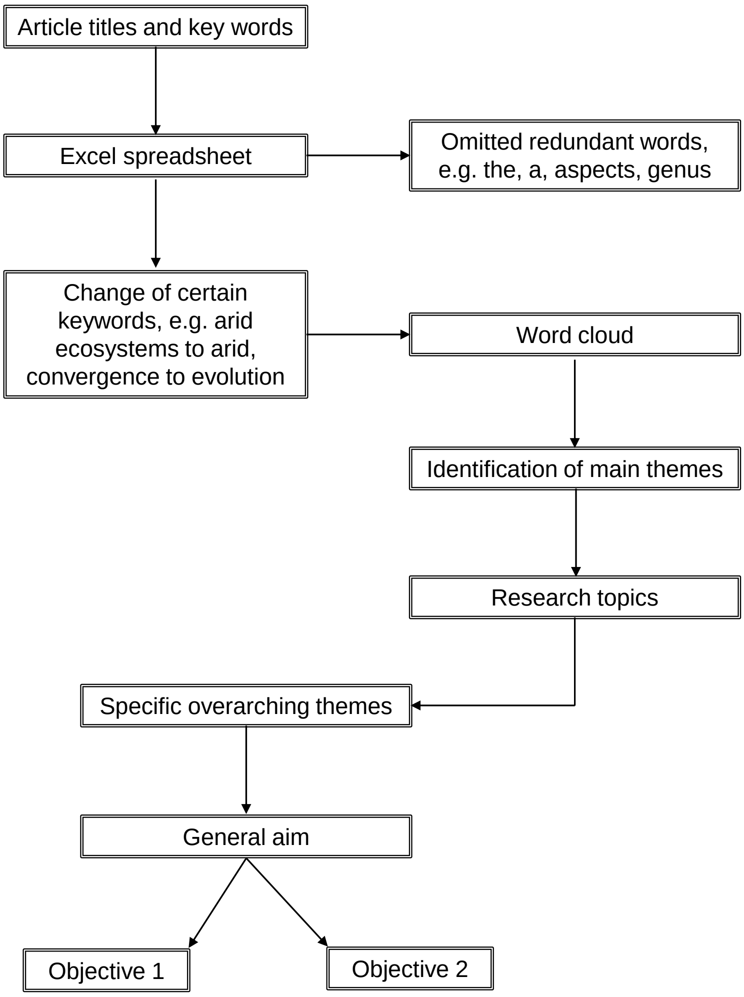

Figure 3.1. Summary of the research context followed and the links with the aim and objectives of the review.

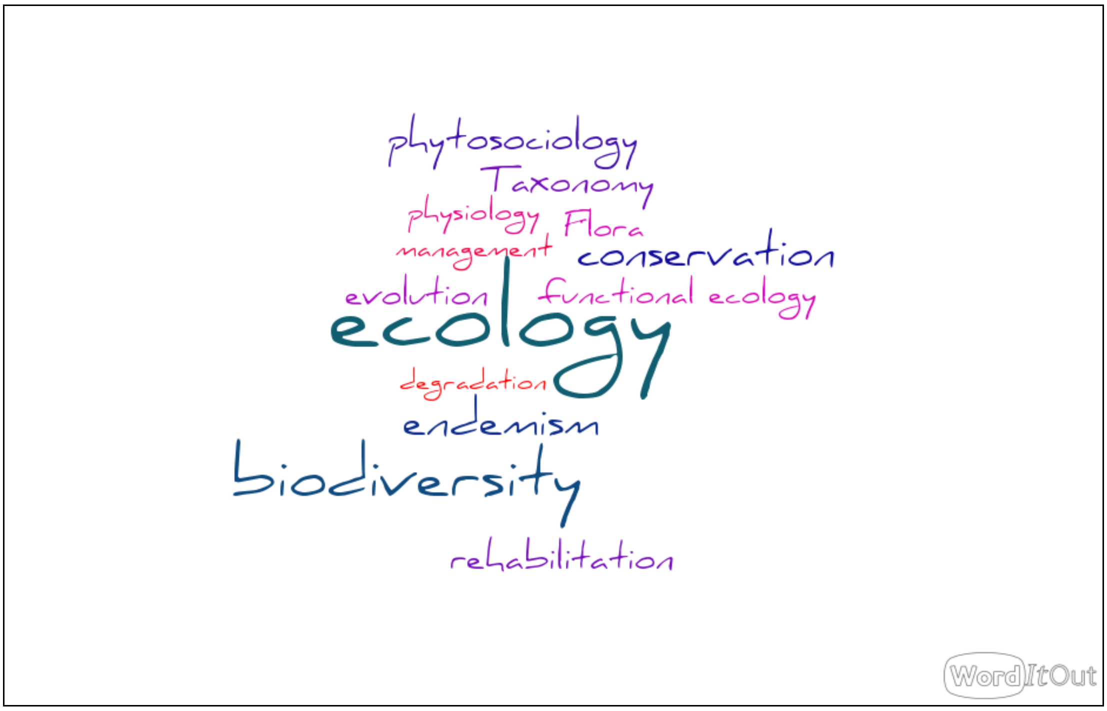

Figure 3.2. Word cloud created by the online word cloud generator, WordItOut (2020).

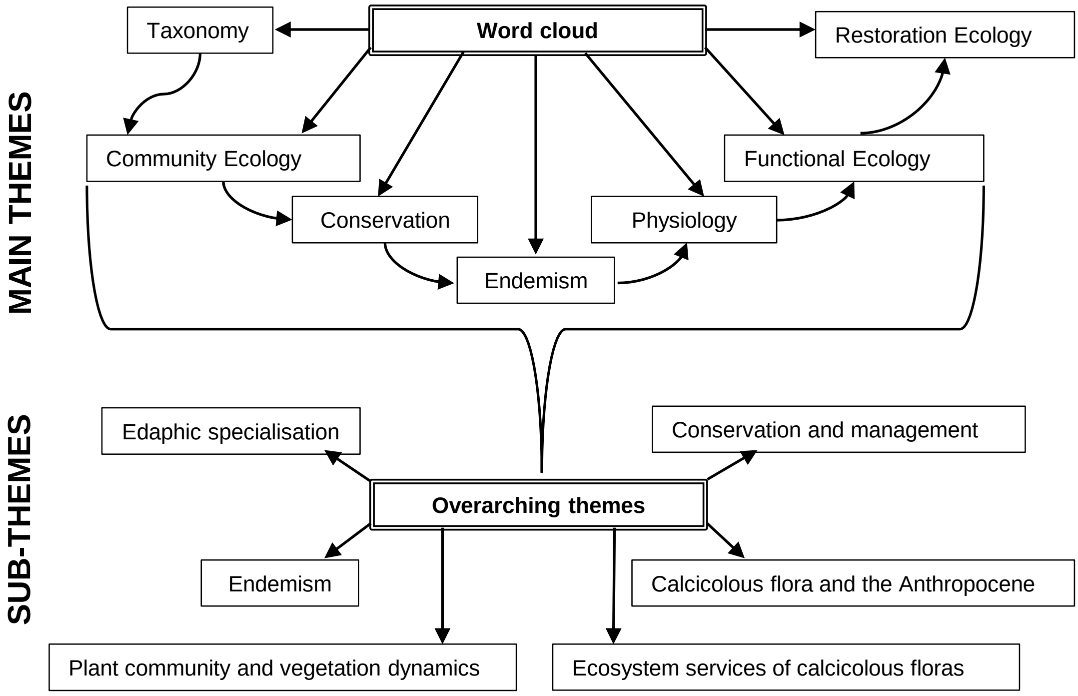

Figure 3.3. Main themes and the relationship thereof regarding differentiated overarching themes.

3.3. Results and discussion

A total of 39 studies were reviewed. Detailed records of key metrics are provided in Appendix A. The majority of studies were conducted in the Afrotropical Biogeographical Realm (Figure A2; Appendix A) within the Mediterranean Forests, Woodlands and Scrub World Biome (Figure A3) and in regions with a semi-arid climate that receives winter rainfall (Figure A4). Studies were biased towards South Africa (Figure A5), the Fynbos Biome (Figure A6) and the Cape Floristic Region (CFR) (Figure A7). Research in carbonate plant communities showed peaks of interest during the periods 2006-2010 followed by 1991-1995 (Figure A8). Research was primarily conducted within the broad themes of Taxonomy, Phytosociology and Community Ecology (Figure A9). Categories of species that were mostly addressed in studied literature included endemic plant species, edaphic specialists, new species, calcicoles and species listed on the Red List (Figure A10). It should be considered that findings from this review are based on a limited number of studies and that the sole use of Scopus may have resulted in the unintentional exclusion of other relevant research studies. However, this review contributes to a valuable inceptive insight regarding calcicolous floras in Africa. It further emphasises the necessity for more botanical studies to promote our understanding of the functioning of these unique plant communities, especially under climate- and land use change. Under each overarching research theme, major findings of reviewed studies will be discussed.

3.3.1. Speciation and functional organisation

3.3.1.1. Edaphic specialisation

The level of local endemism among limestone endemics in the CFR was primarily ascribed to edaphic specialisation, since the calcicolous flora occurring on fragmented limestone islands were isolated and surrounded by acidic substrates (Cowling & Holmes, 1992; Willis *et al.,* 1996a). These acidic substrates, derived from quartzite, harboured plant assemblages that differed from those on carbonate substrates derived from dolomite (Matthews *et al.,* 1993). Differences between acidic and carbonate plant communities were reported to be primarily related to edaphic characteristics, with soils derived from dolomite displaying higher Mg and Ca content than acidic substrates (Matthews *et al.,* 1993). It is therefore suggested that the evolution of endemics, driven by environmental stress factors, resulted in intensified natural selection of the dolomitic flora, with the possibility of an increased mutation rate (Matthews *et al.,* 1993). Edaphic speciation resulted in plant species with a high affinity for Ca-rich substrates (Frisby *et al.,* 2019), as well as the development of unique trait sets associated with the calcicolous flora (Cowling & Holmes, 1992; Willis *et al.,* 1996a). Unique trait sets were furthermore considered as a reflection of incidental speciation events rather than contemporary or historical ecological conditions. Consequently, rapid edaphic specialisation was promoted due to catastrophic selection that enabled those species that are remarkably adapted, to survive extreme events (Cowling & Holmes, 1992; Willis *et al.,* 1996a).

Several new species, characteristic of carbonate soils, were identified and described in South Africa over a period of 11 years. Several of these species were found within centres of plant endemism, mostly in the Savanna and Fynbos Biomes. From 2008 to 2019, four new plant species of various plant families were described in semi-arid savannas. These savanna species included *Deverra rapaletsa* Magee & Zietsman in the Apiaceae (Van Munster *et al.,* 2019), *Dracaena transvaalensis* Baker (Van Jaarsveld, 2016) in the Dracaenaceae, *Euclea sekhukuniensis* Retief, Siebert & A.E.van Wyk. in the Ebenaceae (Retief *et al.,* 2008), and *Rennera stellata* P.P.J. Herman (Herman, 1999), which is currently known as *Pentzia stellata* (P.P.J.Herman) Magee, in the Asteraceae (Frisby *et al.,* 2019). *Deverra rapaletsa* is a uniquely prostrate, multi-stemmed perennial of small stature, with a woody rootstock, that is currently known from two populations and, considered common in habitats that consist of weathered limestone outcrops on the Ghaap Plateau within the Griqualand West Centre of Endemism (GWC) (Van Munster *et al.,* 2019). *Dracaena transvaalensis* is a rare endemic of dolomitic substrates in the Wolkberg Centre of Plant Endemism and prefers open savanna landscapes on steep slopes and kloofs in full sun or light shade. The natural habitat of *D. transvaalensis* is subjected to occasional fires and, thus, the presence of corky bark at the base of stems serves as a protection mechanism against fire (Van Jaarsveld, 2016). *Euclea sekhukuniensis* prefers open niches on ultramafic soils where it has possibly developed a physiological mechanism, the accumulation of Ca in stems, leaves and roots, enabling it to tolerate or exclude toxic heavy metals in ultramafic soils (Retief *et al.,* 2008). *Pentzia stellata*, also occurring on the Ghaap Plateau, is associated with calcrete pans underlain by unweathered calcrete bedrock in GWC and considered a habitat specialist (Herman, 1999).

Over three years, six new plant species were described from limestones in the CFR (Magee & Manning, 2010a; Magee & Manning, 2010b; Van Wyk *et al.,* 2010; Magee *et al.,* 2011; Goldblatt & Manning, 2012). In the Asteraceae, two new limestone endemic species, *Gazania lanata* Magee & Boatwr. and *Pentzia trifida* Schltr.ex.Magee & J.C.Manning were described (Magee & Manning, 2010b; Magee *et al.,* 2011). *Gazania lanata* is a tufted cushion-forming perennial plant and is known from only one population near Robertson (Magee *et al.,* 2011). It grows at the foot of the Langeberg Mountains in shallow skeletal soils above dolomite lenses (Magee *et al.,* 2011). *Pentzia trifida* is a multi-stemmed aromatic shrublet, rarely prostrate, but with erect or spreading well-branched stems. This species is commonly distributed along the Agulhas Plain from Bredasdorp eastwards to Stillbay (Magee & Manning, 2010b).

Two new members were described in the Apiaceae in one year, *Glia decidua* B-E.van Wyk and *Annesorhiza calcicola* Magee & J.C.Manning (Magee & Manning, 2010a; Van Wyk *et al.,* 2010). *Glia decidua*, a summer deciduous perennial geophyte with slender, unbranched stems arising from a short persistent woody rootstock, is a habitat specialist that grows on soils derived from limestone and shale (Van Wyk *et al.,* 2010). Hence, this plant has a localised distribution in the western coastal region of the Western Cape Province in the renoster- and shrubveld of the Swartland. It is only known from a few localities in the vicinity of Piketberg, Malmesbury and Saldanha Bay (Van Wyk *et al.,* 2010). *Annesorhiza calcicola*, a deciduous geophyte of small stature, is known only from a few limestone outcrops around Jacobsbaai on the West Coast of South Africa. Its distribution range is restricted to limestone outcrops in the Saldanha Peninsula (Magee & Manning, 2010a).

The Iridaceae was also found to harbour a new plant species characteristic to carbonate soils in the Fynbos Biome, *Moraea hainebachiana* Goldblatt & J.C.Manning (Goldblatt & Manning, 2012). Restricted to the district of Saldanha Bay, *M. hainebachiana* is an edaphic specialist with a preference for rocky limestone flats and slopes as well as calcareous sands along the coast and adjacent hills. It was also found in humus-rich pockets of loam between fractured limestone rocks and in coarse calcareous sand (Goldblatt & Manning, 2012). One limestone endemic plant species in the Iridaceae was described from the Succulent Karroo Biome within the Knersvlakte Centre (Goldblatt & Manning, 2013). *Hesperantha dolomitica* Goldblatt & J.C.Manning is a narrow endemic of limestone outcrops, found on north-facing slopes of the Vars River in southern Namaqualand. It is a geophyte and a habitat specialist since it prefers to grow between limestone crevices as well as loamy red soil types at the base of south-facing limestone cliffs.

To conclude, the reviewed papers allowed us to postulate that there is a link between edaphic specialisation and endemism across three different biomes in South Africa. The Fynbos Biome harboured the majority of newly described species. In general, endemic plant species that were described displayed an affinity to carbonate substrates, therefore these species are habitat specialists, with localised distribution patterns and characterised by unique morphological, growth and life form traits, as well as physiological mechanisms (i.e. *E. sekhukuniensis*). Plant families such as the Apiaceae (3 new species), Asteraceae (3), and the Iridaceae (2) produced most of the newly described endemic plants. These plant species were known only from a few localities on limestone, dolomite and/or calcrete, suggesting that these species should deserve special attention from conservation managers and for Red Data List assessments.

3.3.1.2. Endemism

Limestone endemic plant species were consistently found in a variety of biomes and vegetation types. In Mediterranean fynbos within the CFR, the flora of the Agulhas Plain was characterised by high levels of local and regional endemism (Cowling & Holmes, 1992). Local endemics, restricted to limestone islands of the CFR, included taxa within the Ericaceae, Fabaceae, Polygalaceae, Rhamnaceae, Rutaceae and Sterculiaceae (Cowling & Holmes, 1992; Willis *et al.,* 1996a). When local and regional endemism were compared between two different continents with similar vegetation types and climates, i.e. fynbos in South Africa and kwongan (similar to fynbos) in Australia, these endemics had similar habitat preferences. South African and Australian limestone endemic plant species displayed an affinity to sclerophyllous shrublands (Cowling *et al.,* 1994). However, taxonomically these endemic species differed since local fynbos limestone endemics were primarily within the Ericaceae, Mesembryanthemaceae, Polygalaceae, Proteaceae and Rutaceae, while the Restionaceae and Thymeleaceae were rich in regional endemism. In contrast, Australian limestone endemics were restricted to three plant families with the Proteaceae that dominated local and regional endemism, whereas local endemics were members in the Epacridaceae and Myrtaceae (Cowling *et al.,* 1994).

In a semi-arid grassland system, the number of endemic species differed among dolomite and quartzite substrates (Matthews *et al.,* 1993). Narrow endemics were associated with both soil types with the dolomitic soil harbouring lower numbers of endemic species compared to those on the quartzite. These dolomitic endemics were herbaceous species from the Acanthaceae, Euphorbiaceae, Lamiaceae and Liliaceae. Furthermore, some endemic species had an affinity for dry grassland habitats whereas others were less restricted (Matthews *et al.,* 1993). Narrow endemic plant species were also found in mountainous regions in a semi-arid savanna landscape with two species being restricted to dolomite soil of the Ghaap Plateau (Frisby *et al.,* 2019). Similarly, to the grassland ecosystem, the savanna endemic species were well represented in the Acanthaceae. Other families included the Aizoaceae and Asteraceae.

From the reviewed literature, evidence exists that calcicolous floras of fynbos, grassland and savanna are rich in endemic plant species which belong to various plant families. Thus, there seems to be a clear indication of edaphic specialisation across all three biomes in South Africa that resulted in the development of edaphic specialists on Ca and Mg-rich substrates. Endemic plant species were listed on the Red Data List and should be considered in future conservation and management programmes in each biome. It is also important to not only focus on the conservation of endemic species *per se* but additionally conserve unique drivers that contribute to soil-plant interactions in their distinct environments. This thesis will contribute to the investigation of endemic plant species on carbonate soils, especially on the dolomitic Ghaap Plateau. Van Staden *et al.,* (2020) has already contributed to our understanding of the floristics of carbonate plant communities within a semi-arid savanna landscape in South Africa. Certain edaphic specialists, restricted to carbonate plant communities, were identified which suggested habitat specialisation (Van Staden *et al.,* 2020).

3.3.1.3. Functional attributes

Limestone endemics within the CFR were characterised by specific dominant functional trait sets as a result of speciation and specialisation (Raitt & Moffett, 1987; Cowling & Holmes, 1992; Cowling & Witkowski, 1994; Mustart *et al.,* 1994; Willis *et al.*, 1996a). These traits included life forms, growth forms, dispersal strategies, plant height as well as certain physiological mechanisms (Cowling & Holmes, 1992; Cowling *et al.*, 1994; Cowling & Witkowski, 1994; Mustart *et al.,* 1994; Willis *et al.*, 1996a).

Locally, some endemic plant species, especially forbs and trees, were considered generalists which were adapted to grow on a variety of substrates, including limestone (Raitt & Moffett, 1987; Cowling & Holmes, 1992). Other, woodier endemics were usually taller with erect growth forms and long-distance dispersal strategies through zoochory (Cowling & Holmes, 1992). Limestone endemic specialists were reported to be low-growing dwarf shrubs as well as non-sprouting shrubs with soil stored seeds that can be dispersed by wind (anemochory) and/or ants (myrmecochory) (Cowling & Holmes, 1992; Cowling *et al.*, 1994; Willis *et al.*, 1996a). Consequently, these specialist plant species have short dispersal ranges, a trait considered to be correlated with endemism, and thus resilience through dispersal was highly unlikely (Cowling & Holmes, 1992; Cowling *et al.*, 1994; Willis *et al.*, 1996a). Some studies revealed that local endemic species can form a symbiotic relationship with microbes, indicating the relationship between local endemism and edaphic specialisation (Cowling & Holmes, 1992; Cowling *et al.*, 1994; Willis *et al.*, 1996a). Additionally, Ca was considered to fulfil an important role in nodulation and N-fixation since a calcicole leguminous plant species, *Indigofera* sp. nov., was considered a Ca accumulator (Raitt & Moffett, 1987). However, edaphic factors were overridden by fire effects in limestone fynbos due to no clear plant-soil interactions between reproductive and germination traits (Cowling & Witkowski, 1994; Mustart *et al.,* 1994).

Overall, endemic plant species seemed to be characterised by certain unique trait sets due to specialisation and ecological histories to overcome low survival rates caused by limited dispersal mechanisms. Short dispersal ranges, as well as symbiotic relationships with microbes, served as an additional relationship between endemism and edaphic specialisation. It is evident that scale is an important factor to consider even when researching functional traits. On a continental scale, clear plant-soil interactions were distinguished. On a local scale, edaphic factors were overridden by niche availability and fire that were considered primary drivers of reproductive traits. Calcicole floras were characterised by certain physiological adaptations linked to mineral nutrition such as Ca availability. This was a clear indication that edaphic factors influenced these floras not only ecologically, based on their distribution ranges, but also at physiological level.

3.3.2. Plant community characteristics and vegetation dynamics

3.3.2.1. Plant-soil-environment interactions

Over a period of 16 years, various plant communities located on carbonate soils, across various climates and in different vegetation types, were described for Africa (Bredenkamp & Theron, 1991; Bezuidenhout *et al.*, 1994; Burke, 2001; Abd El-Ghani & El-Sawaf, 2005; Siebert & Siebert, 2005; Zietsman & Bredenkamp, 2006; Abd El-Ghani & Marei, 2007; Zietsman & Bredenkamp, 2007; Van Rooyen *et al.*, 2008). Habitat heterogeneity, i.e. topography, soil type, land type, soil depth, clay content, rockiness, altitude, slope, microclimate, exposure to strong winds and soil moisture availability were considered the main drivers of compositional differences (Bredenkamp & Theron, 1991; Bezuidenhout *et al.*, 1994; Burke, 2001; Siebert & Siebert, 2005; Zietsman & Bredenkamp, 2006; 2007; Van Rooyen *et al.*, 2008).

Plant communities of dolomitic grassland, calcareous soil and calcrete savanna in South Africa (Bredenkamp & Theron, 1991; Bezuidenhout *et al.,* 1994; Siebert & Siebert, 2005), as well as in Egyptian arid Mediterranean coastal desert (Abd El-Ghani & El-Sawaf, 2005; Abd El-Ghani & Marei, 2007) were found to be diverse. Differences between assemblages were primarily influenced by soil characteristics and topography. Similarly, semi-arid Mediterranean fynbos in the CFR associated with calcareous coastal thicket, dune vegetation, limestone inland plains, and hills harboured distinct and species rich plant communities (Zietsman & Bredenkamp, 2006; 2007). Conservation of carbonate plant communities in semi-arid grasslands, savannas, Mediterranean fynbos and an arid desert-savanna ecotone are of significant importance especially considering their unique flora, habitat diversity, endemic species and conservation status in southern Africa (Bredenkamp & Theron, 1991; Burke, 2001; Zietsman & Bredenkamp, 2006; 2007; Van Rooyen *et al.*, 2008).

Reviewed literature highlighted that many plant communities and higher-level vegetation associations were described for the first time from 1991 to 2007 in carbonate habitats. Many of these were restricted to certain habitat types, characterised by high species richness and diversity. There is a distinct and direct relationship between plant communities, edaphic factors and habitat heterogeneity. From all the studies reviewed, it was clear that habitat heterogeneity drove differences in carbonate plant communities across climates and biomes on the African continent. Plant communities of carbonate soils are high priority areas for conservation due to their unique characteristics, diversity and richness. This thesis will contribute to our understanding of plant-soil-environment interactions on plant species diversity and community structure patterns which will include carbonate plant communities associated with the Ghaap Plateau.

3.3.2.2. Community response patterns to disturbances

Succession in response to disturbances (e.g. grazing, trampling, fire, tree fall, molehills, mowing, revegetation after mining) or along a disturbance gradient (Pierce & Cowling, 1991; Hall *et al.*, 2003; Visser *et al*., 2012), livestock and drought impacts (Gamoun *et al.,* 2010; Gamoun, 2013; Ratovonamana *et al.,* 2013), as well as bush encroachment (Pule *et al.,* 2018), were the focus of studies on carbonate plant communities in Africa.

Human interaction was found to enhance community response patterns in disturbed plant communities (Pierce & Cowling, 1991; Hall *et al.*, 2003; Visser *et al*., 2012). Seedbanks of endemic rich dune limestone fynbos was reported to be small, consisted of short-lived species and seeds that were soil-stored (Pierce and Cowling, 1991). These traits, associated with the limestone fynbos, suggested that frequent disturbances (i.e. frequent mowing or heavy livestock grazing) lead to depletion of fynbos shrubs. A lack in disturbances together with regular fire events over a long time period, was considered to result in thicket encroachment. Therefore, active management was needed to ensure intermediate disturbance levels to allow persistence of shrub species through the reproduction cycle of adult plants that maintained viable seed banks (Pierce & Cowling, 1991). Human intervention to govern succession on limestone was highly important following mining activities and old field succession (Hall *et al.*, 2003; Visser *et al*., 2012). The use of topsoil of the initial vegetation (i.e. thicket) to landscape limestone quarry floors, was found to be useful to promote revegetation through natural succession. The use of topsoil with thicket propagules provided the necessary physical, biological and chemical characteristics that were of significant importance to assist with the succession of thicket vegetation (Hall *et al.*, 2003). Within revegetated sites, successional displacement was evident in plant communities with early pioneer species being replaced by later successional species – an indication of facilitation (Hall *et al.*, 2003). The use of seed mixtures that consisted of native, responsive and complementary grass species in combination with leguminous plant species, proved to enhance P levels in old barley fields in calcareous drylands (Visser *et al*., 2012). As a result, primary productivity levels were also enhanced in these landscapes. Under livestock grazing regimes (heavily grazed and protected) and drought between soil types, primary productivity of limestone plant communities varied (Gamoun *et al.,* 2010; Gamoun, 2013; Ratovonamana *et al.,* 2013). Under herbivore exclusion (i.e. protected) vegetation communities underlain by sandy soil were more productive than protected limestone communities (Gamoun *et al.,* 2010). Despite their lower productivity levels, soil crust formation was lower on limestone soils than sandy soils. This was ascribed to the compact nature and higher rock cover associated with limestone soils (Gamoun *et al.,* 2010). Consequently, wind erosion is limited on limestone soils and more plant species were preserved. Therefore, limestone plant communities were considered resistant to livestock trampling (Gamoun *et al.,* 2010; Ratovonamana *et al.,* 2013). However, limestone plant communities were severely influenced by drought under livestock exclusion since species richness and plant diversity decreased in the drought year in comparison to wetter years (Gamoun, 2013). Drought, therefore, contributed to habitat degradation of arid limestone rangelands (Gamoun, 2013). Despite loss of floristic diversity, limestone plant communities maintained vegetation cover over three years under wet, moderate and dry conditions (Gamoun, 2013). During the dry season, limestone communities contributed to fodder for livestock through high biomass production of perennial grass, herb and/or shrub indicator plant species (Ratovonamana *et al.,* 2013). Loss of primary productivity through encroaching problem plants, such as *Seriphium plumosum* L. resulted in the decline of carrying capacities of limestone grasslands (Pule *et al.,* 2018). However, *S. plumosum* was sensitive to environmental conditions associated with dolomite soils since these soils were fertile with high Na content and seasonally waterlogged.

From the literature reviewed, it can be concluded that seed banks of calcareous dune vegetation types were affected along a disturbance gradient. Endemic rich fynbos on dune systems was severely affected especially by frequent disturbances. Human intervention was required through reseeding and addition of fertilisers, especially P, to aid the revegetation of degraded habitats. As a result, climax stable states can be reached over the long term. Furthermore, there are clear advantages of using topsoil of the initial vegetation type as well as leguminous plant species to enhance succession. When left undisturbed (herbivore exclusion) calcareous rangelands in arid desert systems hosted plant communities with high biomass yield. However, when exposed to frequent and heavy grazing events, biomass levels decreased, resulting in less productive communities. Despite being less productive due to overgrazing, the plant species pool was maintained due to the associated soil texture and rock cover of limestone substrates that protected plant communities against wind erosion. Thus, limestone rangelands in arid and tropical semi-arid climates were considered resilient against livestock grazing but sensitive to drought. Primary productivity, soil characteristics, precipitation and grazing intensities were significant determinants of disturbance response patterns of calcareous rangelands. The role of soil characteristics was also emphasised in a semi-arid grassland, since the encroaching *S. plumosum,* which threatens the carrying capacity of rangelands and biodiversity, was found to be sensitive to soil properties. Long-term monitoring programmes are essential to prevent further habitat degradation of disturbed calcareous plant communities and inform aid management policies to maintain ecosystem function. Lastly, the thesis will provide insight regarding drivers (i.e. soil properties, precipitation or a combination of the two) of primary productivity (biomass yield) across different mountain ecosystems which will include the carbonate plant community of the Ghaap Plateau.

3.3.2.3. Niche theory

Different niches were occupied by dolomitic habitats (Laurie *et al.*, 1997; Chimphango *et al.*, 2015). Some species were found to be obligate co-occurring and restricted to small limestone potholes that formed microsites (Laurie *et al.*, 1997). After germination species were forced to share resources and grow together, especially after a fire event. The co-existence of species within potholes was explained by the lottery principle, suggesting that each individual had an equal chance of establishing randomly in a pothole (Laurie *et al.*, 1997). In contrast to the restricted niche availability of the previous study, leguminous plant species that prevailed on limestone, granite and sandstone habitats were able to exploit a variety of biogeochemical niches (Chimphango *et al.*, 2015). Limestone soils that were occupied by leguminous plant species were enriched with nutrients such as total N, total P, K, Mg, Na and C.

Carbonate species were adapted to co-exist in restricted niches with restricted soil nutrients and those that were leguminous were able to exploit a variety of biogeochemical niches. The obligate co-existence of two limestone species was explained by the lottery principle. With regards to legume and non-legume niches, soil nutrients were the primary driver in determining biogeochemical niches. Leguminous plants were found to occur on various niches and fulfil an important ecological role in terms of nutrient cycling in limestone habitats.

3.3.3. Ecosystem services of calcicolous floras

Calcicolous floras provide or have the potential to provide valuable ecosystem services. These included the provision of food and liquor to humans (Van Wyk *et al.*, 2010), forage provision to livestock and game (Abd El-Ghani & Marei, 2007; Gamoun *et al.*, 2010; Radloff *et al.*, 2010; Gamoun, 2013; Ratovonamana *et al.*, 2013) and the potential to assist with mine dump rehabilitation, especially those species that had the ability to exclude heavy metals (Retief *et al.*, 2008). Some endemic species were found to have a medicinal value (Abd El-Ghani & Marei, 2007; Van Wyk *et al.*, 2010). Therefore, calcicolous floras deserve special attention regarding their provisioning ecosystem services and need to be further investigated to determine other valuable services that are currently unknown.

3.3.4. Calcicolous flora and the Anthropocene

Endemic species within calcicolous floras were threatened by overgrazing (Herman, 1999; Abd El-Ghani & Marei, 2007), overharvesting for medicinal use (Abd El-Ghani & Marei, 2007), habitat loss (Matthews *et al.*, 1993; Willis *et al.*, 1996b; Herman, 1999; Van Wyk *et al.*, 2010; Magee *et al.*, 2011), habitat loss through mineral mining (Magee *et al.*, 2011; Goldblatt & Manning, 2013), urbanization (Goldblatt & Manning, 2012), crop cultivation (Van Wyk *et al.*, 2010) as well as infrastructure development (Abd El-Ghani & Marei, 2007) and drought events (Gamoun, 2013). Some of these endemic species were listed with a conservation status such as endangered (Abd El-Ghani & Marei, 2007; Goldblatt & Manning, 2013), rare (Cowling & Bond, 1991; Willis *et al.*, 1996a; Herman, 1999; Van Jaarsveld, 2016; Frisby *et al.,* 2019), vulnerable (Frisby *et al.,* 2019) data deficient (Magee *et al.*, 2011) and threatened (Zietsman & Bredenkamp, 2006; Frisby *et al.,* 2019). Furthermore, most were only known from a few localities (Herman, 1999; Abd El-Ghani & Marei, 2007; Magee *et al.*, 2011; Goldblatt & Manning, 2013) emphasising the need to monitor populations of these species under future land use- and climate change.

3.3.5. Conservation and management

Carbonate plant communities within the Fynbos and Grassland Biomes were revealed to be poorly conserved (Matthews *et al.,* 1993; Willis *et al.*, 1996a; 1996b). Reserves focusing on the conservation of taxa in the Proteaceae did not conserve limestone endemics associated with the Fynbos Biome (Willis *et al.*, 1996a). This is highly problematic for the conservation of these edaphic specialists, especially considering that most of the associated endemics occurred on fragmented limestone islands (Cowling & Holmes, 1992; Willis *et al.,* 1996a). These edaphic limestone specialists are threatened by generalist species with long-distance dispersal strategies (Cowling & Bond, 1991). Therefore, in the event of a disturbance, a limestone specialist with a short-distance dispersal strategy and with small population sizes was considered vulnerable to be outcompeted by generalists on fynbos limestone islands (Cowling & Bond, 1991). To successfully conserve local limestone endemics and to prevent species losses, the essential reserve size required is between 4 and 15 ha (Cowling & Bond, 1991). Additionally, if the main aim of conservation practices in the CFR region is to protect populations of habitat specialists and local endemic plant species, then conservation should be aimed at selecting areas of sufficient size to maximize habitat protection of endemic species (Cowling & Bond, 1991). Conservation should also be more focused on core areas where more than one endemic plant species is present (Willis *et al.*, 1996b). Additionally, it was suggested that (1) long-term data and more research were needed to assist with the conservation of the distinct floristic diversity and drivers associated with limestone endemic fynbos (Willis *et al.*, 1996a) as well as (2) managers and landowners should adopt an integrated landscape management approach (Willis *et al.*, 1996b). Since conservation of species alone was found to be inadequate, a holistic approach was suggested to be followed in the future. Therefore, processes that drove interactions between species and their environments would be conserved in carbonate landscapes (Matthews *et al.*, 1993; Willis *et al.*, 1996a).

In conclusion, local endemic and limestone specialists on fragmented islands were considered the most vulnerable to extinction. The likelihood of these species being replaced by generalists was high since the latter were associated with species characterised by dispersal mechanisms that provided them with a competitive advantage. Reserves in the CFR were found to be adequate in size for conserving these fragmented limestone islands. However, in terms of spatial configuration, reserves were found to conserve limestone endemics inadequately. The core area should form the basis of future conservation policies and an integrated landscape approach is needed to achieve the long-term conservation of the limestone endemic flora. It was also deemed important to conserve these plant communities outside protected areas and to rather focus on the conservation of the required habitat preferences of the limestone flora in both Fynbos and Grassland Biomes. This thesis aims to contribute to the conservation of carbonate plant communities. From Van Staden *et al.* (2020) it was revealed that the Ghaap Plateau harboured the highest numbers of endemic plant species emphasising the need for conserving carbonate plant communities. The Ghaap Plateau was also included within the core area of GWC which will guide more focused conservation practices. The thesis will also serve as a baseline study for future botanical studies in GWC that can be used to assist in the management of these plant communities under drought conditions in the future.

3.4. Synthesis and future challenges

Most of the relevant publications were biased towards the Afrotropical Biogeographical Realm (Figure A2; Appendix A). Carbonate plant communities in the Mediterranean Forests, Woodlands and Scrub World Biome were best researched, followed by the Deserts and Xeric Shrublands (Figure A3). The majority of studies were conducted in South Africa (Figure A5). More specifically, research in southern Africa was primarily conducted within the Fynbos and Savanna Biomes (Figure A6). The high number of studies within the Fynbos Biome is ascribed to the uniqueness and diversity hotspots associated with the biome that contribute to the popularity of fynbos research under South African botanists. As a result, the CFR was the best-researched centre of endemism (Figure A7). In total 26 studies (one study in two biomes) focused on carbonate vegetation communities within centres of endemism (Figure A7). Endemic species were included in 22 publications, edaphic specialists in 13 and calcicoles in 7 publications (Figure A10). A clear link between edaphic specialisation and endemism is evident from publications. Therefore, the main driver of evolution and distribution of calcicolous floras is linked to the specific soil properties associated with carbonate soils, indicating a clear plant-soil relationship. As a result, plant species in calcicolous floras, especially those that are endemic, are characterised by specific mechanisms such as specific morphological and physiological trait sets that are linked to edaphic specialisation, enabling these species to overcome environmental challenges. Surprisingly, we have learned that in fynbos communities, fire and niche availability were more important drivers than edaphic factors. In other biomes, habitat heterogeneity contributed to species rich and diverse plant communities.

Research focusing on physiological functional traits of calcicolous flora, was limited. Therefore, our understanding of the physiological processes and underlying mechanisms that enable calcicoles to grow and colonise carbonate habitats are poor. Additionally, a link should be established between calcicole plant species physiology, functional traits, speciation and adaptations that provide them with competitive abilities (Raitt & Moffett, 1987; Cowling & Holmes, 1992; Matthews *et al.,* 1993; Laurie *et al.,* 1997). Through the inclusion of functional diversity in species diversity assessments, vegetation change can be better detected and will enhance our understanding of ecosystem functioning of plant communities on carbonate soils (Díaz & Cabido, 2001; Hanke *et al.,* 2014; Xu *et al.,* 2018; Yoko *et al.,* 2020). Including both species and functional diversity aspects in future studies, will improve conservation and management guidelines specifically developed for carbonate plant communities.

This review revealed that ecosystem services are primarily provided by calcicolous floras in Africa. It is clear that calcareous systems are also important for the maintenance of livelihoods through the provision of ecosystem services (i.e. forage production for livestock, food and medicine). Therefore, it is certainly important to study vegetation dynamics (Rees *et al.,* 2001; Mace *et al.,* 2012). Particularly considering that climate change is predicted to result in extreme droughts, these plant communities may be even more threatened, and we need to know how we can manage and sustain the valuable ecosystem services that they provide to humans, as well as to conserve their unique associated plant diversity and distinct plant communities.

Calcicolous floras are primarily threatened by anthropogenic disturbances, poor rangeland management strategies as well as natural disasters such as drought. Considering these threats, this review confirms that the calcicolous flora is poorly conserved in Africa. Many endemic species falls under a conservation status category, such as rare, endangered, vulnerable threatened and data deficient (Matthews *et al*., 1993; Van Wyk *et al.,* 2010; Claassens & Von Staden, 2011; Magee *et al.,* 2011; Van Jaarsveld, 2016; Frisby *et al.,* 2019; Van Staden *et al.,* 2020), although most of these species are not included in formally protected areas (Matthews *et al*., 1993; Willis *et al.,* 1996a; Van Staden *et al.,* 2020). Land use, especially agricultural and mining practices, is a major threat to carbonate soil-plant communities that result in habitat loss and/or fragmentation. However, there is still a lack of knowledge with respect to the restoration of calcareous landscapes. More studies are required to understand the physical and chemical properties of carbonate soil to assist rehabilitation programmes through the establishment of pre-adapted plant communities. The likelihood of reaching the original vegetation state is doubtful, but it is important to establish a transformed state that can still be viable and provide ecosystem functioning through human intervention and long-term monitoring (Hall *et al.,* 2003; Visser *et* *al.,* 2012). These mined landscapes can then be used for grazing, after rehabilitation and been abandoned, to promote the livelihoods of people. However, these landscapes should be subjected to proper management to prevent overgrazing that will contribute to further degradation (Tesfahunegn *et al.,* 2012; Akbari *et al.,* 2020).

Drivers of endemism were only discussed in studies from three South African biomes, i.e. Fynbos, Savanna and Grassland. Current complex global changes (Mirtl *et al.,* 2018; Silveira *et al.,* 2019) necessitate the understanding of responses of endemic calcicolous floras in Africa. In terms of disturbance related response patterns in carbonate plant communities, there are still knowledge gaps that need to be addressed, also outside of South Africa across various climates, landscapes and biomes. Furthermore, there may still be undescribed plant communities harbouring endemic calcicolous plant species that we are unaware of on the continent. There was also a lack of studies that focussed on mountains. This gap in the literature regarding carbonate plant communities on mountains was also already addressed by Van Staden *et al.* (2020). Mountainous landscapes serve as refuge areas for other plant species under climate change (Chakraborty, 2019; Perrigo *et al.,* 2019). Thus, it is important to understand how these carbonate mountains function with regards to drivers of their unique plant communities and their functional traits aiding with their establishment, despite the role of habitat heterogeneity. Especially considering that edaphic generalists may outcompete edaphic specialists (Cowling & Bond, 1991; Harrison *et al.,* 2009).

With regards to the discovery, identification and description of new calcicole plant species, it is considered impossible that South Africa could be the only region where such species were discovered. It is suggested that the Scopus search strings were not specific enough and consequently certain taxonomic studies were missed. However, if not, then there is an urgent need for more exploration studies of carbonate soils in Africa. However, funding for such studies remains limited (Margules & Pressey, 2000). More studies are required to investigate whether the carbonate flora is adequately conserved and properly managed in Africa. To achieve optimal conservation, it is important to go beyond the conservation of a specific plant species or a specific functional group, but to conserve the processes and environmental conditions that are drivers of their distribution patterns, species richness and diversity (Margules & Pressey, 2000; Branquinho *et al.,* 2019). Therefore, a holistic conservation approach is required. Botanists, conservation managers and policymakers should collaborate with landowners to ensure that these plant communities are properly understood, conserved and managed. In addition, ecological modelling studies such as those conducted by Tietjen and Jeltsch (2007), Tietjen *et al.* (2010) as well as Guo *et* *al.* (2018) can improve our understanding of carbonate plant communities under future climate- and land use change scenarios. Such studies should be conducted to promote our understanding of these unique landscapes in Africa under global change. Baseline studies are also encouraged to generate valuable data that can assist in long-term monitoring studies and ensure that calcicolous flora is properly conserved and managed in the future.

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Chapter 4

Floristics of GWC mountain ecosystems

4.1. Introduction

Mountain ecosystems are characterised by distinct floras (Burke, 2001; Harrison *et al.*, 2009) due to habitat heterogeneity (Dufour *et al.*, 2006; Noroozi *et al.*, 2018; Chakraborty, 2019). Mountains therefore function as edaphic islands (Burke, 2001; Rajakaruna, 2004) which exhibit specific microclimates and -habitats (Kruckeberg, 1969) to which plant species are adapted by developing special traits (Rajakaruna, 2004; 2018), resulting in speciation and species rich floras (Kruckeberg, 1969). Edaphic floras are therefore rich in endemic, edaphic specialists (Siebert *et al.*, 2001; Schmiedel & Jürgens, 2004). This phenomenon is typical for banded ironstone (Jacobi *et al.*, 2007; Markey & Dillon, 2010; Miller *et al.*, 2019), quartzite (Wild *et al.*, 1963; Schmiedel & Jürgens, 1999; Curtis *et al.*, 2013), and carbonate soils (Peñas *et al.*, 2005; Siebert & Siebert, 2005; Mota *et al.*, 2008). Many unique edaphic floras of mountain ecosystems have been found to be associated with centres of endemism (Van Wyk & Smith, 2001; Williamson & Balkwill, 2015; Noroozi *et al.*, 2018; Manish, 2019).

Mountain floras of GWC are characterised by banded ironstone, quartzite as well as dolomite (Frisby *et al.*, 2019), and are associated with heterogeneous undulating landscapes with diverse climate and unique vegetation types (Mucina & Rutherford, 2006). Despite the distinct vegetation of GWC and known endemic flora (24 endemic and two near-endemic plant species (Frisby *et al.*, 2019)), our understanding of plant diversity patterns in this region is limited. Botanical studies in GWC are limited (Ferreira, 1927; Wilman, 1946; Mostert, 1967; Frisby *et al.*, 2019; Van Munster *et al.*, 2019) which necessitates descriptive assessments of endemic edaphic flora across different mountain geologies of GWC to encourage conservation initiatives.

Globally, centres of endemism are inadequately conserved with some regions not being included within borders of protected areas (Millar *et al.*, 2017). For this reason, centres of endemism require enhanced conservation efforts since it is essential to understand the patterns and drivers of endemism (Slatyer *et al.*, 2007; Noroozi *et al.*, 2018; Taylor-Smith *et al.*, 2020). Accurate identification of the floristic borders of centres of endemism are imperative to aid with designs for effective and strategic biodiversity conservation as well as management (Slatyer *et al.*, 2007; Wang *et al.*, 2020). Accurate demarcation of centres of endemism at a finer scale is necessary to ensure comprehensive conservation and management of species that need to be protected (Cañadas *et al.*, 2014). Endemic species have the potential to serve as flagship species, and conservation action will become more effective by focusing on regions where endemics occur exclusively (Noroozi *et al.*, 2018;

Taylor-Smith *et al.*, 2020). This seems logical, especially given that funding for conservation is limited (Margules & Pressey, 2000; Myers *et al.*, 2000).

This study was conducted to inform conservation strategies by providing conservation authorities with detailed information to ensure proper conservation of GWC, through focusing on priority areas where endemic species occur at a finer scale. This chapter addresses two primary aims to develop a better understanding of the GWC and its flora. Firstly, the borders of GWC will be refined to establish which main mountain ranges fall within the centre by using a MaxEnt spatial model based on geology, climate and topography in combination with distribution data of GWC endemics. Refining the borders of GWC will (i) result in a smaller geographical region that will allow for focused botanical studies and (ii) ensure targeted conservation of endemic plant species. Secondly, flora associated with the main mountain ecosystems within these newly refined borders will be described. By doing so, knowledge regarding floristic characteristics of the ecosystems will depict the distinctness of the mountain floras. Mountain floras will be described based on (i) dominant plant families, (ii) common species, (iii) indicator plant species, (iv) threatened and endemic species, and (v) species composition.

4.2. Materials and methods

4.2.1. Data collection and -analysis

4.2.1.1. Refining the borders

MaxEnt software (Elith *et al.*, 2011; Phillips *et al.*, 2019) was used to develop an ecological niche model for GWC based on bioclimatic variables. MaxEnt uses probability of occurrence to calculate the conditions in which species occur (Phillips *et al.*, 2009). A total of 95 verified occurrence records for 24 endemic and two near-endemic species identified by Frisby *et al.* (2019) were used as presence records in the model. A total of 19 bioclimatic variables obtained from WorldClim version 2 (Fick & Hijmans, 2017) represented environmental conditions (Table B1; Appendix B). An 80/20 split was applied to the occurrence records, with 80% of records (n=76) used to train the model and 20% (n=19) used to test the accuracy of the model prediction. Default settings were used, except for the replication number that was set to 100. The Area Under Curve (AUC) score was used to determine the accuracy of the model (Bean *et al.*, 2012), where an AUC of 1 would indicate a perfect prediction, and 0.5 a random prediction (Phillips *et al.*, 2006). To convert the model output to a binary output usable for delineation purposes, a threshold was applied. The tenth percentile training presence logistic threshold (i.e. 0.277), which is suitable to use when studying centres of endemism (Escalante *et al.*, 2013) as well as studies relying on presence only data (Callen & Miller, 2015), was used. The binary output was finally intersected with the boundary delineated by Frisby *et al.* (2019) as well as the geology preferred by endemics in GWC (Table B2).

4.2.1.2. Floristic analysis

4.2.1.2.1. Historical data

Species lists for GWC were obtained from BODATSA (Ranwashe, 2019). This data was supplemented with specimen records obtained from herbaria with collections from the Griqualand West (GW) region, including A.P. Goossens Herbarium, McGregor Museum Herbarium, H.G.W.J. Schweickerdt Herbarium, Kimberley South African National Parks Herbarium, National Museum Herbarium, Geo Potts Herbarium and Pretoria National Herbarium. All distribution data were captured at species level at Quarter-Degree Grid (QDG) resolution. Further distribution data were supplemented using various sources from literature (Van Wyk & Smith, 2001; Mucina & Rutherford, 2006).

4.2.1.2.2. Data analysis

Plant lists were compiled for each mountain system based on historical distribution records that were obtained from herbarium records and combined with collected field data (Table B3). A total of 44 specimens collected in the field could not be identified below genus level and were excluded from plant lists. Combined historical and field collected data from the 1 m² subplots were used to identify the 20 largest plant families of each mountain ecosystem which were furthermore ranked based on the number of species. Spearman's rank correlation coefficient tests were performed in STATISTICA version 13.3 (TIBCO Software Inc., 2017) to assess similarity of plant family rankings between mountains. This correlation analysis followed a pairwise comparison between mountain combinations and Spearman's rho (ρ), ranging from -1 and 1 (Schober *et al.*, 2018), which was calculated for each pairwise rank. Jaccard similarity coefficients were performed on presence or absence of collected species data within 1 m² subplots using Paleontological Statistics (PAST) (Hammer *et al.*, 2001). This analysis was conducted to establish the degree of similarity between sampled mountain systems based on presence/absence of herbaceous species. Plant species sampled in subplots of the MW plots were ranked based on their overall abundances to reveal common plant species. A Non-metric Multidimensional Scaling (NMDS) scatter plot of data collected in the 1 m² subplots, using the Bray-Curtis dissimilarity distance measure, was constructed in PRIMER 6 (2012) to compare herbaceous species composition of mountain ecosystems. To assess whether clustering in the NMDS was significant, Non-parametric Permutational Multivariate Analysis of Variance (PERMANOVA) analysis was conducted in PRIMER 6 (2012). Furthermore, indicator species analysis was performed in RStudio using the IndVal function under the labdsv package (Roberts, 2016). Lastly, abundance of indicator plant species within subplots were correlated with environmental variables through conducting Canonical Correspondence Analysis (CCA) in CANOCO 5 (Šmilauer & Lepš, 2014). Significance levels for all analyses were set at the standard significance level of $p<0.05$.

4.3. Results and discussion

4.3.1. Refined borders of GWC

The niche model had a mean AUC of 0.979 for the 100 replicate runs, suggesting high model performance and a very good prediction (Phillips *et al.*, 2006). Bioclimatic variables that showed the highest model contribution included temperature seasonality (annual range in temperature), precipitation seasonality (annual range in precipitation) and precipitation of the driest quarter (Table 4.1). This model output was overlaid onto the geology harbouring GWC endemics and core area boundary proposed by Frisby *et al.* (2019). The refined area (Figure 4.1), where all three layers overlap, is strongly associated with mountainous habitats with their unique geology and cooler climate, implying that endemic plant species are absent from the warmer, sandy valleys. The mountains of GWC are identified as hotspots within a centre of endemism due to topographic heterogeneity, geology and climate (Cañadas *et al.*, 2014; Noroozi *et al.*, 2018; Perrigo *et al.*, 2019; Tordoni *et al.*, 2020). The newly refined boundaries of GWC covers 24 075 km², a surface area three times smaller than the core area of 75 172 km² as proposed by Frisby *et al.* (2019). These boundaries are identified as a conservation priority area and emphasises the need to focus on a finer scale when defining centres of plant endemism. Focusing conservation efforts on the endemic rich mountains will ensure that rare species are protected (Noroozi *et al.*, 2018). However, a systematic conservation approach (Margules & Pressey, 2000) and development of conservation plans are required (Tordoni *et al.*, 2020), since identified hotspots of endemism within GWC lie outside the borders of established protected areas, i.e. Mokala National Park, Witsand Nature Reserve and Tswalu Kalahari Reserve.

Table 4.1. Estimates of the relative contributions of bioclimatic variables (BIO) to the MaxEnt model for GWC endemics. Values shown are averages of 100 replicate runs.

Variable	Percent contribution (%)
BIO1 = Annual Mean Temperature	0.2
BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp)	1
BIO3 = Isothermality (BIO2/BIO7) (* 100)	0
BIO4 = Temperature Seasonality (standard deviation *100)	37.2
BIO5 = Max Temperature of Warmest Month	0.4
BIO6 = Min Temperature of Coldest Month	0.4
BIO7 = Temperature Annual Range (BIO5-BIO6)	2.4
BIO8 = Mean Temperature of Wettest Quarter	0.5
BIO9 = Mean Temperature of Driest Quarter	0.2
BIO10 = Mean Temperature of Warmest Quarter	0
BIO11 = Mean Temperature of Coldest Quarter	0.1
BIO12 = Annual Precipitation	5.5
BIO13 = Precipitation of Wettest Month	0.1
BIO14 = Precipitation of Driest Month	1.6
BIO15 = Precipitation Seasonality (Coefficient of Variation)	27.8
BIO16 = Precipitation of Wettest Quarter	0.1
BIO17 = Precipitation of Driest Quarter	21.4
BIO18 = Precipitation of Warmest Quarter	1.3
BIO19 = Precipitation of Coldest Quarter	0

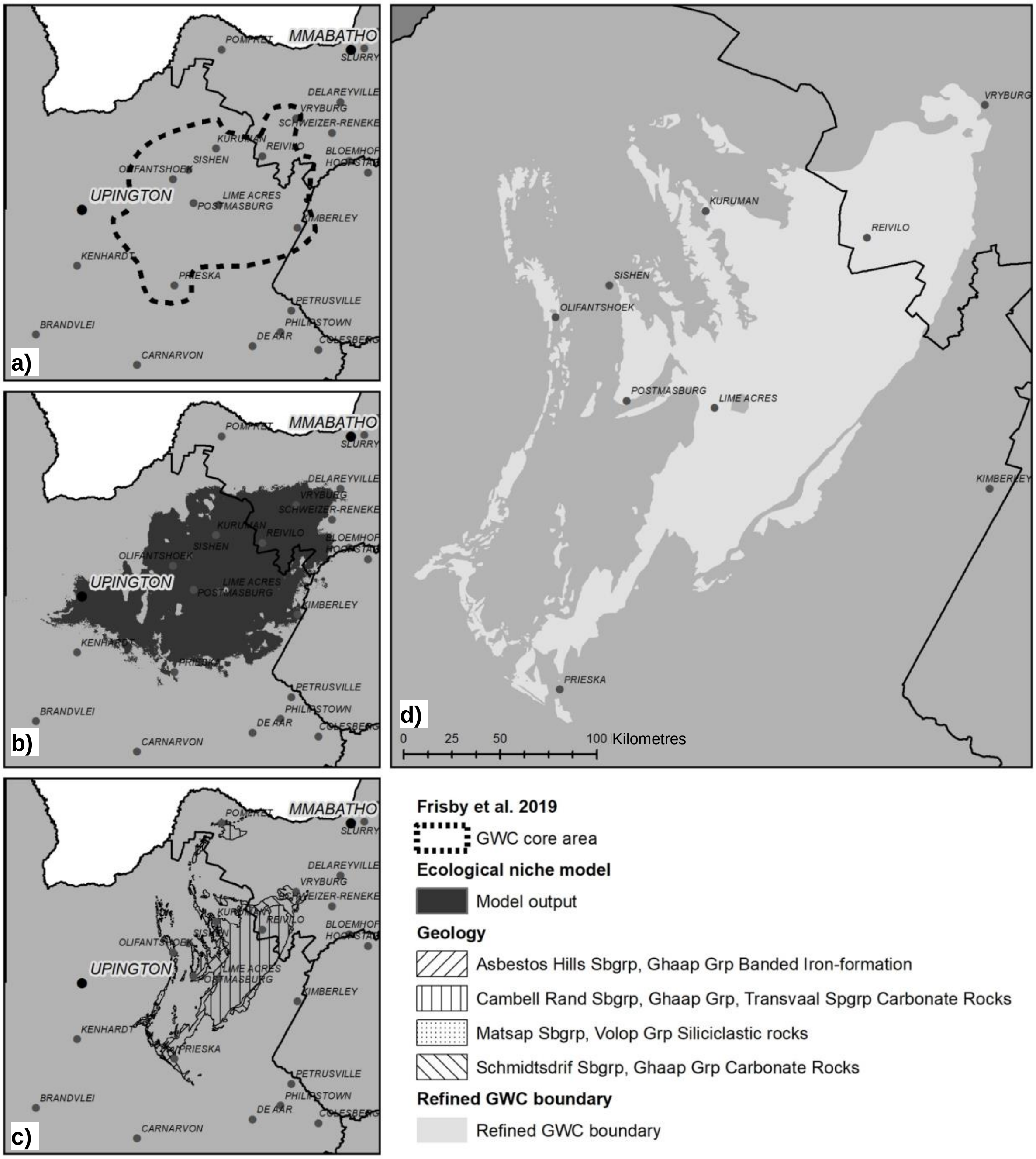

Figure 4.1. Refined GWC borders as predicted by overlays of the ecological niche model for endemic plant species within the a) core area defined by Frisby *et al.* (2019), and the rock types known to harbour GWC endemics. The b) ecological niche model output was overlain with c) the geology to provide the d) final output of the ecological niche model. Note that the lighter grey in d) represents the newly refined bordes of GWC.

4.3.2. Soil characteristics

Total calcium (Ca) content exceeded 11 000 mg/kg on the Ghaap Plateau, whilst magnesium (Mg) reached levels above 5 000 mg/kg (Table 4.2) for samples collected in the field. The Ca:Mg ratio was therefore above 2 and the soil pH>7. These soil chemical properties of dolomite and limestone soil are supported by Lee (1999). Total iron (Fe) levels were high (>50 000 mg/kg) on the ironstone hills (Table 4.2) due to presence of hematite (Fe_2O_3) and magnetite (Fe_3O_4) (Trendall, 2013). Ca:Mg ratios were high due to lower concentrations of Mg (<3000 mg/kg) and higher Ca content (>3000 mg/kg). Furthermore, the two banded ironstone habitats were characterised by more acidic soils (pH<7) (Thompson & Sheehy, 2011). This suggests that banded ironstone differs from acidic serpentine soils that are usually associated with higher concentrations of Mg than Ca (Robinson *et al.*, 1996; Alexander, 2011). Aluminium (Al) levels exceeded 30 000 mg/kg on the Langberg and Asbestos Hills (Table 4.2). Despite Al being one of the most abundant metals in soils, the availability thereof to plants is dependent on low soil pH (Gupta *et al.*, 2013; Bojórquez-Quintal *et al.*, 2017). Alumium is generally bound in the clay mineral structure, but if soil acidity increases and the pH decreases below 4.5, Al can become available to plants and inhibit plant growth (Abedi *et al.*, 2013; Bojórquez-Quintal *et al.*, 2017). However, Al may be beneficial to certain taxa or contribute to the development of tolerance mechanisms in plants (Bojórquez-Quintal *et al.*, 2017). In addition, Al levels act as an environmental filter (Abedi *et al.*, 2013) that contribute to compositional and structural changes in plant communities (Mota *et al.*, 2018). Acidic and sandy soils, especially those associated with quartzite, are known to be rich in Al, low in clay content, potassium (K), sodium (Na), Mg and Ca, and, hence, are considered nutrient-poor (Negreiros *et al.*, 2014; Do Carmo & Jacobi, 2016). Electrical conductivity (EC), an indicator of soil fertility (Fourie, 2019), was below 23 mS/m for the dry Langberg and Asbestos Hills indicating lower soil fertility (Table 4.2). In contrast, EC values were higher (>30 Ms/m) for the Kuruman Hills and Ghaap Plateau. A soil fertility gradient, together with a rainfall gradient was therefore observed for GWC as indicated by the dendrogram of Jaccard similarity based on sampled species (Figure 4.2).

Table 4.2. Mean concentrations with standard deviation of four elements and physical properties of soils associated with each mountain (n=8). LB - Langberg; AH - Asbestos Hills; KH - Kuruman Hills; GP - Ghaap Plateau; EC - Electrical conductivity; CEC - Cation Exchange Capacity.

	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)	Al (mg/kg)	Ca:Mg	pH	EC (Ms/m)	CEC cmol(+)/kg
LB	1347±921	2643±664	13741±1279	33868±3568	0.5±0.6	4.9±0.4	19.3±11.2	14.9±1.3
AH	4040±1237	3320±651	52437±10021	36318±4703	1.2±0.3	6.0±0.3	22.4±11.9	19.1±2.2
KH	3126±2573	2946±438	61660±19585	27055±5043	1.1±0.8	5.5±0.3	31.8±20.2	20.6±2.7
GP	11844±9241	5296±2790	18876+4721	30142±6981	2.2±3.2	7.6±0.6	32.6±14.2	20.2±3.1

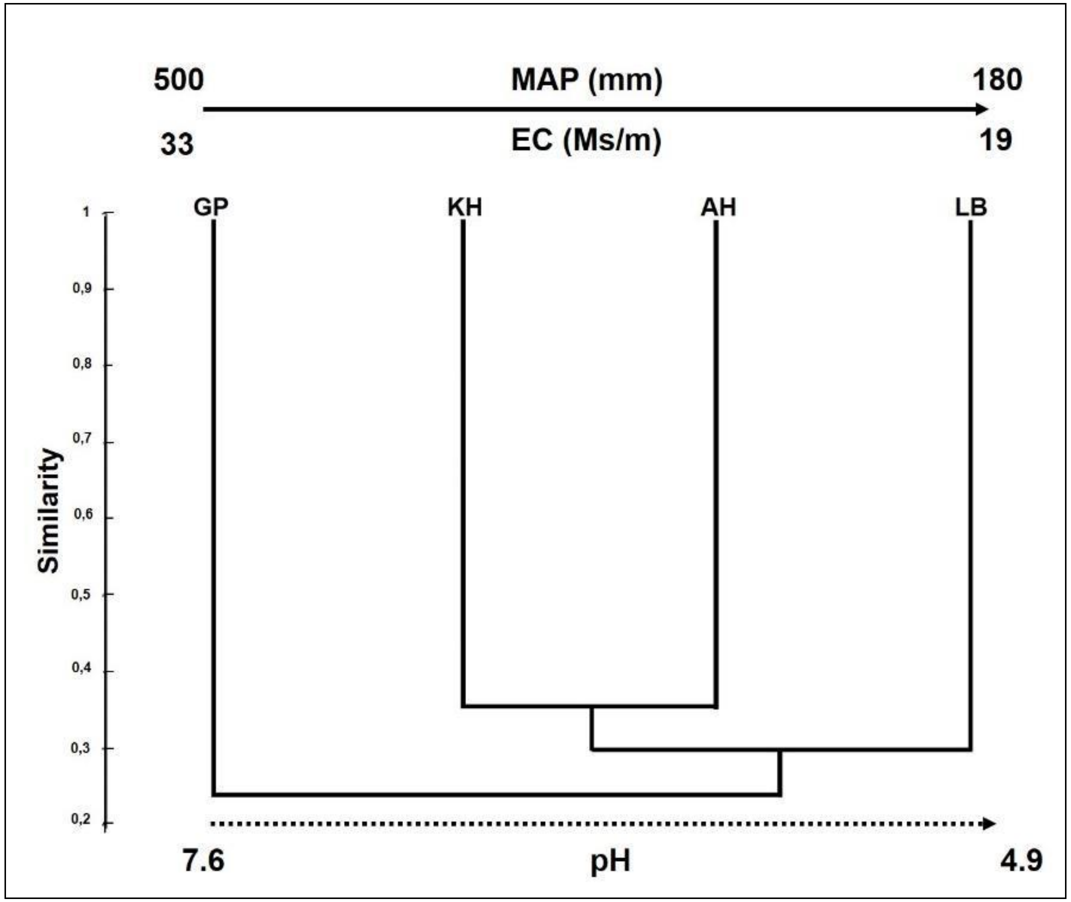

Figure 4.2. Dendrogram of Jaccard similarity indicating the relatedness of each mountain across the pH-, nutrient- and rainfall gradient. Clusters were based on presence and absence of sampled plant species. *EC,* Electrical Conductivity; *MAP,* Mean Annual Precipitation; *AH*, Asbestos Hills; *GP,* Ghaap Plateau; *KH,* Kuruman Hills; *LB,* Langberg.

4.3.3. Flora of GWC mountain ecosystems

4.3.3.1. Sampling effort

A plant list of historical data records was compiled for each mountain system within GWC. As would be expected, historical data indicated higher taxa numbers than field data (based on eight MW plots per system; Table 4.3). Restricted sampling effort resulted in certain taxa not being found (Spyreas, 2016). This is ascribed to the season of sampling after the dought which may resulted in unfavourable conditions for some plants to germinate and occur. However, each mountain flora was associated with unique plant species. These species were restricted to specific habitats and can be considered habitat specialists within GWC (Anderson & Ferree, 2010; Williamson & Balkwill, 2015). Comparisons between field data and historical data revealed that unique species of the Asbestos Hills were more restricted in distribution and difficult to locate, despite a comparable number of species recorded overall. The opposite was observed for the Ghaap Plateau with unique species seemingly widespread and easily recorded. The latest discovery of a new endemic plant species *Deverrara paletsa* Magee & Zietsman, restricted to the Ghaap Plateau (Van Munster *et al.*, 2019), reinforces the uniqueness of the Ghaap Plateau flora, and the possibility of more species that are yet to be discovered. Floristic sampling on the Asbestos Hills were hampered due to poor rangeland condition (overgrazing), which possibly favoured common species tolerant to disturbance (Table 4.3). Conversely, sampling success for edaphic specialists was greater on the banded ironstone of the Kuruman Hills where the rangelands were managed responsibly.

Table 4.3. Comparison of field collected (Field) data with historical herbarium records (Hist.) regarding taxa numbers represented in the flora of each mountain of the Griqualand West Centre of Plant Endemism. Unique species are those plant species that are not shared between mountain ranges.

	Langberg		**Asbestos hills**		**Kuruman hills**		**Ghaap plateau**	
	Hist.	**Field**	**Hist.**	**Field**	**Hist.**	**Field**	**Hist.**	**Field**
Families	65	39	75	40	83	38	73	45
Genera	192	89	252	93	287	89	223	94
Species	325	126	472	114	551	114	410	134
Species: Genus	1.69	1.42	1.87	1.23	1.92	1.28	1.84	1.43
Species/Family	5	3.23	6.29	2.85	6.64	3	5.62	2.98
N Unique Species	102	35	112	14	152	30	103	43
% Unique Species	31.38	27.78	23.73	12.28	27.59	26.32	25.12	32.09

4.3.3.2. Dominant plant families

Combined historical and field data revealed that the four most species rich families across the four mountains were the Poaceae, Asteraceae, Fabaceae and Malvaceae in descending order (Table B4). These plant families are known to be of the largest and most widespread families, not only in southern Africa, but on a global scale. Members of these four families are known to occupy a variety of habitats and persist under various environmental conditions (Koekemoer *et al.*, 2014). More specifically, the Asteraceae, Fabaceae and Poaceae have been found to dominate plant communities on limestone and dolomite (Ludwig, 1999; Siebert & Siebert, 2005; Covelo *et al.*, 2017), banded ironstone (Jacobi & Do Carmo, 2008; Meissner & Wright, 2010; Markey & Dillon, 2011; Gibson *et al.*, 2012), as well as quartzite (Curtis *et al.*, 2013; Silva *et al.*, 2019). Since GWC is situated in the Savanna Biome, the representation by members of the Malvaceae can be ascribed to their preferred association and diversification in savanna landscapes (Koekemoer *et al.*, 2014; Soares *et al.*, 2015). The joint fifth most species-rich plant families in GWC, i.e. Cyperaceae and Scrophulariaceae, are respectively associated with either lower rainfall (Langberg and Asbestos Hills) or higher rainfall mountains (Kuruman Hills and Ghaap Plateau). The Scrophulariaceae is widely distributed globally and is common in drier, open savanna-grasslands, as well as mountainous areas (Fischer, 2004; Koekemoer *et al.*, 2014). Furthermore, some taxa are habitat specialists since they prefer rocky and dry granitic outcrops and/or ferricretes and, hence are often drought tolerant (Clements *et al.*, 2002; Fischer, 2004; Koekemoer *et al.*, 2014). Many Scrophulariaceae have also been found to be metallophytes and therefore able to tolerate heavy metals in soils especially copper (Cu) and cobalt (Co) in south-central Africa (Faucon *et al.*, 2009). In contrast, plants belonging to the Cyperaceae is mostly found in moister habitats in savanna-grassland regions (Koekemoer *et al.*, 2014). Since the Ghaap Plateau is underlain by dolomite and limestone, soils tend to be rich in lime (CaO), alkaline, high in clay content and poorly drained (Mustart *et al.*, 1994). This provides a suitable habitat for taxa in the Cyperaceae. Ludwig *et al.* (2004) as well as Swadek and Burgess (2012) conducted studies on North American limestones and found that the Cyperaceae was respectively the fourth and fifth most diverse plant family. Both studies recorded 17 taxa within the Cyperaceae, a number that corresponds to the number of taxa present on the Ghaap Plateau (Table B4). The Kuruman Hills and Ghaap Plateau are rocky habitats. Consequently, the presence of rock crevices, drainage lines and shallow depressions where rainwater can collect, serve as microhabitats for the Cyperaceae to establish successfully (Porembski & Barthlott, 2000; Jacobi & Do Carmo, 2008).

4.3.3.3. Diversity on family- and species level

The most diverse families of the Asbestos Hills correlated significantly with the diverse families of the Kuruman Hills (Table 4.4; ρ=0.88; $p<0.05$). Jaccard similarity, based on sampled plant species (Table 4.5), also revealed the highest similarity between these two mountains (38.2%). Similarities between the Kuruman- and Asbestos Hills could be ascribed to both these mountains being characterised by banded ironstone (Van Wyk & Smith, 2001) and the same vegetation type, namely the Kuruman Mountain Bushveld (Mucina & Rutherford, 2006). Dendrograms of Spearman correlation (Figure B1; Appendix B) and Jaccard similarity (Figure 4.2) indicated floristic differences between the two banded ironstone habitats. This result is most likely attributed to rainfall, since the Kuruman Hills receives higher rainfall than the southern lying Asbestos Hills (Figure 4.2).

The Langberg family diversity was moderately correlated (Table 4.4) with the Asbestos Hills (ρ=0.77; $p<0.05$), and the least with the Ghaap Plateau (ρ=0.56; $p<0.05$). This is likely attributed to differences in pH values (low *vs.* high) since the Langberg has acidic soils and the Ghaap Plateau alkaline (Table 4.2). Jaccard similarity indicated that the Asbestos Hills and Langberg share 34.4% of their species (Table 4.5), despite differences in geology. Both these landscapes are characterised by lower rainfall, suggesting a shared drought tolerant and/or resistant flora (Kimball *et al.*, 2017).

The Kuruman Hills and Ghaap Plateau mountain systems revealed similar family diversity (Table 4.4; ρ=0.72; $p<0.05$). This finding could be attributed to higher rainfall associated with these two systems within GW. One of the most species-rich plant families shared in high abundance, Cyperaceae, is adapted to these moister systems (Table B4). However, on species level, the Ghaap Plateau and Kuruman Hills had the lowest Jaccard similarity (Table 4.5; 21.7%) which indicates species specific colonization on contrasting geological substrates. Spearman correlation (Table 4.4) revealed that the Ghaap Plateau and Asbestos Hills were also similar in their most diverse plant families (ρ=0.70; $p<0.05$), but even more so at species level (Table 4.5, 34.6%). This was unexpected since these systems differ in geology and rainfall regimes. A possible explanation for this similarity could be that the Ghaap Plateau and Asbestos Hills are in close proximity to one another (less than 50 km). Therefore, plant species may easily spread and colonise between the two systems especially when species have wide niche breadths and are generalist plant species (Nekola & White, 1999; Sklenář *et al.*, 2014; Zhang *et al.*, 2016).

Table 4.4. Spearman rank correlation (ρ) test of the highest ranked and most diverse plant families. All correlations were significant ($p<0.05$). ** highest correlation; * lowest correlation.

	Asbestos Hills	Langberg	Kuruman Hills
Langberg	0.77		
Kuruman Hills	0.88**	0.66	
Ghaap Plateau	0.70	0.56*	0.72

Table 4.5. Jaccard similarity coefficient measuring the degree of similarity of plant species between sampled mountain systems. Values are expressed as percentages. ** highest similarity; * lowest similarity.

	Langberg	Kuruman Hills	Asbestos Hills
Kuruman Hills	31.2		
Asbestos Hills	34.4	38.2**	
Ghaap Plateau	24.3	21.7*	34.6

4.3.3.4. Species composition

Non-metric Multi-Dimensional Scaling analysis of floristic data revealed clustering according to mountain ecosystems (Figure 4.3). Permutational Multivariate Analysis of Variance indicated that the clustering was significant (Table B5; Pseudo-F=9.138; $p<0.001$). Although the Langberg plots were dispersed without a clear cluster, herbaceous assemblages differed significantly between mountains (Table B5). These findings are in accordance with studies which have found that plant communities underlain by banded ironstone (Jacobi *et al.*, 2007; Gibson *et al.*, 2012), dolomite and limestone (Siebert & Siebert, 2005; Clements *et al.*, 2006; Zietsman & Bredenkamp, 2007; Mota *et al.*, 2008), and quartzites (Wild *et al.*, 1963; Schmiedel & Jürgens, 2004) are distinct. In semi-arid savannas, soil nutrients and rainfall are the most important factors determining vegetation dynamics, especially for the herbaceous layer (Buitenwerf *et al.*, 2011; Van Coller *et al.*, 2018; Siebert & Dreber, 2019). Despite similar geologies, the separate clustering displayed by the Kuruman Hills and Asbestos Hills emphasises the importance of rainfall in driving compositional differences, since both mountain ecosystems have the same parent material, but the latter is a drier system.

Each mountain system was characterised by certain commonly occurring species (Table B6) as indicated by the top 20 highest ranked taxa based on abundance values *per se*. Despite certain of these taxa being shared between different mountain systems, their relative frequency differed per mountain ecosystem. For example, *Eragrostis nindensis* Ficalho & Hiern was shared between the Langberg, Asbestos Hills and Kuruman Hills, but this grass species revealed the highest abundance on the Langberg (Table B6). Indicator plant species (Table 4.6) are characterised by high relative frequency of occurrence in a specific mountain habitat (specificity) and thus were primarily found in that habitat in high numbers (Dufrêne & Legendre, 1997; Negrão *et al.*, 2017). In contrast to common species, indicator plant species provide valuable ecological information on various species groups of different plant communities (Dufrêne & Legendre, 1997), especially with respect to their habitat preferences and adaptations to persist in certain environmental conditions (Siebert *et al.*, 2010; Leitman *et al.*, 2015).

The effects of rainfall and soil properties on indicator plant species were confirmed by CCA analysis (Figure 4.4). Explanatory variables accounted for 48% of the total variation. The first canonical axis explained 70% of total variation and the second axis 41% of the variance. The Ghaap Plateau was positively correlated with Ca:Mg ratio, soil pH and negatively correlated with Fe content (Figure 4.4), with a clear separation between the plots of the Ghaap Plateau and banded ironstone hills. Indicator plant species of the Ghaap Plateau preferred alkaline soil with high Ca:Mg ratios. Conversely, those of the Kuruman Hills are adapted to more acidic soils with high Fe content. A study conducted by Li *et al.* (2015) in subtropical China, revealed separation of indicator plant species across a pH gradient in combination with other environmental variables. Therefore, soil chemical characteristics can be considered as one of the most significant factors driving floristic composition across mountain ecosystems (Boneschans *et al.*, 2015; Burke, 2019) and explain the preferences of indicator plant species associated with each mountain (Soares *et al.*, 2015).

Indicator plant species of the Langberg were positively correlated with higher sand content, whereas those of the Ghaap Plateau as well as Kuruman Hills correlated positively with mean annual precipitation (MAP) and CEC (Figure 4.4). Indicator plant species of the Langberg, with its low MAP, high sand content and low CEC values, were therefore separated clearly from other wetter and more nutrient-rich mountain systems. Plots of the Asbestos Hills were clustered intermediately between those of the Ghaap Plateau and Kuruman Hills. This suggests niche partitioning (MacArthur & Levins, 1967; Naaf & Wulf, 2012) and a filtering effect (Diaz *et al.*, 1998; Franklin *et al.*, 2013) for herbaceous indicator plant species across the nutrient- and rainfall gradient. The two drier and nutrient-poor systems (Langberg and Asbestos Hills) were predominantly characterised by perennial species of only two life form types (lignified forbs and grasses; Table 4.6). However, regions of higher rainfall and nutrients (Kuruman Hills and Ghaap Plateau) consisted of both perennial and annual indicator plant species comprising four life form types (lignified forbs, herbaceous forbs, grasses and sedges; Table 4.6). Despite this study not following a trait-based approach, the larger variety of life forms and life history characteristics of indicator species associated with the Kuruman Hills and Ghaap Plateau, suggests that niches increase along a soil fertility- and precipitation gradient (Schellenberger Costa *et al.*, 2017). The greater variety of traits for indicator species of wetter and more nutrient-rich habitats (i.e. different life forms and life histories) can be ascribed to niche partitioning (Naaf & Wulf, 2012). Conversely, nutrient-poor and drier mountains have indicator plant species with fewer traits (Wright *et al.*, 2002; Shovon *et al.*, 2020). Therefore, reduction of trait richness of indicator plant species in the drier Langberg and Asbestos Hills are ascribed to environmental filtering. Thus, these dominant traits provide species with competitive vigour and stress tolerance to persist in the associated extreme environmental conditions (Negreiros *et al.*, 2014). This suggests habitat specialisation of indicator plant species (Li *et al.*, 2015). However, further studies are necessary to study these patterns.

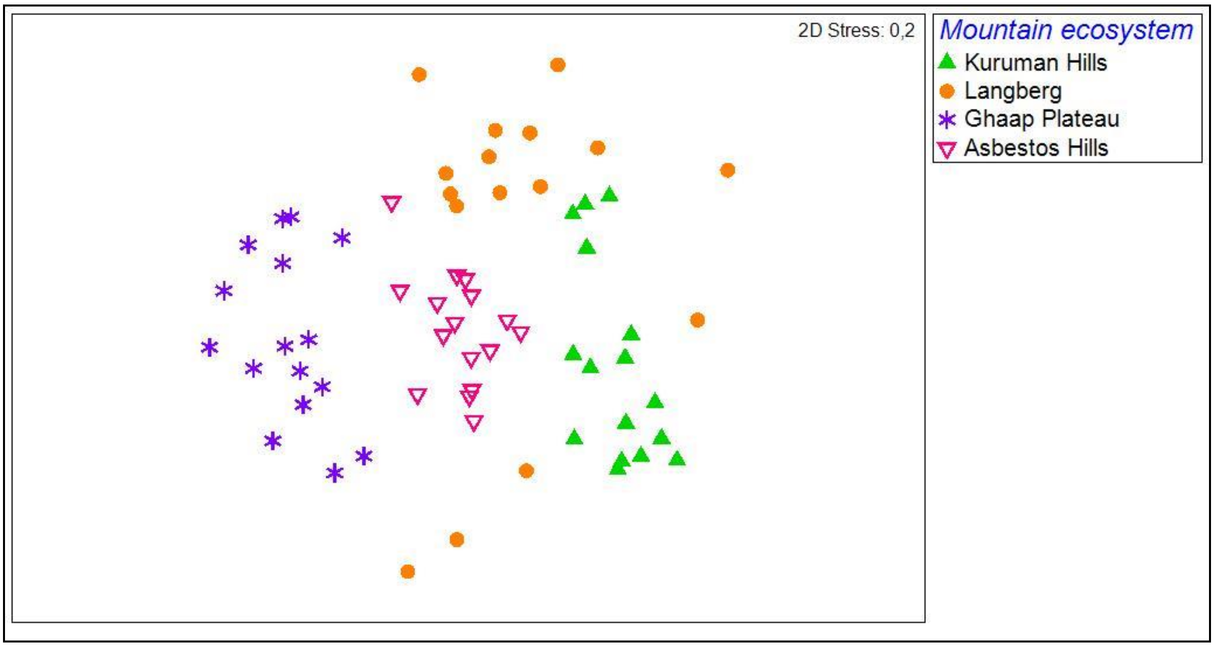

Figure 4.3. Non-metric Multi-Dimensional Scaling (NMDS) ordination of sampled subplots representing herbaceous species assemblages of the four mountains.

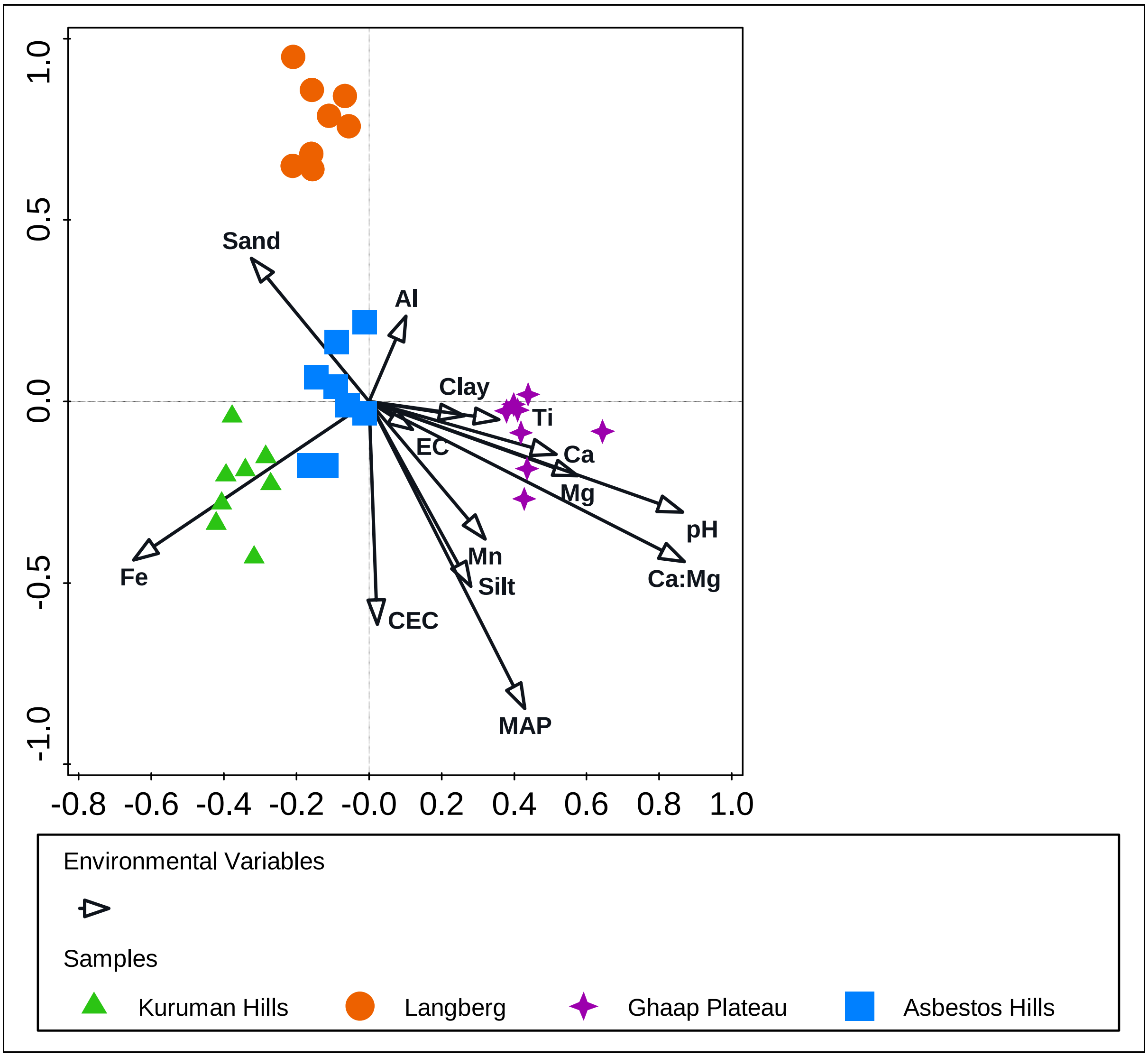

Figure 4.4. Canonical Correspondence Analysis (CCA) of indicator plant species per plot and associated environmental variables within each mountain. Species included in the analysis are listed in Table 4.7.

Table 4.6. List of indicator plant species associated with each mountain as determined by indicator species analysis (Indval function of the labdsv package in RStudio). Frequency values, life histories and life forms of indicator plant species for each mountain are presented.

Mountain	Family	Species	Indval	p-value	Frequency	Life history	Life form
Langberg							
	Poaceae	*Brachiaria nigropedata* (Ficalho & Hiern) Stapf	0.48	0.001	13	Perennial	Grass
	Convolvulaceae	*Evolvulus alsinoides* (L.) L.	0.44	0.001	7	Perennial	Lignified forb
	Poaceae	*Eragrostis nindensis* Ficalho & Hiern	0.32	0.019	14	Perennial	Grass
	Poaceae	*Eragrostis chloromelas* Steud.	0.2	0.037	6	Perennial	Grass
Asbestos Hills							
	Acanthaceae	*Glossochilus burchellii* Nees	0.69	0.001	11	Perennial	Lignified forb
	Poaceae	*Tragus koelerioides* Asch.	0.59	0.001	21	Perennial	Grass
	Poaceae	*Aristida diffusa* Trin.	0.57	0.001	32	Perennial	Grass
	Poaceae	*Cymbopogon pospischilii* (K.Schum.) C.E.Hubb.	0.54	0.001	28	Perennial	Grass
	Verbenaceae	*Chascanum pinnatifidum* (L.f.) E.Mey.	0.35	0.003	15	Perennial	Lignified forb
	Malvaceae	*Sida chrysantha* Ulbr.	0.32	0.007	11	Perennial	Lignified forb
	Malvaceae	*Corchorus aspelinifolius* Burch.	0.25	0.034	12	Perennial	Herbaceous forb
	Lamiaceaae	*Leucas capensis* (Benth.) Engl.	0.21	0.028	5	Perennial	Lignified forb
Kuruman Hills							
	Poaceae	*Diheteropogon amplectens* (Nees) Clayton	0.81	0.001	13	Perennial	Grass

	Cyperaceae	*Bulbostylis hispidula* (Vahl) R.W.Haines	0.67	0.001	15	Annual	Sedge
	Poaceae	*Cymbopogon caesius* (Hook. & Arn.) Stapf	0.5	0.002	8	Perennial	Grass
	Euphorbiaceae	*Phyllanthus parvulus* Sond.	0.46	0.002	35	Perennial	Lignified forb
	Poaceae	*Brachiaria serrata* (Thunb.) Stapf	0.45	0.001	14	Perennial	Grass
	Poaceae	*Elionurus muticus* (Spreng.) Kunth	0.44	0.001	10	Perennial	Grass
	Asteraceae	*Pegolettia retrofracta* (Thunb.) Kies	0.32	0.003	7	Perennial	Lignified forb
	Verbenaceae	*Chascanum adenostachyum* (Schauer) Moldenke	0.31	0.005	5	Perennial	Lignified forb
	Poaceae	*Anthephora pubescens* Nees	0.31	0.008	17	Perennial	Grass
	Ebenaceae	*Euclea undulata* Thunb.	0.19	0.046	3	Perennial	Lignified forb
	Polygalaceae	*Polygala hottentotta* C.Presl	0.19	0.048	3	Perennial	Lignified forb
Ghaap Plateau							
	Cyperaceae	*Bulbostylis humilis* (Kunth) C.B.Clarke	0.3	0.001	25	Annual	Sedge
	Poaceae	*Enneapogon desvauxii* P.Beauv.	0.69	0.001	11	Perennial	Grass
	Poaceae	*Fingerhuthia africana* Lehm.	0.5	0.001	18	Perennial	Grass
	Oxalidaceae	*Oxalis depressa* Eckl. & Zeyh.	0.44	0.001	7	Perennial	Herbaceous forb
	Poaceae	*Tragus racemosus* (L.) All.	0.44	0.001	7	Annual	Grass
	Euphorbiaceae	*Euphorbia inaequilatera* Sond.	0.42	0.002	14	Perennial	Herbaceous forb
	Molluginaceae	*Limeum fenestratum* (Fenzl) Heimerl	0.38	0.002	6	Annual	Lignified forb
	Molluginaceae	*Limeum argute-carinatum* Wawra ex Wawra & Peyr.	0.34	0.003	7	Annual	Lignified forb

Poaceae	*Eragrostis lehmanniana* Nees	0.33	0.019	23	Perennial	Grass
Cyperaceae	*Cyperus bellus* Kunth	0.31	0.002	5	Perennial	Herbaceous forb
Poaceae	*Oropetium capense* Stapf	0.25	0.008	4	Perennial	Grass
Poaceae	*Eragrostis trichophora* Coss. & Durieu	0.24	0.019	8	Perennial	Grass
Poaceae	*Enneapogon scoparius* Stapf	0.19	0.045	3	Perennial	Grass

Table 4.7. List of endemic plant species (Frisby *et al.,* 2019), number of individuals recorded during plot surveys, mountains where an endemic plant species is known to occur, number herbarium QDG records and Red List category. AH - Asbestos Hills; GP - Ghaap Plateau; KH - Kuruman Hills; LB - Langberg.

Family	**Taxon**	**Individuals recorded**	**Mountains**	**QDG records**	**Red list category**
Acanthaceae					
	Barleria media C.B.Clarke	-	GP, KH	4	Vulnerable
	Blepharis marginata (Nees)	51	AH, GP, KH, LB	12	Least concern
	Glossochilus burchellii Nees	56	AH, GP, KH	10	Least concern
	Justicia puberula Immelman	4	GP, KH, LB	30	Least concern
Aizoaceae					
	Antimima lawsonii (L.Bolus) H.E.K.Hartmann	-	AH, GP, KH	5	Rare
	Hereroa wilmaniae L.Bolus	3	AH, GP, KH, LB	15	Data deficient
	Lithops aucampiae L.Bolus subsp. *euniceae* (de	-	AH	2	Vulnerable

	Boer) D.T.Cole				
	Lithops bromfieldii L.Bolus	-	LB	4	Least concern
	Lithops lesliei (N.E.Br.) N.E.Br. subsp. *burchellii* D.T.Cole	-	AH, GP	3	Near threatened
	Prepodesma orpenii (N.E.Br.) N.E.Br.	-	AH, GP, KH, LB	23	Least concern
Amaryllidaceae					
	Nerine hesseoides L.Bolus	-	GP	4	Least concern
Anacardiaceae					
	Searsia tridactyla (Burch.) Moffett	30	AH, GP, KH, LB	63	Least concern
Apiaceae					
	Deverra rapaletsa Magee & Zietsman	-	GP	2	Not yet assessed
Asteraceae					
	Amphiglossa tecta (Brusse) Koekemoer	1	AH, GP, LB	3	Critically rare
	Cineraria exilis DC.	-	GP, KH	1	Data deficient
	Dicoma kurumanii S.Ortiz & Netnou	4	GP, KH	1	Rare
	Eriocephalus ericoides (L.f.) Druce subsp. *griquensis* M.A.N.Müll.	17	AH, GP, KH, LB	26	Least concern
	Gnaphalium englerianum (O.Hoffm.) Hilliard & B.L.Burtt	-	GP, KH	2	Least concern
	Pentzia stellata (P.P.J.Herman) Magee	-	GP	11	Near threatened

	Tarchonanthus obovatus DC.	40	AH, GP, KH, LB	53	Least concern
Celastraceae					
	Maytenus ilicina (Burch.) Loes.	-	AH, GP, KH, LB	11	Least concern
	Putterlickia saxatilis (Burch.) M.Jordaan	3	AH, GP, KH, LB	28	Least concern
Fabaceae					
	Calobota cuspidosa (Burch.) Boatwr. & B.-E.van Wyk	23	AH, GP, KH, LB	45	Least concern
Poaceae					
	Brachiaria dura Stapf var. *pilosa* J.G.Anderson	-	LB	4	Data deficient

Note: QDG's were obtained from BODATSA (Ranwashe, 2019). Categories for threat were based on the National Red List (South African National Biodiversity Institiute, 2019).

4.3.3.5. Threatened and endemic species

The Ghaap Plateau hosted the highest number of GWC endemic plant species, followed by the ironstone hills (Table B7). These findings are in accordance with several studies which revealed that limestone and dolomite (Cowling & Holmes, 1992; Ludwig, 1999; Zietsman & Bredenkamp, 2007; Mota *et al.*, 2008), as well as banded ironstone (Gibson *et al.*, 2012; Robinson *et al.*, 2019), harbour high numbers of endemics. Six GWC endemic plant species (Table B7) can be considered narrow endemics since they are restricted to a single mountain range (Mason, 1946a; 1946b; Wild *et al.*, 1963; Cowling *et al.*, 1994). Three of these restricted endemics were associated with the Ghaap Plateau that included a recently added species, *Nerine hesseoides* L.Bolus (Table B8), after an outlying locality was confirmed to be a different species (B. Van Wyk personal communication, October 28, 2019) . Two other endemics were associated with seasonal pans of the Ghaap Plateau. The ironstone hills harbour one narrow endemic, while the Langberg with its deeper, sandy soils harbours two species. Therefore, these plant species have an edaphic preference (Mason, 1946b; Rajakaruna, 2004; 2018) and can be considered as rare (Stebbins, 1942; Gaston, 1997). Edaphic restricted endemic plant species may be prone to extinction (Harrison *et al.*, 2009) due to low genetic variability (Stebbins, 1942). Despite low genetic diversity, narrow resource use abilities and narrowed niche range (Gaston & Kunin, 1997), these plants are highly specialised and thus edaphic specialists (Mason, 1946b; Anderson & Ferree, 2010).

Eleven of the 24 GWC endemics were recorded during the field surveys. More commonly sampled endemics included *Blepharis marginata* (Nees) C.B.Clarke, *Calobota cuspidosa* (Burch.) Boatwr. & B.-E.vanWyk, *Glossochilus burchellii* Nees*, Searsia tridactyla* (Burch.) Moffett and *Tarchonanthus obovatus* DC. (Table 4.7) (Frisby *et al.,* 2019). These endemic plant species are also associated with a wider distribution range within GWC and can be considered regional endemics (Cowling & Holmes, 1992; Cowling *et al.*, 1994) with wider ecological niches compared to narrow endemics (Gaston & Kunin, 1997). The random sampling approach of this study did not allow the targeting of rare species with patchy distributions and habitat specificity (Stohlgren *et al.*, 2005). It is suggested that future studies determine optimal sampling effort, sampling time and plot size to ensure more comprehensive data capturing of endemic species in GWC, especially at landscape scale (Zhang *et al.*, 2014). By doing so, conservation efforts of endemic plant species can be promoted since all 24 endemic plant species encountered in this study are of conservation concern, irrespective that none of the endemics are currently regarded as endangered (Bamigboye, 2019; South African National Biodiversity Institute, 2019).

4.4. Summary

This study refined the borders of GWC which enabled the floristic description of the four, endemic-rich mountains within these new borders. These borders were based on an ecological model, which was constructed using presence and absence records of GWC endemics and environmental parameters. Distribution patterns of endemics were restricted to certain mountains and rock types which allowed for refinement of the model.

A clear soil fertility (based on EC values) and rainfall gradient was identified for the GWC and, subsequently, each mountain flora was associated with different family- and species diversity, and composition. All four mountains were dominated by the Asteraceae, Fabaceae Malvaceae and Poaceae. Furthermore, the Scrophulariaceae dominated on the mountains of lower rainfall that are nutrient-poor (Langberg and Asbestos Hills), whereas the Cyperaceae were prominent on the two mountain systems of higher rainfall and which are more nutrient-rich (Kuruman Hills and Ghaap Plateau). Indicator plant species explained the compositional differences since each mountain ecosystem was characterised by habitat specialists adapted to prevailing edaphic and climatic conditions. Primary drivers of the distribution of indicator species were soil pH, Ca:Mg ratios and rainfall. These drivers contributed to niche partitioning and environmental filtering (dry and nutrient-poor *vs.* wet and nutrient-rich).

From a conservation perspective, future botanical studies, and conservation and management strategies, should focus within the refined borders of GWC. The mountains are hotspots of endemics in GWC and should be considered as conservation priority areas. The Ghaap Plateau and the ironstone hills are of particular conservation importance as these systems harbour most of the GWC endemics. Special attention should be given to narrow endemic plant species with restricted distributions within borders of GWC as well as those species having a threatened status.

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Chapter 5

Drivers of plant diversity patterns and vegetation structure

5.1. Introduction

Savanna plant diversity and vegetation structure are known to be driven by various biotic and abiotic environmental factors (Skarpe, 1992; Venter *et al.*, 2003; Rutherford *et al.*, 2006; Furley, 2010). Soil fertility is considered a major driver as it is the primary environmental factor used to differentiate between eutrophic (nutrient-rich) and dystrophic (nutrient-poor) savanna types (Scholes, 1990; Scholes, 1997). In addition to soil fertility, rainfall is an equally important driver of savanna vegetation dynamics and structure (Skarpe, 1992; Sankaran *et al.*, 2005; O'Connor, 2015; Van Coller *et al.*, 2018). Landscape topography gives rise to local and spatial variation, resulting in distinctive plant communities that vary in species diversity and structure along catenal sequences (Burke *et al.*, 2003; Gotze *et al.*, 2008; Siebert *et al.*, 2010; Williamson & Balkwill, 2015; Do Carmo & Jacobi, 2016; Niu *et al.*, 2019b; Borden *et al.*, 2020; Ibrahim *et al.*, 2020). In addition to variance in topography, that contribute to habitat heterogeneity, microclimate contributes to spatial turnover in mountainous landscapes (Jobbágy *et al.*, 1996; Porembski, 2007; Van der Ent *et al.*, 2016; Mota *et al.*, 2018; Tordoni *et al.*, 2020).

Mountains or rocky outcrops are considered to function as isolated eutrophic (Pokorny, 2004; Kowalska *et al.*, 2017) or dystrophic (Benites *et al.*, 2007; Weel *et al.*, 2015) edaphic islands (Kruckerberg, 1991; Rajakaruna, 2004; Van der Ent *et al.*, 2016) as a result of the underlying parent material. Since different rock types are associated with different soil types with specific soil properties, edaphic specialisation resulted in the development of plant communities composed of edaphic specialist plant species over evolutionary time (Kruckeberg, 1969; Rajakaruna, 2004; Rajakaruna, 2018). Plant communities occurring on specific soils are therefore structured by a combination of geology, climate and landscape heterogeneity (Jenny, 1941; Kruckeberg, 1969; Goldin, 1976; Kruckeberg, 1986; Schmiedel & Jürgens, 1999; Damschen *et al.*, 2010; Gibson *et al.*, 2012; Carbutt & Edwards, 2015; Burke, 2019; Van Staden *et al.*, 2020). These unique soil-plant-climate relationships structured specialist plant communities over evolutionary time (Kruckeberg, 1986; Körner, 2004; Brady *et al.*, 2005; Carbutt & Edwards, 2015; Rajakaruna, 2018; Dong *et al.*, 2019). However, these distinct vegetation relationships and edaphic floras in mountains are threatened due to climate change and anthropogenic impacts (Carbutt & Edwards, 2015; Rajakaruna, 2018; Niu *et al.*, 2019a; Pringle, 2019; Corlett & Tomlinson, 2020).

The effects of climate change on plant diversity and community structure are extensively covered in ecological literature (Peñuelas *et al.*, 2007; Yang *et al.*, 2011; Baldwin *et al.*, 2014; Masubelele *et al.*, 2015; Niu *et al.*, 2019a; Hannusch *et al.*, 2020). According to Lester *et al.* (2014) understanding effects of climate change on plant communities remains challenging in regions that are understudied and lack long-term ecological data. Therefore, to further our understanding of climate change, studies that focus on interactions between plant communities, soil, geology and rainfall in understudied mountainous landscapes, such as Griqualand-West (GW), are becoming increasingly important. Griqualand West GW contains four mountain ecosystems that are floristically distinct due to differences in rainfall and soil properties (Van Staden *et al.*, 2020). Distinct soil properties derived from the underlying geological parent material are formed through weathering over long periods of time and hence contribute to vegetation patterns (Jenny, 1941; Kruckeberg, 1969; Kowalska *et al.,* 2017). The combined role of soil properties and rainfall as drivers of vegetation remains poorly understood in GW (Van Wyk & Smith, 2001; Frisby *et al.*, 2019). The primary aim of this chapter was therefore to investigate the role of soil properties, related to three contrasting rock types (i.e. banded ironstone, quartzite and dolomite) and rainfall (i.e. 225-425 mm) as drivers of plant diversity and vegetation structure. The objectives were to (i) compare soil properties, rainfall, herbaceous plant diversity and community structure between mountain ecosystems and, (ii) relate plant diversity and community structure to soil properties and rainfall.

Tito *et al.* (2020) concluded that mountains have the potential to serve as natural laboratories to study direct and indirect impacts of climate change on plant communities of mountains along natural environmental gradients. Additionally, through understanding soil-plant-climate relationships in diverse landscapes, proactive management and conservation strategies can be developed, that will contribute to the maintenance of diversity (Rodrigues *et al.*, 2018). Thus, this study will not only provide baseline findings related to plant-soil-climate interactions but will also contribute to inform the management and conservation of GW mountain plant communities. These novel findings can be used as a benchmark in future ecological modelling studies to investigate climate change effects on GW mountain plant communities or long-term monitoring studies.

5.2. Materials and methods

5.2.1. Data analysis

5.2.1.1. Soil properties and rainfall

A portable X-Ray Fluorescence (XRF) analyser was used to analyse composite soil samples for total macro and micro nutrients (Koch *et al.*, 2017) per plot, i.e. the recalcitrant soil pool for each mountain system. Three XRF-readings were taken per sample and the average calculated for each element. These elements included calcium (Ca), magnesium (Mg), potassium (K), phosphorous (P), sulphur (S), aluminium (Al), iron (Fe), titanium (Ti) and manganese (Mn). The Ca:Mg ratio was also calculated. Three fraction particle size distribution (percentage clay, -silt and -sand), pH (water), electrical conductivity (EC) and cation exchange capacity (CEC) were analysed by following the procedures as prescribed by the Non-Affiliated Soil Analysis Work Committee (1990).

In PRIMER 6 (2012), soil data were standardised through logarithmic transformation [log(x+1)], except pH which is already in a logarithmic scale. These transformations were applied to soil data to equalise contributions of soil properties on axes when investigated with multivariate analysis (Rodrigues *et al.,* 2018). The [log(x+1)] transformations were followed by the calculation of a dissimilarity matrix based on the Bray-Curtis index. By following the Permutational Multivariate Analysis of Variance (PERMANOVA) plus routine (Anderson, 2001), non-parametric PERMANOVA was conducted on the matrix to assess whether mountain ecosystems differ in their soil properties. Type III Sums of squares was selected together with unrestricted permutation of raw data as the permutation method. The number of permutations was set to 999. Significant terms (i.e. between mountains) were investigated with posteriori pairwise comparisons using PERMANOVA t-statistics and p-values. Furthermore, homogeneity of dispersion was tested using PERMDISP by selecting deviations from the centroid and 999 restricted permutations (Anderson *et al.*, 2008; Anderson & Walsh, 2013). Comparison of mountain communities, based on soil composition, was visualised by performing a Principle Component Analysis (PCA) in CANOCO version 5 (Šmilauer & Lepš, 2014).

Each separate soil variable and rainfall data were tested for normality using the Shapiro-Wilk and Lilliefors tests. When data were normally distributed, one-way Analysis of Variance (ANOVA) was conducted on variables to test for significant variance among the four mountain ranges. Thereafter, to test for significant differences in variables between mountain ranges, Tukey’s post-hoc Honestly Significant Difference (HSD) test was performed. When assumptions of normality were still violated after being log-transformed [log(x+1)], non-parametric Kruskal-Wallis ANOVA by Ranks, followed by post-hoc tests for two-tailed multiple comparisons of mean ranks for multiple independent groups were performed. These analyses were performed in STATISTICA version 13.3 (TIBCO Software Inc., 2017).

5.2.1.2. Herbaceous composition and soil properties

The species-abundance dataset was [log(x+1)] transformed. Log transformation was used to reduce skewness of the composition data to (1) achieve a normal distribution, (2) weigh down the importance of highly abundant plant species and (3) allow application of multivariate analysis on species data (Legendre & Gallagher, 2001, Legendre *et al.,* 2005;

Ha *et al.,* 2008; Lane, s.a.). After transformation the Bray-Curtis dissimilarity matrix was calculated. Herbaceous species composition was then investigated using PERMANOVA and PERMDISP analysis. PERMANOVA was performed to establish whether herbaceous composition differed among mountains (Anderson 2001; Anderson & Walsh 2013). To test and measure homogeneity of multivariate dispersions among *a priori* groups (Anderson *et al.,* 2008), i.e. mountain plant communities, PERMDISP was applied to the dataset.

The relationship between plant community composition and soil properties was examined using distance linear modelling (DistLM) analysis in PRIMER 6 under the PERMANOVA add on (Anderson *et al.*, 2008). The multivariate dataset consisted of species abundances and soil properties of the four mountain systems. The dataset was log transformed [log(x+1)] to allow multivariate analysis on both species data and soil properties (Legendre & Gallagher, 2001). Thereafter, the Bray-Curtis similarity index was selected with soil properties as predictor variables, followed by stepwise selection procedures, Akaike's information criterion (AIC) and selection of 999 permutations (Anderson *et al.*, 2008). The AIC provides the most parsimonious distance based linear model and the selection of predictor variables with the highest significance. Results provided by the model were then visualised by performing distance-based redundancy analysis (dbRDA) (Legendre & Anderson, 1999; Anderson & Walsh, 2013).

5.2.1.3. Plant species diversity and community structure

Variables related to herbaceous species diversity were calculated for each sampled 1 m² subplot. These included species richness, Pielou's evenness, Shannon Diversity- and Simpson Diversity index. Additionally, total individuals were calculated as a function of density per subplot. These data values were generated from an untransformed abundance data matrix using PRIMER 6 (2012). Herbaceous vegetation structure was described according to the average density, percentage cover and plant height (cm) per subplot, and from calculated frequency values per life form (grasses, forbs and lignified forbs) along each point-intercept transect. The structure of the woody layer was described according to calculated life form frequency (shrubs and trees), average plant height (m) and canopy area (m²) for each Modified-Whittaker plot. Similarly, to the analysis described for soil properties, these variables were tested for normality. One-way ANOVA (to test for significant variance in diversity and structure variables) followed by Tukey's post-hoc HSD tests (for detection of significant difference between mountains) were applied to normally distributed data. Non-parametric Kruskal-Wallis ANOVA by Ranks (to test for variance in diversity and structure variables), followed by post-hoc tests for two-tailed multiple comparisons of mean ranks for multiple independent groups (to detect significant differences across mountains) were performed on data that violated assumptions of normality, despite [log(x+1)] transformations. These analyses were performed in STATISTICA version 13.3 (TIBCO Software Inc., 2017).

5.2.1.4. Soil properties and rainfall as drivers of diversity and structure

Multiple linear regression models with forward selection procedures were performed in STATISTICA version 13.3 (TIBCO Software Inc., 2017) to investigate which soil properties and/or rainfall acted as drivers of species diversity and structure. Significant relationships between selected dependent and independent variables were established by performing separate regression models for each diversity and structure measure. Diversity and structure measures were selected as the dependent variables and soil properties and rainfall as independent variables. Results revealed by these models were visualised using redundancy analysis (RDA) in CANOCO version 5 (Šmilauer & Lepš, 2014).

5.3. Results

5.3.1. Soil properties and rainfall

Results from the PERMANOVA analysis revealed that the mountain ecosystems differed significantly in terms of soil properties (Pseudo-F=23.847, p=0.001, Table C1; Appendix C). However, observed differences between the Kuruman Hills and Asbestos Hills (t=2.687, p=0.012, Table C1), Langberg and Ghaap Plateau (t=2.073, p=0.047, Table C1) and Ghaap Plateau and Asbestos Hills (t=3.133, p=0.004, Table C1) could be ascribed to data dispersion (PERMDISP F=4.481, p=0.007, Table C1). The distinctiveness of mountains based on soil properties was confirmed by the PCA (Figure 5.1). The first two PCA axes explained 74.23% of the cumulative variation (Axis 1 = 55.86%; Axis 2 = 74.28%). The first PCA axis showed a positive correlation between sand content and P, and a negative correlation for Ca:Mg, Ca and pH (Figure 5.1). The ordination diagram revealed that the Langberg sites were separated from the Ghaap Plateau due to higher sand content associated with the Langberg, as well as higher Ca, Ca:Mg ratio and pH of the Ghaap Plateau (Table 5.1). The Asbestos Hills clustered separately from the Langberg as a result of higher Ca, Ca:Mg ratio and pH (Table 5.1). Along the second axis, all mountain sites showed wide distribution and hence made it difficult to distinguish a clear separation. ANOVA tests revealed significant variance among mountain ecosystems with respect to mean annual precipitation (MAP) (X^2 =48.1; p<0.001, Figure 5.2) and soil properties (Table 5.1), except for %clay (p=0.598, Table 5.1) and EC (p=0.208, Table 5.1).

Compared to the Ghaap Plateau, Asbestos- and Kuruman Hills (ironstone hills), CEC (p<0.001) and Mn (p<0.001) levels were significantly lower on the Langberg (Table 5.1). Moreover, when compared to the ironstone hills, the Langberg was represented by significantly lower Ca (p<0.001, Table 5.1), pH (p<0.001, Table 5.1), S (p=0.023, Table 5.1),

%silt (p=0.001, Table 5.1) and Ti (p=0.009, Table 5.1). In contrast, K (p=0.031) and P (p=0.022) were significantly higher on the Langberg compared to the Kuruman- and Asbestos Hills, respectively. Compared to the Ghaap Plateau, %sand was significantly higher on the Langberg (p=0.006, Table 5.1). Despite being both on ironstone, the Asbestos Hills had significantly higher Al (p=0.001) and Ti (p=0.018) than the Kuruman Hills. These two ironstone mountain ecosystems were associated with exceptionally high levels of Fe which was significantly higher compared to the Langberg (p<0.001, Table 5.1). The Ghaap Plateau had significantly lower Fe (p=0.019), but significantly higher K (p=0.003) and pH (p=0.003) than the Kuruman Hills. Furthermore, the Ghaap Plateau was characterised by significantly higher Ca content compared to all three other mountain ecosystems (p<0.001, Table 5.1). The Ghaap Plateau also had significantly higher pH (p<0.001), Mg (p=0.04) and Ca:Mg ratio (p=0.006) than the Langberg.

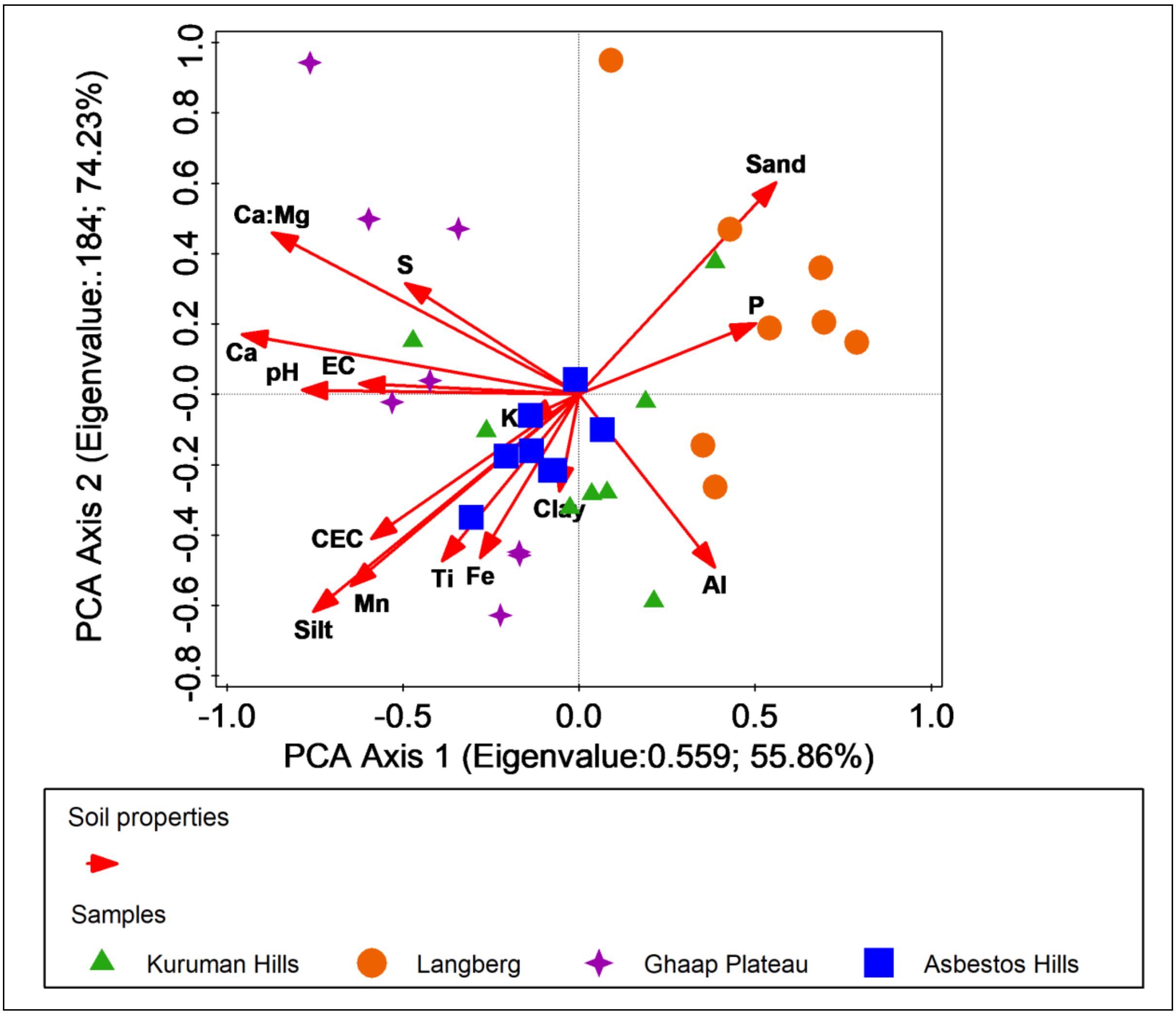

Figure 5.1. Principal Component Analysis (PCA) of mountains and their composition of soil properties.

Table 5.1. Soil physical and chemical characteristics (mean ±SD) of each mountain system. Different lowercase letters in the same line denote significant differences as determined by pair-wise tests ($p<0.05$). NS indicates no significant differences ($p>0.05$).

Soil variable	Langberg	Asbestos Hills	Kuruman Hills	Ghaap Plateau	F	χ^2	p
Clay (%)	3.6±1.1	4.0±1.7	3.5±1.2	4.4±1.5		1.9	0.598^{NS}
Silt (%)	1.8±1.1^{a}	6.3±2.4^{b}	4.7±1.8^{ab}	6.3±2^{b}		16.4	0.001
Sand (%)	94.6±1.6^{b}	89.7±3.8^{ab}	91.8±1.6^{ab}	89.4±3.2^{ac}		12.5	0.006
Ca (mg/kg)	1347±953.6^{c}	4040±1280.8^{b}	3125.6±2663.8^{bc}	11844±9565^{a}	18		<0.001
Mg (mg/kg)	2642.6±687.2^{bc}	3319.8±673.8^{ab}	2945.8±453.8^{ab}	5296.2±2888.3^{a}		8.4	0.038
K (mg/kg)	9160.1±1282^{b}	8851.6±511.5^{ab}	6445.6±1222.5^{a}	9622.7±1336.1^{b}		14.2	0.003
Ca:Mg	0.6±0.6^{b}	1.2±0.3^{ab}	1.0±0.8^{ab}	3.0±3.3^{a}		12.4	0.006
P (mg/kg)	1556.6±85.9^{a}	1266.5±244.2^{bc}	1366.1±230.4^{ab}	1299.2±193.7^{ab}	3.4		0.031
S (mg/kg)	432.3±377.7^{bc}	591.7±245^{ac}	922.7±196.0^{a}	786.2±398.1^{ac}	3.7		0.023
Al (mg/kg)	33867.7±3692.7^{ab}	36317.8±4868.3^{bc}	27054.8±5220.4^{a}	30141.7±7225.6^{ab}	4.6		0.01
Fe (mg/kg)	13740.9±132.5^{b}	52437.1±10372.8^{ac}	61660.3±20272^{a}	18876.2±4886.6^{bc}		26.1	<0.001
Ti (mg/kg)	2696.4±370.6^{a}	3292.5±3134^{b}	2653.9±448.3^{a}	3076.2±454^{ab}	4.7		0.009
Mn (mg/kg)	215.3±40.1^{b}	933.6±446.7^{a}	1206.5±831.1^{a}	1305.7±1028.3^{a}	15.6		<0.001
pH	4.9±0.4^{a}	6.0±0.4^{bc}	5.4±0.3^{ab}	7.6±0.6^{c}		25.6	<0.001
Electrical Conductivity (EC) (mS/m)	19.3±11.6	22.4±12.3	31.8±20.9	32.6±14.7	1.6		0.208^{NS}
Cation Exchange Capacity (CEC) (cmol(+)/kg)	14.9±1.4^{b}	19.0±2.3^{a}	20.6±2.8^{a}	20.2±3.2^{a}	8.6		<0.001

Kruskal-Wallis ANOVA by Ranks indicated a significant variance in rainfall for the mountains (X^2=23.667, p<0.001). Two-tailed multiple comparisons revealed that the Langberg was the driest system and differed significantly from the wetter Kuruman Hills (p=0.002) and wettest Ghaap Plateau (p<0.001) (Figure 5.2). Furthermore, the Asbestos Hills also differed significantly from the wet Ghaap Plateau (p=0.035) (Figure 5.2).

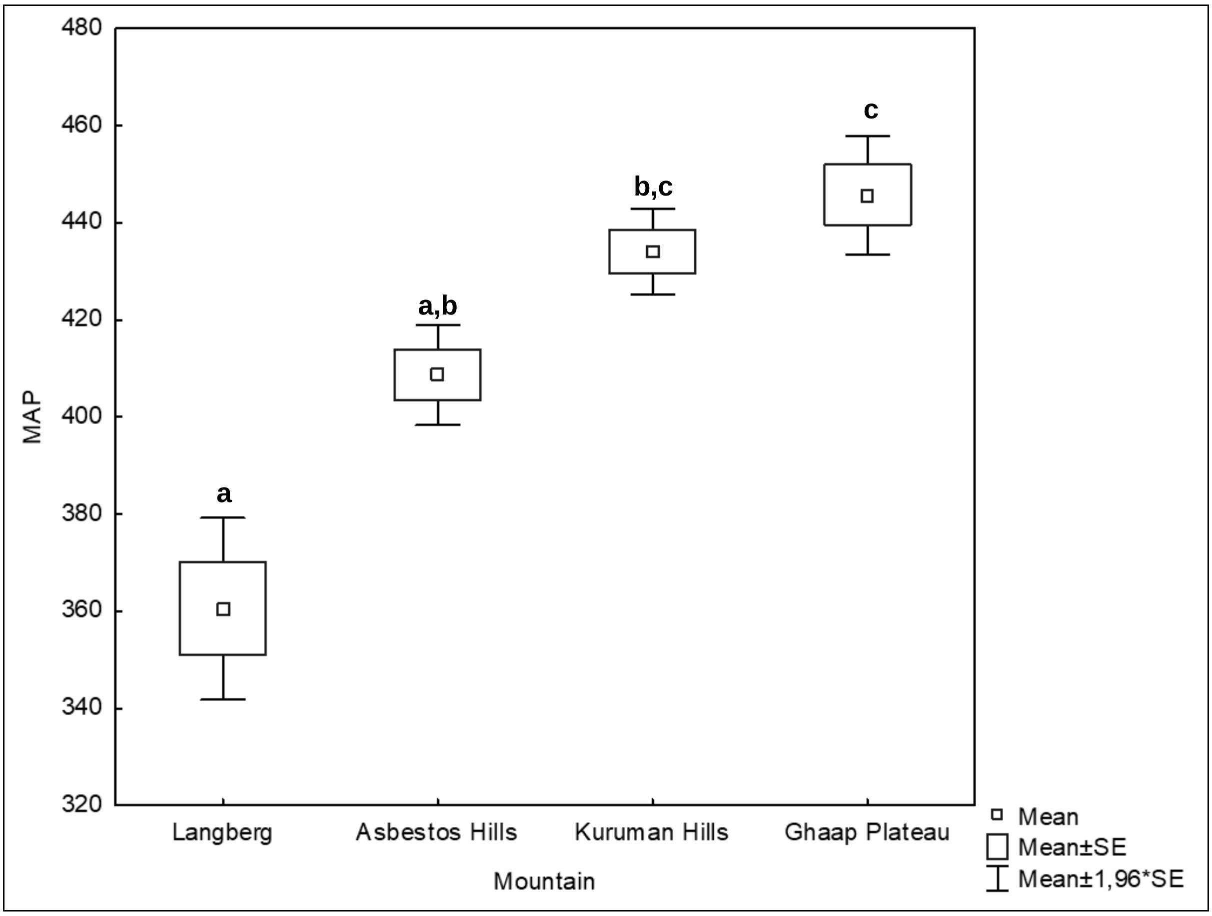

Figure 5.2. Mean annual precipitation (MAP) across mountain ecosystems. Different lowercase letters significant differences as determined by pairwise tests (p<0.05).

5.3.2. Herbaceous composition and soil properties

PERMANOVA tests on the multivariate dataset of species composition and soil properties, revealed significant differences between all mountain ecosystems (Pseudo-F=8.998, p=0.001, Table C2). PERMDISP results (Table C2) revealed data dispersion between the (i) Kuruman Hills and Langberg (t=2.253, p=0.05, Table C2), (ii) Ghaap Plateau and Asbestos Hills (t=2.565, p=0.02, Table C2), (iii) Ghaap Plateau and Langberg (t=2.41, p=0.034; Table C2) and (iii) Langberg and Asbestos Hills (t=4.226, p<0.001, Table C2). In contrast, PERMDISP results of the Kuruman Hills were non-significant when compared to their southern counterparts, the Asbestos Hills (t=1.854, p=0.101, Table C2) as well as the Ghaap Plateau (t=0.253, p=0.81, Table C2). Therefore, differences revealed by PERMANOVA between these plant communities (i.e. Kuruman Hills *vs.* Asbestos Hills; Ghaap Plateau *vs.* Kuruman Hills) are true differences between the different mountains and not due to data dispersion.

Percentage clay and EC did not vary significantly across mountain plant communities (Table 5.1), therefore these two properties were omitted for further analysis. Soil properties that best explained variations in herbaceous plant community composition, were identified by DistLM. Among the fourteen analysed soil properties, ten were AIC selected as the most important factors driving compositional differences (Figure C1; Appendix C, Table 5.2). However, with further inspection, variables that were characterised by a short vector length (Figure C1) were excluded from the dbRDA to include the most important soil properties associated with each mountain plant community (Figure 5.3). The first and second dbRDA axis explained 36.81% of the cumulative variation (Table 5.3). A gradient associated with Ca and Fe was associated with the first axis. Sites of the Ghaap Plateau with high Ca and low Fe clustered towards the negative plain and were separated from the ironstone hill sites with their high Fe content in the positive plain. Since the Ghaap Plateau was characterised by a higher Ca:Mg ratio than the Langberg (Table 5.1), the second axis is suggested to represent a Ca:Mg ratio gradient. Therefore, composition of these mountain plant communities were separated based on Ca, Fe and Ca:Mg ratio.

Table 5.2. Results of DistLM for herbaceous plant communities of four mountains and 14 predictor groups (soil properties) sorted according to Pseudo-F values. SS (trace) = portion of sum of squares; Prop. = proportion of the variance in the herbaceous communities explained by each soil variable.

Marginal tests

Variable	SS (trace)	Pseudo-F	p	Prop.
†Fe	1380.2	8.0	0.001	0.114
†%Silt	1299.5	7.5	0.001	0.108
†Ca	1247.7	7.1	0.001	0.103
†K	1167.7	6.6	0.001	0.097
CEC	1140.5	6.5	0.001	0.094
†Mg	1100.4	6.2	0.001	0.091
%Sand	1054.0	5.9	0.001	0.087
†Ca:Mg	1002.0	5.6	0.001	0.083
†Ti	989.8	5.5	0.001	0.082
pH	964.9	5.4	0.001	0.08
†S	942.4	5.2	0.001	0.078
†Mn	842.4	4.7	0.001	0.07
Al	649.5	3.5	0.001	0.054
†P	604.4	3.3	0.001	0.050

†AIC selected soil properties

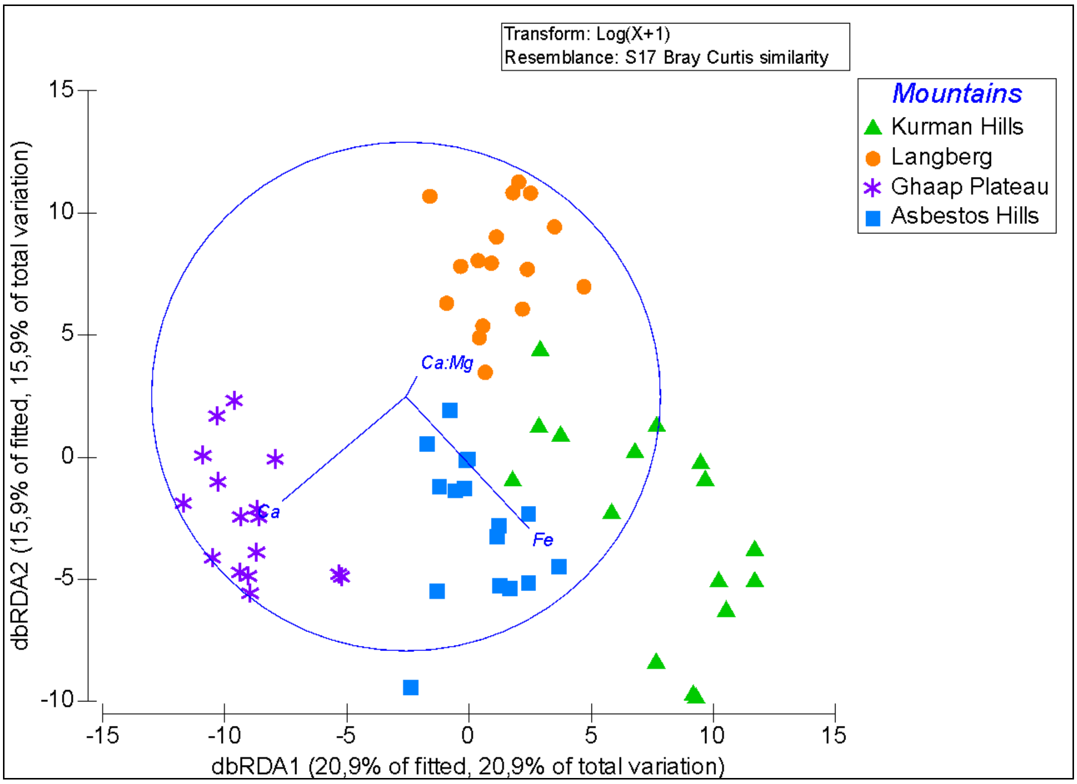

Figure 5.3. Distance-based redundancy analysis (dbRDA) depicting the relationship between herbaceous species composition and three soil properties identified as drivers of compositional differences between mountain plant communities.

Table 5.3. Percentage of variation explained by individual axes of the dbRDA. Percentage of variance explained by individual axes is related to the percentage variance explained from the fitted linear model, whereas percentage explained out of total variation indicates the total variation in the resemblance matrix (original dataset) (Anderson *et al.*, 2008; Morgan, 2013). The cumulative column is an indication of the percentage of variation that is accounted by the first number (n) components. Thus, for the second axis, the cumulative percentage of variance is the sum of the percentage of variance calculated for both the first and second axis (IBM Knowledge Center, 2020).

Axis	**% explained variation out of fitted model**		**% explained variation out of total variation**	
	Individual	Cumulative	Individual	Cumulative
1	20.92	20.92	20.93	20.93
2	15.89	36.81	15.89	36.82
3	10.6	47.41	10.6	47.42
4	9.0	56.41	9.0	56.43

5.3.3. Diversity and community structure

5.3.3.1. Diversity measures

One way ANOVA revealed significant variances among mountain plant communities for species richness and Shannon Diversity (Table 5.4). The Langberg was species poor in comparison with the ironstone hills and less diverse in comparison with the Asbestos Hills. Furthermore, the Ghaap Plateau was characterised by more species rich plant communities than those associated with the quartzitic Langberg (Table 5.4) and less diverse than the Asbestos Hills. Kruskal-Wallis ANOVA by ranks identified significant variance for Pielou’s Evenness and Simpson Diversity among mountain habitats (Table 5.4). Despite the Ghaap Plateau having high species richness, certain plant species tended to dominate within these dolomitic plant communities. This could explain the low Simpson Diversity index values compared to the Asbestos Hills where species rich and diverse plant communities were evenly distributed in plant species numbers (Table 5.4).

5.3.3.2. Herbaceous plant density and height

Kruskal-Wallis ANOVA by ranks and one-way ANOVA revealed highly significant variance for density and plant height, respectively (Table 5.4). Plant communities on the drier Langberg revealed a lower density of herbaceous plants compared to the Asbestos Hills, Kuruman Hills and Ghaap Plateau along a moisture gradient (driest to wettest). The ironstone hills were characterised by less dense herbaceous plant communities than the dolomitic Ghaap Plateau. Despite the latter being the wettest system along the aridity gradient, herbaceous plants were smaller in stature than the quartzitic Langberg and Kuruman Hills, but similar to the Asbestos Hills (Table 5.4).

5.3.3.3. Cover variables

Significant variance was revealed for %grass and %rock cover (one-way ANOVAs) as well as %herbaceous forb cover and %bare soil (Kruskal-Wallis ANOVA by Ranks) (Table 5.4). Tukey’s post-hoc HSD tests revealed that the wetter Kuruman Hills had higher grass cover than the drier Langberg. Furthermore, plant communities of the Ghaap Plateau had lower rock cover than the Asbestos Hills. In contrast, post-hoc tests for two-tailed multiple comparisons of mean ranks for multiple independent groups revealed that bare soil cover was higher on the Ghaap Plateau in comparison to the ironstone hills (Table 5.4). The Kuruman Hills with its higher grass cover, had lower %bare soil compared to the quartzitic and drier Langberg with its lower grass cover and hence higher %bare soil. Cover by herbaceous forbs were higher in the two wetter plant communities, i.e. Kuruman Hills and Ghaap Plateau, than those plant communities persisting under drier conditions, i.e. Langberg and Asbestos Hills (Table 5.4).

5.3.3.4. Life form frequencies

Herbaceous forbs and shrubs were the only two life forms which differed significantly in frequency across mountain ecosystems (Table 5.4). In accordance with the higher %forb cover associated with the wetter mountains, herbaceous forbs occurred more frequently in plant communities of the Kuruman Hills and Ghaap Plateau, than the two drier plant communities. However, shrubs were more frequently encountered in the two drier plant communities (Langberg and Asbestos Hills) compared to the wetter Kuruman Hills (Table 5.4).

5.3.3.5. Woody plant height and canopy area

Significant variance among mountains were revealed for all the woody plant height and canopy area variables (Table 5.4). Lignified forbs encountered on the Langberg and Kuruman Hills were larger in stature with wider canopies, while those prevailing on the

Asbestos Hills and Ghaap Plateau were smaller with narrower canopies (Table 5.4). Additionally, shrubs on the Ghaap Plateau were smaller compared to those growing on the Langberg and ironstone hills. Shrub canopy areas were also narrower for individuals encountered on the Ghaap Plateau compared to wider shrubs of the Langberg and Asbestos Hills (Table 5.4). In contrast to the lignified forbs and shrubs, trees reached an average height above 2 m on the dolomitic Ghaap Plateau. These individuals were taller with wider canopy areas than trees growing on the Kuruman Hills.

5.3.4. Effect of soil properties and rainfall on herbaceous diversity and vegetation structure

Correlations revealed between soil characteristics, diversity measures and structure variables can be considered as trends of which some may be coincidental.

5.3.4.1. Herbaceous diversity

The regression model that best explained variability in species richness, explained 47.3% of the variation ($F_{7.561}$=7.191, p<0.001, Table C3). Five significant explanatory soil properties were identified by the model, i.e. soil pH, Mg, Ca:Mg ratio, Ca and %sand. Of these variables, soil pH and Ca were positively correlated with species richness, indicating that increasing values in these soil properties enhanced species richness. Species richness was sensitive to increasing Mg and %sand, as well as higher Ca:Mg ratios since these variables were negatively correlated with species richness.

When considering species evenness, Fe, CEC and %silt accounted for 48.3% of the variation in the model ($F_{8.55}$=6.425, p<0.001, Table C3). This model revealed that as Fe and CEC increased, so did evenness. In contrast, %silt was negatively correlated with evenness. Significant variables associated with the Shannon Diversity were Al, CEC and Ti, which accounted for 33.0% of the variance ($F_{7.56}$=3.943, p=0.002, Table C3). Both Al and CEC were positively correlated with Shannon Diversity and Simpson Diversity, while the opposite was revealed for Ti (Table C3). Additionally, to these three variables, Simpson Diversity increased with increasing Fe content and decreased with increasing P. Variables revealed by the regression model for Simpson Diversity accounted for 39.3% of the variation and the model ($F_{7.56}$=5.17, p<0.001, Table C3).

Table 5.4. Diversity- and structural measures (mean ±SD) for each mountain. Dissimilar letters in the same line denote significant differences as determined by pairwise tests ($p<0.05$). NS indicates no significant differences ($p>0.05$).

Response variables	Langberg	Asbestos Hills	Kuruman Hills	Ghaap Plateau	F	χ^2	p
Diversity measures							
Species richness	10.06±3.84^{a}	14.81±3.66^{b}	13.63±3.96^{b}	14.44±2.87^{b}	5.798		0.002
Pielou's evenness	0.78±0.13^{a}	0.82±0.04^{a}	0.80±0.05^{a}	0.65±0.14^{b}		15.841	0.001
Shannon Diversity	1.77±0.50^{a}	2.20±0.32^{b}	2.07±0.32^{ab}	1.74±0.44^{a}	5.179		0.003
Simpson Diversity	0.76±0.17^{ab}	0.86±0.05^{a}	0.84±0.06^{ab}	0.71±0.15^{b}		11.9	0.008
Structure							
Density	42.31±17.20^{a}	74.38±23.42^{b}	85.13±47.03^{b}	194.56±105.97^{c}		34.869	<0.001
Herbaceous plant height (cm)	37.50±11.09^{a}	25.03±4.67^{b}	33.36±3.58^{a}	25.03±4.67^{b}	14.197		<0.001
Percentage cover							
Grass	24.19±12.87^{b}	26.75±15.00^{ab}	36.88±11.92^{a}	31.06±10.41^{ab}	4.279		0.008
Herbaceous forbs	1.31±1.01^{b}	1.06±0.85^{b}	3.69±2.24^{a}	4.94±4.31^{a}		25.615	<0.001
Lignified forbs	6.88±6.85	9.38±6.20	8.94±5.71	5.56±6.72	2.098		0.11^{NS}
Debris	26.69±10.42	26.06±16.73	28.69±13.66	22.88±9.32		2.232	0.526^{NS}
Bare soil	28.19±7.51^{bc}	17.63±20.76^{ac}	5.50±4.07^{a}	37.88±21.17^{b}		32.446	<0.001

Rock	50.38±16.68^{ab}	60.50±29.98^{a}	49.50±22.64^{ab}	28.25±23.97^{b}	5.194		0.003
Life form frequencies							
Grass	50.00±0.00	50.00±0.00	49.63±1.06	45.38±13.08		2.069	0.558^{NS}
Herbaceous forbs	41.50±7.75^{b}	35.38±11.64^{b}	49.50±0.76^{a}	49.13±1.46^{a}		18.463	0.004
Lignified forbs	48.63±2.33	49.75±0.46	48.38±3.85	48.50±1.77		3.927	0.27^{NS}
Shrubs	26.50±11.84^{a}	26.38±6.63^{a}	10.75±14.21^{b}	19.50±10.11^{ab}	3.631		0.025
Trees	1.75±3.41	0.88±1.46	0.75±1.16	1.00±1.20		0.374	0.947^{NS}
Woody plant height (m)							
Lignified forbs	0.20±0.13^{b}	0.14±0.08^{a}	0.21±0.15^{b}	0.13±0.07^{a}		157.621	<0.001
Shrubs	0.79±0.41^{a}	0.70±0.43^{a}	0.67±0.45^{a}	0.50±0.38^{b}		54.961	<0.001
Trees	2.23±0.13^{ab}	2.26±0.24^{ab}	2.12±0.24^{b}	2.76±0.50^{a}		10.285	0.016
Woody canopy area (m²)							
Lignified forbs	0.28±0.49^{b}	0.15±0.50^{a}	0.32±1.13^{b}	0.10±0.16^{a}		125.9	<0.001
Shrubs	4.28±4.70^{c}	3.64±6.28^{a}	3.59±7.17^{ab}	1.93±3.51^{b}		44.933	<0.001
Trees	20.65±10.15^{ab}	28.06±22.94^{ab}	13.49±11.83^{b}	33.14±18.78^{a}	3.131		0.039

Relationships between diversity and soil properties were visualised using RDA (Figure 5.4). The first RDA axis explained 33.78% of the cumulative variation, whilst the second explained 40.59%. A species richness and %sand gradient were associated with the first axis with the alkaline sites (pH>7) of the Ghaap Plateau clustering separately from the acidic (pH<5), sandy Langberg (Figure 5.4). An Fe content together with a diversity and evenness gradient, characterised the second RDA axis. Thus, the highly diverse ironstone hills with high species evenness clustered from the less diverse dolomitic Ghaap Plateau and quartzitic Langberg which revealed low total Fe content (Figure 5.4).

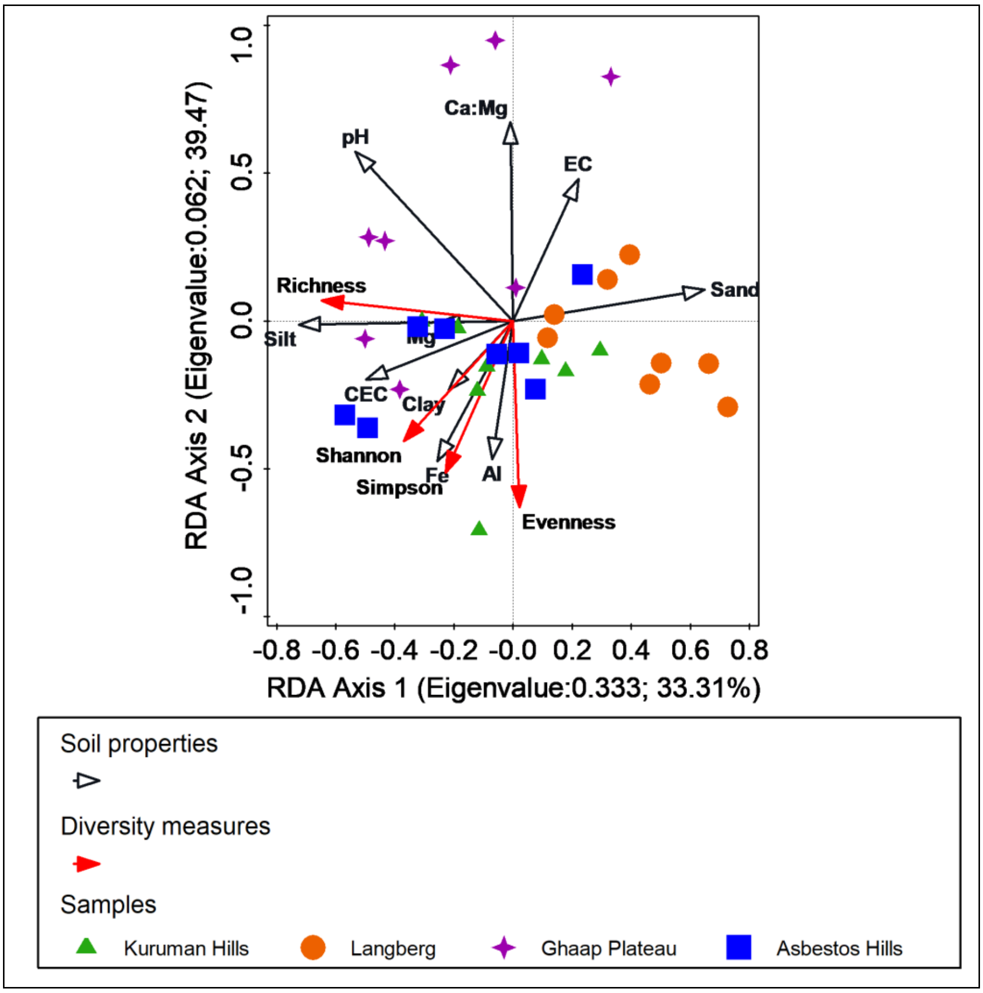

Figure 5.4. Redundancy analysis (RDA) of diversity measures for herbaceous plant communities and soil properties associated with diversity measures. *CEC* – cation exchange capacity, *EC* – electrical conductivity.

5.3.4.2. Herbaceous plant density and height

Multiple regression of herbaceous density yielded seven explanatory variables that accounted for 68.1% of the variation ($F_{9.54}$=12.816, p<0.001, Table C3). Density tended to increase with increasing soil pH, MAP, Mn and P. Conversely, Mg, S and Al seemed to inhibit density, since these two variables were negatively correlated with density. Herbaceous plant height correlated positively with MAP, but negatively with pH (Table C3). In addition to these two variables, low %silt can be considered to favour taller herbaceous plants. The three variables that acted as drivers on herbaceous plant height, explained 45.5% of the variance in the regression model ($F_{9.59}$=12.302, p<0.001, Table C3). In combination, identified drivers of both herbaceous density and height accounted for 49.00% of the cumulative variation. The first RDA axis was found to be associated with gradients of rainfall, soil pH and density (Figure 5.5). Thus, the dry Langberg with more acidic soil was characterised by sparse vegetation, which clustered separately from the wet, alkaline Ghaap Plateau with a dense herbaceous layer (Figure 5.5). Additionally, the Langberg revealed to be associated with herbaceous plants which grow higher with lower %silt (Figure 5.5). An opposite trend was revealed for the Ghaap Plateau which revealed low herbaceous plant height and higher %silt (Figure 5.5). The separate clustering along the second axis between the two ironstone mountains was related to Al and plant height, since the Asbestos Hills is characterised by high Al and lower herbaceous plants than their northern counterpart, the Kuruman Hills.

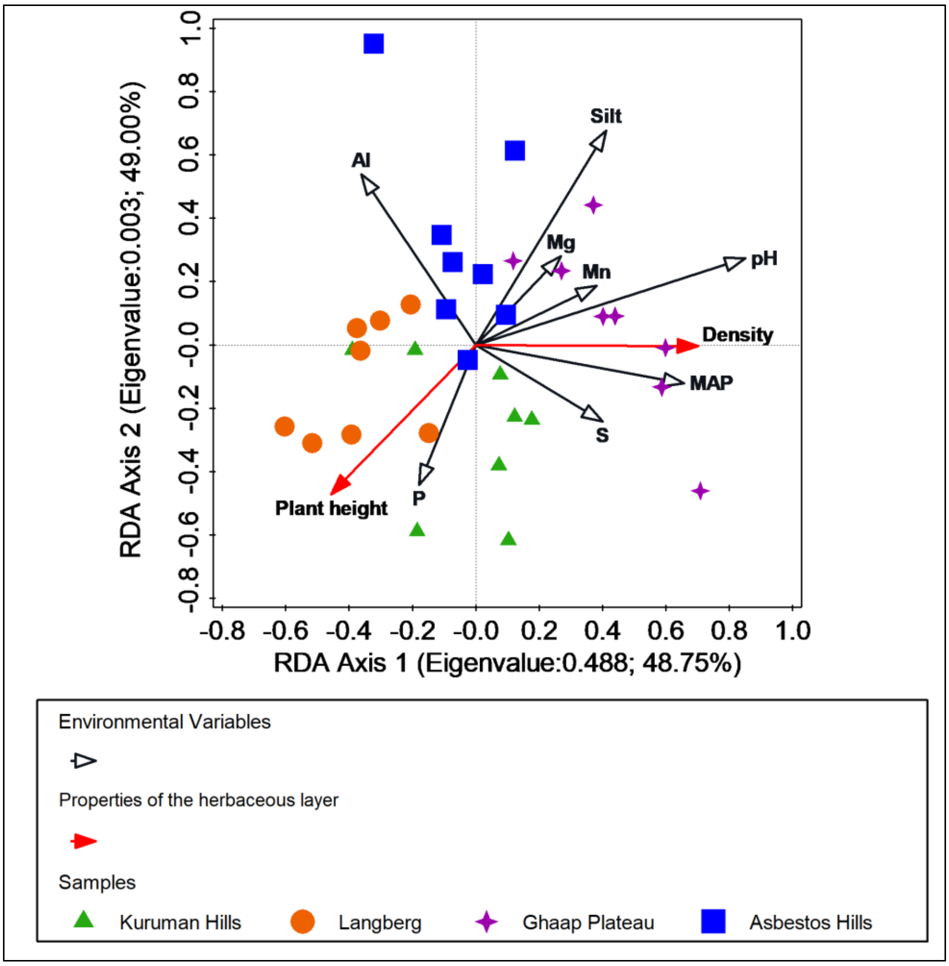

Figure 5.5. Redundancy analysis (RDA) of significant soil properties and mean annual precipitation (MAP) as drivers of herbaceous plant height and -density.

5.3.4.3. Cover variables

The regression model of percentage grass cover revealed four environmental variables that accounted for 33.8% of variance ($F_{6.57}$=4.841, p<0.001, Table C3). Variables that seemed to enhance grass cover included MAP and P, whereas increases in %sand and soil pH resulted in a decrease in grass cover. Herbaceous forb cover was correlated with four variables ($F_{7.56}$=7.575, p<0.001, Table C3). These variables explained a total of 48.6% of the variance and included MAP and Mn, that were positively correlated with cover of herbaceous forbs. High levels of Mg and Fe limited herbaceous forb cover. In contrast to herbaceous forb cover, percentage lignified forb cover was correlated with soil properties and not rainfall. Seven different soil properties, including both physical and chemical properties (explaining 37.0% of the variance) were identified as drivers of lignified forb cover ($F_{10.53}$=3.117, p=0.003, Table C3). The percentage lignified forb cover was enhanced with higher levels of Fe, K and soil pH. However, high Mn, %silt, %sand and Mg had a limiting effect on the cover of lignified forbs in these mountain plant communities.

Soil pH and CEC were negatively correlated with %debris and accounted for 25.0% of the variation ($F_{5.58}$=3.85, p=0.004, Table C3). Therefore, as soil pH and CEC increased, cover of debris seemed to decrease. The model for percentage bare soil suggested that high Fe, CEC and S was associated with decreasing bare soil cover. With increasing rainfall, the %bare soil also increased. These four correlated variables explained 65.6% of the variance ($F_{8.55}$=13.104, p<0.001, Table C3). The percentage rock cover was correlated with Fe, S and Mg (Table C3). All three soil properties were positively correlated with rock cover suggesting that rock cover decreased as levels of Fe, S and Mg decreased. The multiple regression model associated with rock cover explained 49.9% of the variance ($F_{6.57}$=9.471, p<0.001, Table C3). Moreover, the RDA revealed that all explanatory variables, associated with percentage cover measures, explained 44.1% of the total variation. The drier Langberg and Asbestos Hills clustered separately from the wetter Kuruman Hills and Ghaap Plateau (Figure 5.6) as MAP enhanced grass and herbaceous forb cover of the latter two.

5.3.4.4. Life forms

Significant correlations between soil properties and herbaceous life form frequencies were revealed by regression models. The model for grass frequency explained 33.3% of the variation ($F_{4.27}$=3.375, p=0.023, Table C3) with Mn negatively and CEC positively correlated with this life form group frequency. In mountain ecosystems with higher total Mn content, grass and lignified forb frequencies were lower, whereas high CEC values enhanced the frequency of grasses (individuals). In contrast to grasses and lignified forbs, frequency of herbaceous forbs was enhanced by higher levels of Mn. The model for herbaceous forbs accounted for 43.1% of the variation ($F_{5.26}$=3.936, p=0.009, Table C3) and 37.7% lignified forbs ($F_{5.26}$=3.256, p=0.024, Table C3).

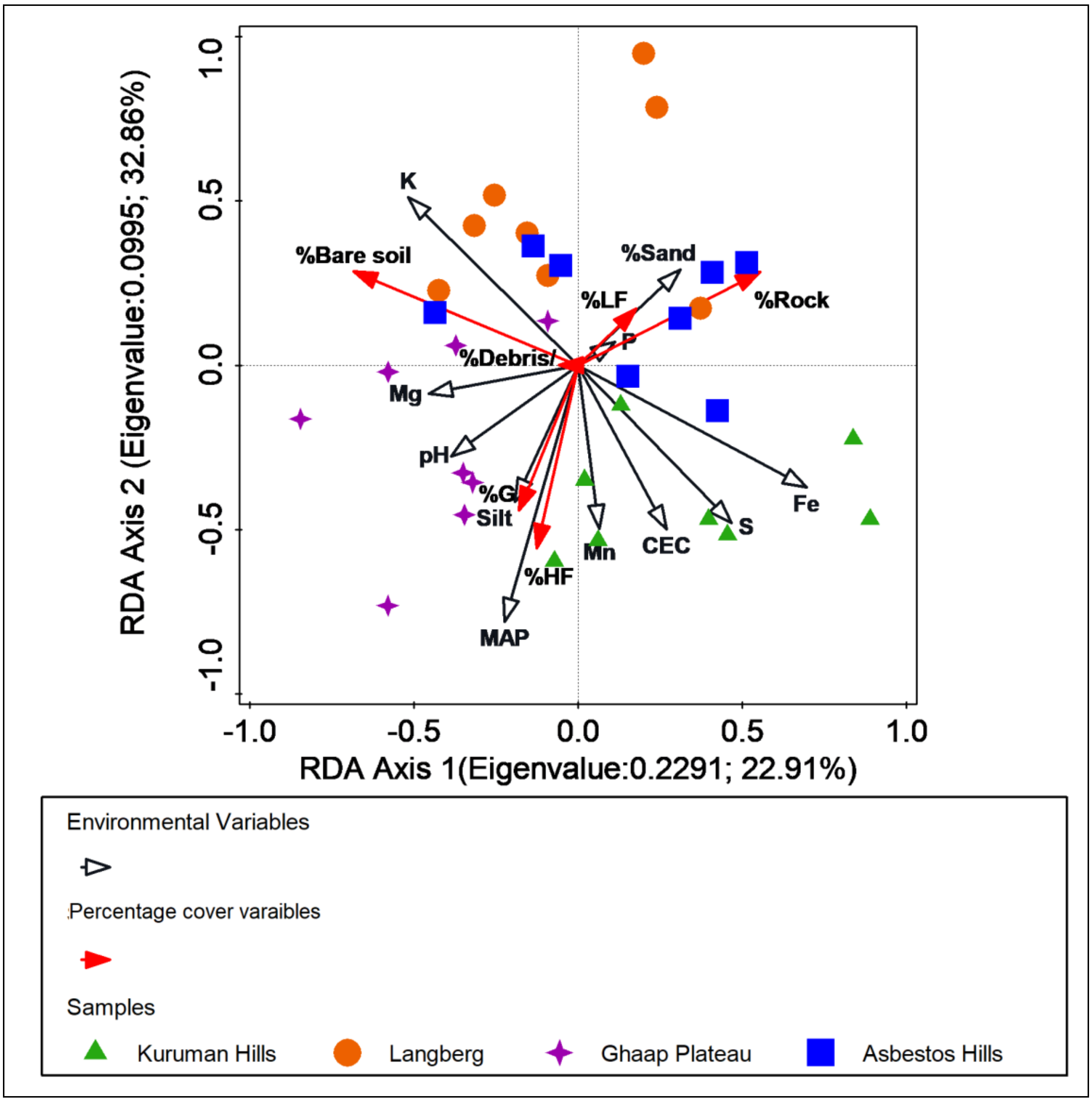

Figure 5.6. Redundancy analysis (RDA) of visually estimated percentage cover variables and their environmental drivers. %G - percentage grass cover, %HF – percentage herbaceous forb cover and %LF – percentage lignified forb cover, MAP - mean annual precipitation.

Frequencies of woody life forms, i.e. shrubs and trees, were associated with more environmental factors than herbaceous life forms (Table C3). The regression model for shrub frequency revealed six significant parameters that explained 87.0% of the variance ($F_{11.2}$=12.15, p<0.001, Table C3). Shrub frequency can be considered to be suppressed by higher MAP, Ca:Mg ratio, Al and P, and enhanced by high Ca and %sand. Only three primary variables were considered to contribute to tree frequency (Table C3). These included Ti, %sand and P. Frequency of trees was higher on sites with higher Ti and %sand, whereas high levels of P tended to be disassociated with tree frequencies. This tree frequency model contributed to 30.5% of variance ($F_{3.28}$=4.103, p<0.001, Table C3).

From the RDA analysis, the wetter mountain plant communities (Kuruman Hills and Ghaap Plateau) with higher herbaceous forb frequencies, clustered separately from the drier communities (Asbestos Hills and Langberg) with lower herbaceous forb frequencies (Figure 5.7). Furthermore, the negative relationship between Mn and frequencies of grasses and lignified forbs can be clearly distinguished, since the Langberg with lowest Mn content clustered apart from the other three mountain systems with higher Mn (Figure 5.7). Additionally, the Langberg clustered away from the Kuruman Hills, since the former was characterised by higher frequencies of shrubs than the latter. This can be ascribed to the lower rainfall associated with the Langberg.

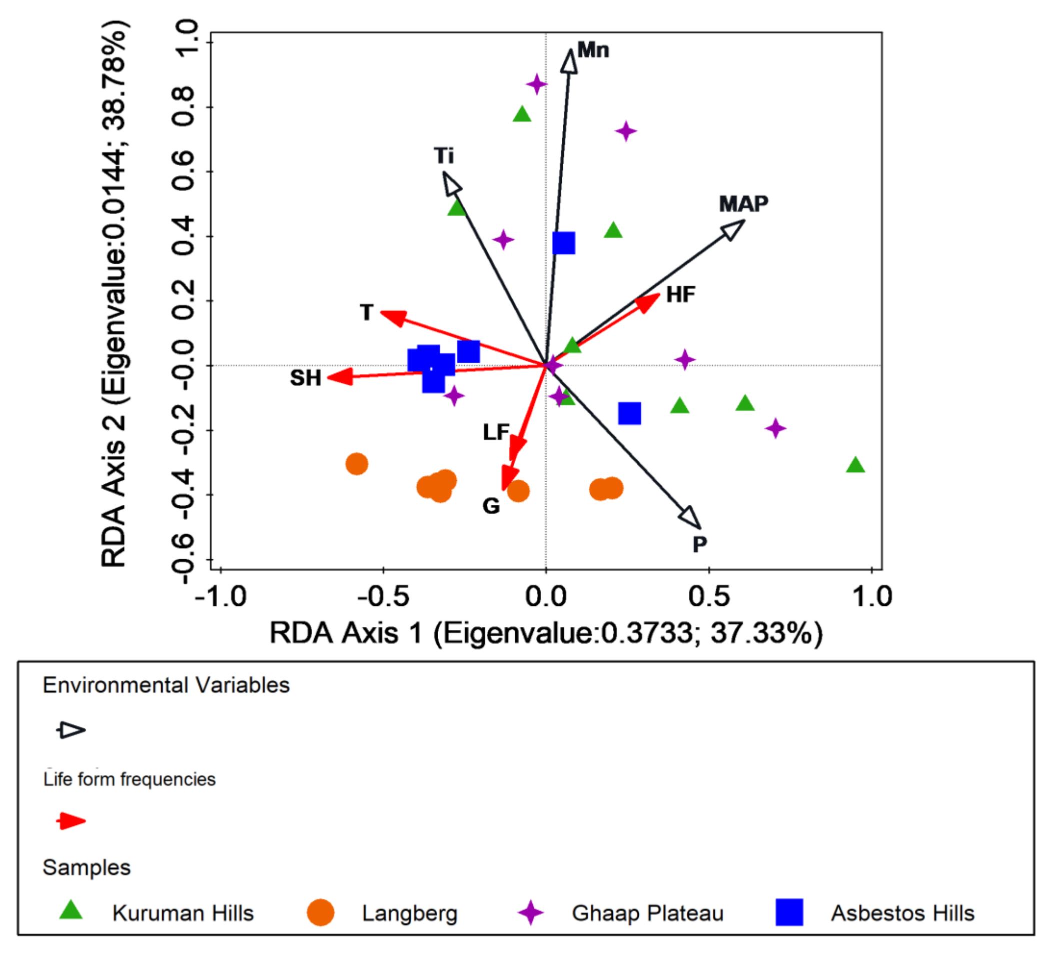

Figure 5.7. Redundancy analysis (RDA) of frequency of each life form group and significant environmental drivers. G - Grasses, HF - herbaceous forbs, LF - lignified forbs, SH - shrubs, T - trees. Note: certain parameters were omitted due to short vector lengths; MAP – mean annual precipitation.

5.3.4.5. Woody structure

Soil properties were the main predictors of woody plant height and canopy area. The model for the plant height of lignified forbs accounted for 40.7% of the variation ($F_{2.29}$=9.967, p=0.001, Table C3). Only Ca was revealed as a significant factor which was negatively correlated with lignified forb height, suggesting that with higher Ca content, plants within this life form were shorter. Shrub plant height was also found to be correlated with one soil property, i.e. %silt and the model explained 22.3% ($F_{3.28}$=2.685, p=0.066, Table C3). Shrub height correlated negatively with this characteristic indicating that shrub height may have been favoured on sites associated with low %silt. The regression model for tree height identified six significant soil properties that explained 61.0% of variation ($F_{12.19}$=2.474, p=0.038, Table C3). Soil characteristics that were negatively correlated with tree height included P, K and Fe, while %sand, Mn and Al were positively correlated. Combined, RDA revealed that explanatory variables accounted for 37.2% of the total variation, associated with woody plant height (Figure 5.8). Since the Ghaap Plateau was characterised by higher Ca and %silt than the Langberg, the separation between these two mountains was clear due to shorter lignified forbs and shrubs present on the Ghaap Plateau (Figure 5.8). Additionally, the Langberg had higher %sand than the Ghaap Plateau which favoured tree height on the former mountain ecosystem.

The regression model for lignified forb canopy area accounted for 33.2% of the variation ($F_{3.28}$=4.633, p=0.01, Table C3), and revealed that Ti content and Ca:Mg ratio were negatively correlated with the lignified forb community. Thus, under lower conditions of these two predictors, canopy areas of lignified forbs can be favoured. Similarly, to shrub plant height, canopy area of shrubs was also found to be negatively correlated with %silt with the model accounting for 27.4% of the variability ($F_{3.28}$=3.518, p=0.028, Table C3). Tree canopy area was positively correlated with %sand, Ti and soil pH (Table C3). Therefore, as these variables increase, canopy areas of trees tend to increase and *vice versa*. This regression model for tree canopy area accounted for 44.7% of the variance ($F_{8.23}$=2.328, p=0.054, Table C3). The RDA found that all explanatory variables accounted for 25.4% of the total variation. Sites of the Langberg and Ghaap Plateau clustered separately from each other (Figure 5.9). This separation was related to lower Ca:Mg ratio and %silt, as well as higher %sand that contributed to wider lignified forbs, shrubs and trees, respectively, on sites of the Langberg. Furthermore, tree canopy area was found to be favoured by alkaline conditions of the Ghaap Plateau (Figure 5.9).

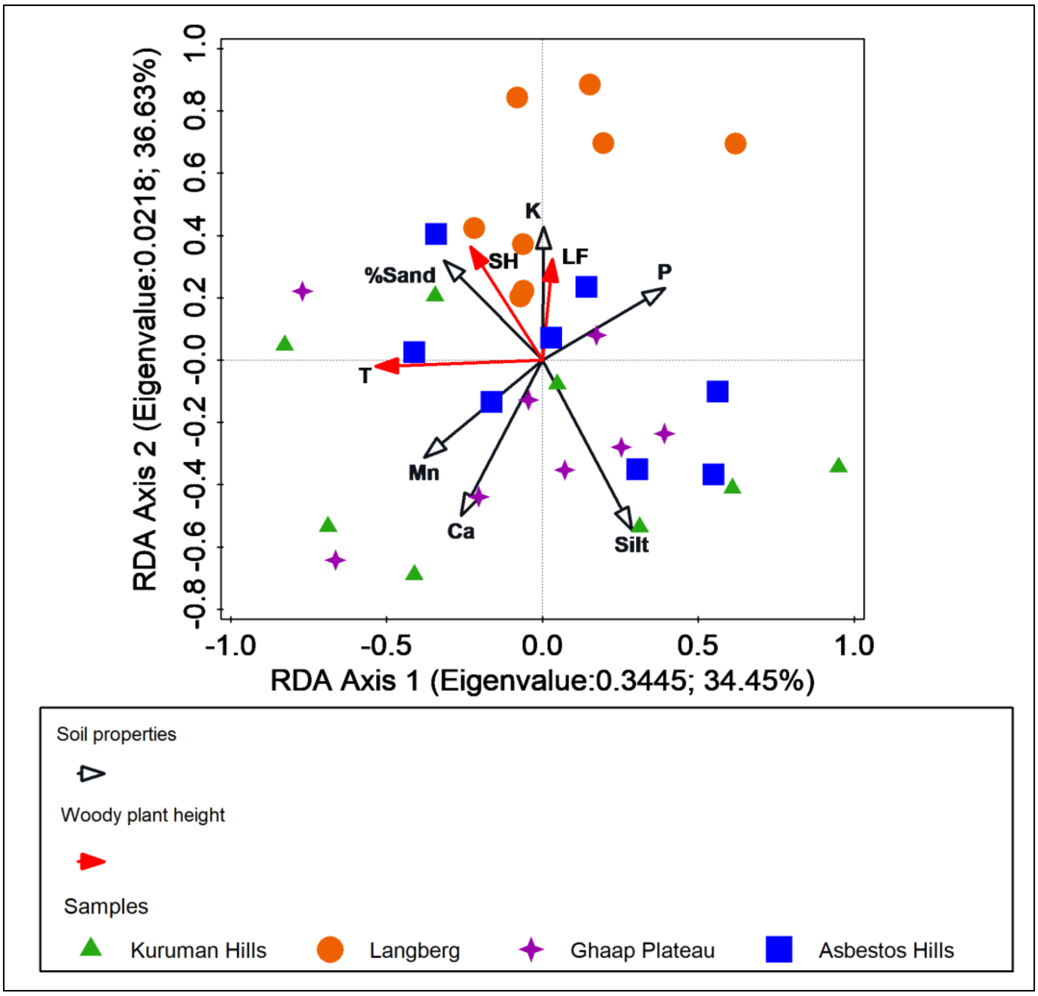

Figure 5.8. Redundancy analysis (RDA) of woody plant height and associated significant soil properties. LF - lignified forbs, SH - shrubs, T - trees. Note: soil properties with short vector lengths were omitted.

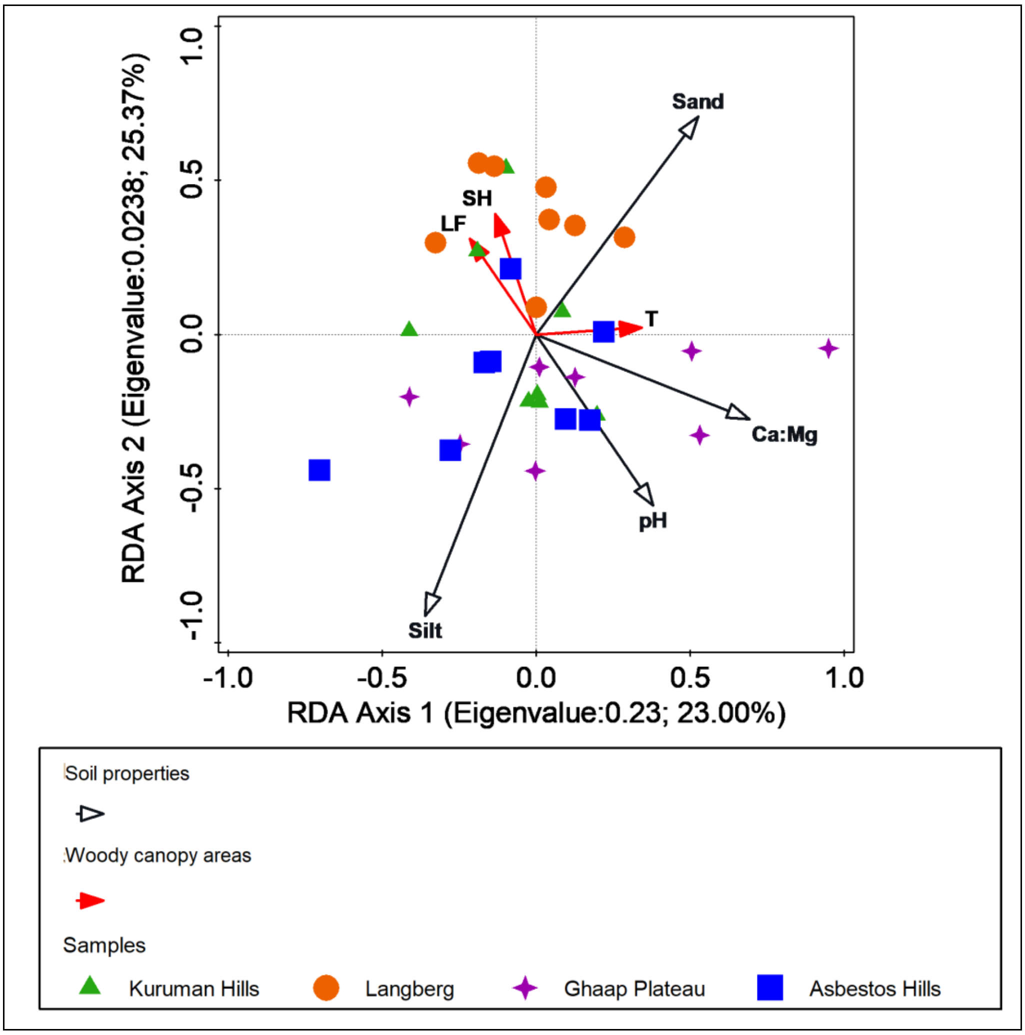

Figure 5.9. Redundancy analysis (RDA) of woody canopy areas and significant soil properties. LF - lignified forbs, SH - shrubs, T - trees. Explanatory variables with short vector lengths were omitted.

5.4. Discussion

5.4.1. Soil properties of GWC mountains

Differences in chemical and physical soil properties across the different mountain ecosystems illustrated the influence of geological heterogeneity on semi-arid savanna landscapes (Jenny, 1941; Kruckeberg, 1969; Brković *et al.*, 2015; Rodrigues *et al.*, 2018). These soil properties are representative of the geological processes that formed these unique geologies in GW. Geochemical analysis of the Transvaal Supergroup revealed that lithologies consisting of limestone and dolomite are distinct from those on banded ironstone formations (BIF) (Klein & Beukes, 1989). Dolomites and BIF were formed through oxidation processes by cyanobacteria in the historical inland ocean (McCarthy & Rubidge, 2005).

Consequently, Fe and Mn were deposited (McCarthy & Rubidge, 2005). Ironstone formations are especially rich in Fe, precipitated as Fe-carbonates, Fe-oxides and Fe-silicates (Klein & Beukes, 1989; Horstmann & Hälbich, 1995; Oonk *et al.*, 2017; Smith, 2018). Therefore, the high levels of Fe revealed by this study for the Asbestos- and Kuruman Hills were expected. The micronutrient, Mn, was also higher on the Ghaap Plateau than the Langberg. At higher pH, Mn tends to be in a form (i.e. Mn^{3+} and Mn^{4+}) that is unavailable for plants (Rengel, 2000) whereas acidic soils are prone to Mn toxicity since Mn becomes more available for plant uptake in the form of Mn^{2+} (Marschner, 1995). Limestone and dolomites of the Transvaal Supergroup are associated with high Al_2O_3 (aluminium oxide) of 30 000 mg/kg (Klein & Beukes, 1989). Thus, the total Al content of the Ghaap Plateau compares favourably to this value. Aluminium is considered as the world's third most abundant metal in soils and becomes toxic to plants at pH levels below 5.5 (Silva, 2012). Furthermore, due to the more acidic nature of soils of the Kuruman Hills and Langberg (pH <5.5) suggest that these two systems may be prone to Al leaching (Silva, 2012). Furthermore, Al^{3+} inhibit transporter cations K^+ and Ca^{2+} or form complexes with P that are insoluble and, hence, reduce P availability to plants (Piñeros & Tester, 1993; Gassmann & Schroeder, 1994; Zheng, 2010; Bojórquez-Quintal *et al.,* 2017).

The Olifantshoek Supergroup consists mainly of arenaceous sediments (sands) (Moen, 2006), derived from deep-water, red-coloured sandstone that formed at the western margin of the Kaapvaal Craton (McCarthy & Rubidge, 2005). Sand consists primarily of the mineral quartz or silicon dioxide (SiO_2). When quartz sand becomes exposed to lithification (when sedimentary depositions are converted to sedimentary rocks), the hard rock type quartzite, resilient to weathering, is formed (McCarthy & Rubidge, 2005). Consequently, soil formation is limited on quartzites (King, 2020) which explains the higher rock cover, as given in the land type inventory for land type Ic2 (MacVicar *et al.,* 1977; Land Type Survey Staff, 1972-2002) which covers the largest part of the Langberg. The soils on the Langberg were found to be dystrophic, acidic and sandy, a set of properties generally associated with quartz environments (Neely & Barkworth, 1984; Messias *et al.*, 2013). In contrast to the quartz fields in the Karoo, the quartzite of the Langberg was found to be low in silt content (Schmiedel, 2002). The Langberg was revealed to be richer in total P and K in comparison to the Asbestos- and Kuruman Hills, respectively. However, with decreasing pH, the availability of P and K is inhibited (Balemi & Negisho, 2012; Weil & Brady, 2017; Brown & Lemon, 2020) suggesting that these nutrients are unavailable to plants on the Langberg.

5.4.2. Herbaceous community composition

Various studies revealed that the rock types found within this study site, namely quartzite (Conceição *et al.*, 2007; Curtis *et al.*, 2013; Do Carmo & Jacobi, 2016; Mota *et al.*, 2018;

Silva *et al.*, 2019), ironstone (Jacobi *et al.*, 2007; Markey & Dillon, 2008; Nunes *et al.*, 2015; Neves *et al.*, 2018), as well as dolomite and limestone (Bezuidenhout *et al.*, 1994; Clements *et al.*, 2006; Molano-Flores *et al.*, 2015; Liu *et al.*, 2019), harbour distinct plant communities. Plant communities of GW associated with these three rock types were distinct from one another, each associated with specific soil properties responsible for driving compositional changes. Calcium was associated with the plant communities of the Ghaap Plateau, Fe with the ironstone Hills and a low Ca:Mg ratio with the Langberg. Therefore, soil properties, derived from the parent geology, are also considered environmental filters (Dubbin *et al.*, 2006; Nunes *et al.*, 2015; Da Silva Menezes *et al.*, 2016; Liu *et al.*, 2019).

Consequently, ecological tolerances of plants are reflected by underlying edaphic conditions (Lososová & Láníková, 2010). Calcium is an essential nutrient for plants that fulfils important physiological and structural roles (Burstrom, 1968). However, excessive concentrations restrict plant growth (White & Broadley, 2003). Therefore, plants occurring on carbonate soils have developed specialised physiological mechanisms to tolerate high Ca levels and are insensitive to nutrient deficiencies related to Fe and P (Lee, 1999). Some plant species have become highly specialised and are restricted to alkaline Ca-rich soils and are referred to as calcicolous flora or calcicoles (De Silva, 1934; Cowling & Holmes, 1992; Kruckeberg, 2002; Zietsman & Bredenkamp, 2006). In contrast, calcifugous plants (calcifuges) associated with sandy acidic soils deficient in Ca, Mg and K, and rich in metals such as Al and Fe, have also developed through edaphic specialisation (De Silva, 1934; Lee, 1999). Consequently, calcifuges developed metal tolerance or exclusion mechanisms to overcome metal toxicity (Lee, 1999; Mossor-Pietraszewska, 2001; Gupta *et al.*, 2013; Rout & Sahoo, 2015). Thus, the calcicolous alkaline plant community (Ghaap Plateau) was different from the calcifugous acidic communities associated with Fe-rich ironstones (Asbestos- and Kuruman Hills) and quartzites (Langberg) that are deficient in Ca and Mg.

5.4.3. Herbaceous diversity and vegetation structure

The herbaceous plant community of the quartzitic Langberg was species-poor and less diverse, but with evenly distributed species. These diversity patterns coincide with studies conducted on various quartzitic systems (Schmiedel, 2002; Conceição *et al.*, 2007; Ozkan *et al.*, 2009; Silva *et al.*, 2019). Soil properties that acted as drivers of herbaceous diversity patterns of the Langberg were related to the dystrophic, acidic and sandy nature of the soil (Schmiedel *et al.*, 2015; Silva *et al.*, 2019). The herbaceous layer was well developed with tall growing grass species (Figure 5.10a), including *Brachiaria nigropedata* (Ficalho & Hiern) Stapf, *Digitaria eriantha* Steud., *Eragrostis chloromelas* Steud. and *Melinis repens* (Willd.) Zizka. These grass species are adapted to persist in the harsh environmental conditions associated with the Langberg and are also tolerant to drought and Al (Mutimura & Everson, 2012; Xavier & D'Antonio, 2017; Nyeleti & Mashau, 2020; Tropical Forages, 2020). Furthermore, in terms of herbaceous density, the steep slopes were sparsely vegetated, a consequence of the acidic sandy nature of quartzites, high Al concentrations and many patches of bare soil and rocks.

With reference to life form groups, forbs were underrepresented in the herbaceous layer due to the lower rainfall associated with the Langberg. In contrast, lignified forbs were tall with wide canopy areas. *Evolvulus alsinoides* (L.) L., an indicator species (Van Staden *et al.*, 2020), was found to be taller than one would expect with long prostrate stems that covered bare soil patches on slopes. Thus, lignified forbs on the Langberg are adapted to the harsh and stressful environmental conditions (Porembski, 2007; Fernandez-Going *et al.*, 2012; Gupta *et al.*, 2013; Fry *et al.*, 2018; Zhu *et al.*, 2019). The woody vegetation structure was characterised by tall growing shrubs and trees such as *Euclea undulata* Thunb., *Croton gratissimus* Burch., *Searsia burchelli* (Sond. ex Engl.) Moffett, *Senegalia mellifera* (Vahl) Seigler & Ebinger and *Tarchonanthus camphoratus* L. with wide canopies (Figure 5.10a). Since the Langberg has a high sand content, soils are more aerated and therefore the water holding capacity is low. Some woody plants have deep root systems that are able to exploit deeper water sources in savanna systems (Walker *et al.,* 1981; Scholes & Archer, 1997; Zhou et al., 2020). However, soils are shallow on the Langberg, suggesting that shrub and tree species have shallower rooting systems that enable them to rapidly exploit water after a rainfall event (Scholes & Archer, 1997; Zhou *et al.,* 2020). Both *C. gratissimus* and *S. mellifera* are known to be hardy drought-tolerant plants with shallow root systems, enabling these plants to grow successfully on the xeric quartzites (Useful Tropical Plants, 2019; Wild Flower Nursery, 2020). The soil is Fe deficient, since Fe^{3+} has a low solubility and availability to plants. However, it is suggested that woody plants have developed mechanisms to persist in these soils e.g. to solubilise Fe^{3+} by secreting phenolics and promote Fe-uptake through the roots (Rout & Sahoo, 2015).

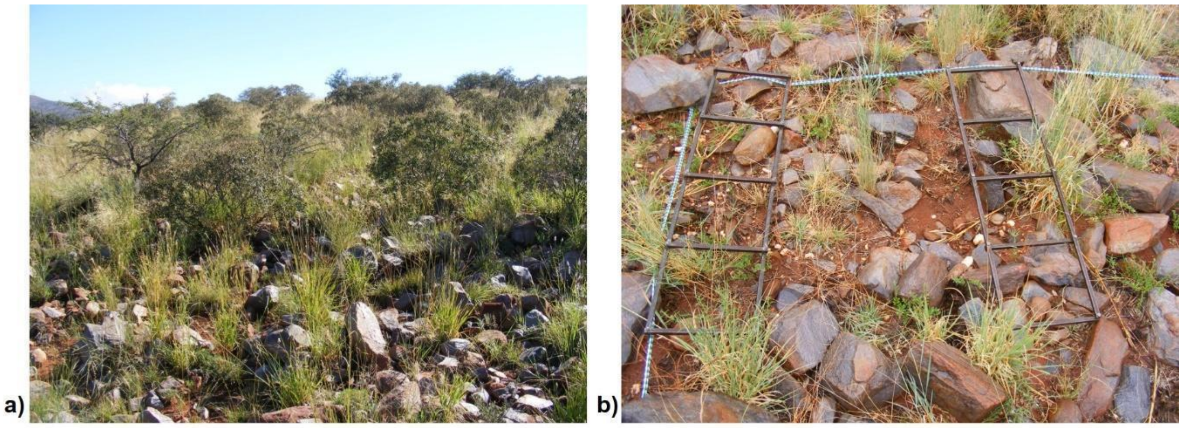

Figure 5.10. The plant community structure of the dry Langberg, a) tall growing *Brachiaria nigropedata* between rocks with *Croton gratissimus* and *Senegalia mellifera* shrubs, and b) the sparsely vegetated slopes with high rock and bare soil cover.

Ironstone communities harboured species rich and diverse plant communities (Jacobi *et al.*, 2007; Markey & Dillon, 2011; Gibson *et al.*, 2012; Do Carmo & Jacobi, 2016; Robinson *et al.*, 2019). Furthermore, the herbaceous layer was not dominated by specific herbaceous species which contributed to diversity (Do Carmo & Jacobi, 2016). In general, diversity patterns on the ironstone hills were driven by Fe, CEC and Al. In contrast to Nunes *et al.* (2015), this study identified Fe as the main driver of not only compositional differences but also of diversity patterns in the ironstone hills. This suggests edaphic filtering due to high Fe content and, hence, the presence of edaphic plant specialists (Gibson *et al.*, 2015; Do Carmo & Jacobi, 2016; Do Carmo *et al.*, 2018). Especially considering that both ironstone plant communities had slightly acidic soils, plant species may be prone to metal toxicity (Vincent & Meguro, 2008). However, more studies are needed to investigate the metalliferous nature of plant species growing in these two ironstone plant communities in GW. The specialised species may either be tolerant to metals, heavy metal excluders or accumulators (Porto & Silva, 1989; Jacobi *et al.*, 2007), physiological and morphological studies will be able to confirm their adaptive mechanisms.

Soil fertility, based on CEC values, on the ironstones was higher than the quartzites, as more nutrients are available to plants (higher pH) that contributed to high species richness and diversity (Brown & Lemon, 2020). Regarding plant community structure, the two ironstone plant communities differed (Figure 5.11) despite having the same vegetation type (Rutherford *et al.*, 2006). The herbaceous layer of the drier Asbestos Hills was shorter than the wetter Kuruman Hills (Figure 5.11a, c), which emphasised the role of rainfall as a major driver of herbaceous layer dynamics in semi-arid savannas (Skarpe, 1992; Buitenwerf *et al.*, 2011; Van Coller *et al.*, 2018). Aluminium content was lower on the Kuruman Hills and therefore herbaceous plant height on ironstones are also promoted by lower total Al content. This finding implies that Al is a limiting soil factor on the Asbestos Hills. This may be ascribed to heavy metal toxicity that causes smaller plants (dwarfism) (Porto & Silva, 1989; Bojórquez-Quintal *et al.*, 2017).

Similar to the dry Langberg, the less arid Asbestos Hills also had low cover and frequency of forbs in contrast to the less xeric mountain systems with higher rainfall. This confirms the role of rainfall variability between the mountain systems that contribute to vegetation structure in combination with edaphic conditions (Jenny, 1941; Kruckeberg, 1969; Siefert *et al.*, 2012). As a result, the herbaceous layer was more developed on the wetter Kuruman Hills compared to the drier Asbestos Hills (Figure 5.11b, d). Lignified forbs were found to be taller with wider canopy areas on the Kuruman Hills. Increased lignified forb height can be due to the less xeric conditions and that this life form group is competing with grasses for sunlight, which in turn enhances the height of the forb layer (Grime, 1973; 1977). In contrast to their northern counterparts, lignified forbs of the Asbestos Hills were smaller in stature and canopy area. These species included *Chascanum pinnatifidum* (L.f.) E.Mey., the endemic *Glossochilus burchellii* Nees, *Leucas capensis* (Benth.) Engl. and *Sida chrysantha* Ulbr.

Regarding woody structure, the two ironstone plant communities differed in their frequencies of shrubs with the Asbestos Hills characterised by a more conspicuous shrub layer (Figure 5.11a, c). Woody species that were frequently encountered on the Asbestos Hills included *Euryops subcarnosus* DC., *Searsia ciliata* (Licht. ex Schult.) A.J.Mill., *T. camphoratus* and *T. obovatus* DC. and the Kuruman Hills with *Ehretia rigida* (Thunb.) Druce, *Euclea undulata*, *Searsia tridactyla* (Burch.) Moffett and *T. camphoratus*.

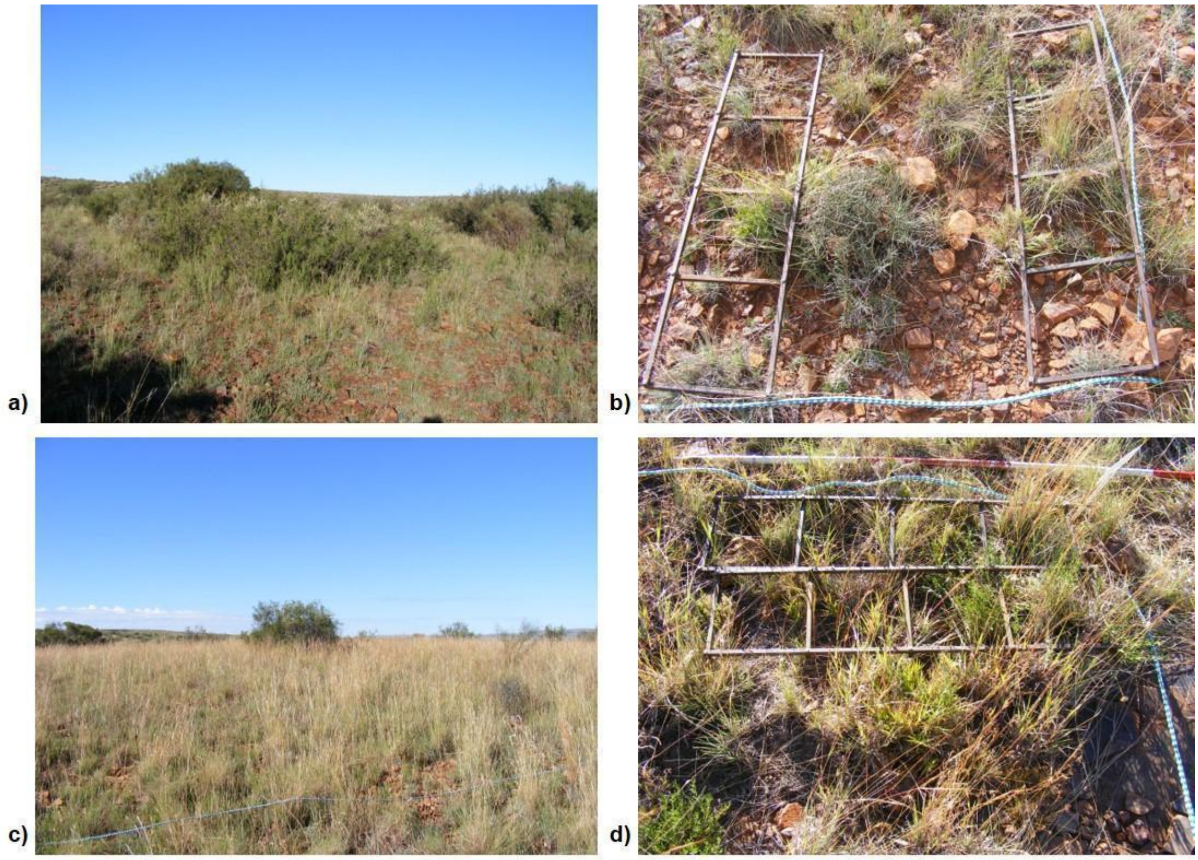

Figure 5.11. Plant communities of the two ironstone mountains, a) and b) vegetation structure of the drier Asbestos Hills with lower herbaceous plant height and higher bare soil and rock cover compared to the wetter Kuruman Hills, c) and d).

The Ghaap Plateau harboured species rich communities that were primarily driven by soil pH and Ca (Willis *et al.*, 1996; Reinhardt *et al.*, 2013; Molano-Flores *et al.*, 2015). Species richness of the Ghaap Plateau was similar to the ironstones yet with lower diversity due to the dominance of small growing indicator species (Stirling & Wilsey, 2001; Wilsey & Stirling, 2007), i.e. *Bulbostylis humilis* (Kunth) C.B.Clarke, *Enneapogon desvauxii* P.Beauv., *Oropetium capense* Stapf, *Oxalis depressa* Eckl. & Zeyh. and *Tragus racemosus* (L.) All. (Van Staden *et al.,* 2020). These small herbaceous species were densely distributed and are considered to be adapted to grow in rocky, shallow, alkaline soils with high lime content (Gordon-Gray *et al.*, 2009; Adhami *et al.*, 2012; Fouché *et al.*, 2014; Koekemoer *et al.*, 2014; Fish *et al.*, 2015; Cohen *et al.*, 2020; World Flora Online, 2020). Rock cover was limited to fragments of weathered dolomite and black mudstone pebbles but with more patches of bare soil than the ironstone hills. Lignified forb species on the Ghaap Plateau were shorter with narrower canopy areas. This reduction in growth is related to the higher Ca content of the soil (Burström, 1968; White & Broadley, 2003; Hepler, 2005). Additionally, plant growth can be limited on alkaline soils due to nutrient deficiencies caused by the binding of nutrients in the soil by free carbonates (Adcock *et al.*, 2007; Silva *et al.*, 2018). Indicator lignified forbs included *L. argute-carinatum* Wawra ex Wawra & Peyr. and *Limeum fenestratum* (Fenzl) Heimerl (Van Staden *et al.*, 2020) as well as the frequently encountered endemic, *Blepharis marginata* (Nees) C.B.Clarke..

The shrub layer of the Ghaap Plateau was characterised by shrub species with reduced plant height (in comparison with the Langberg and ironstone hills) and canopies (compared to the Langberg and Asbestos Hills). Such shrub species included *Asparagus suaveolens* Burch., *Gymnosporia buxifolia* (L.) Szyszyl. and *S. ciliata* with taller tree species, i.e. *Olea europaea* L. subsp. *africana* (Mill.) P.S.Green and *S. lancea* (L.f.) F.A.Barkley with wider canopies. One of the most conspicuous tree species in the landscape of the Ghaap Plateau is *O. europaea* subsp. *africana*, with large specimens forming forests in some parts (Figure 5.12a). The woody species are therefore considered adapted to grow on Ca and Mg-rich soils that are usually deficient in Fe and P. Iron is an essential micronutrient that regulates plant growth since it fulfils a vital role in metabolic processes (Rout & Sahoo, 2015). Despite being abundant in soil, Fe is generally in an insoluble form, especially in carbonate soil (Morrissey & Guerinot, 2009; Zhang *et al.*, 2019). Consequently, plants developed strategies to overcome Fe deficiencies that include Fe storage in plant cells, transportation of Fe from roots to shoot, acquisition of Fe and Fe sensing (Morrissey & Guerinot, 2009; Zhang *et al.*, 2019). Calcicoles are efficient by extracting these elements from recalcitrant pools that contribute to their ability to flourish in these soils (Tsai & Schmidt, 2017). Therefore, the associated plant species can be considered to be adapted to edaphic conditions associated with carbonate soils to promote their growth and hence contribute to a well-developed tree layer (Figure 5.12a). The herbaceous layer was under-developed, but with higher densities and with higher herbaceous forb cover and bare soil (Figure 5.12b).

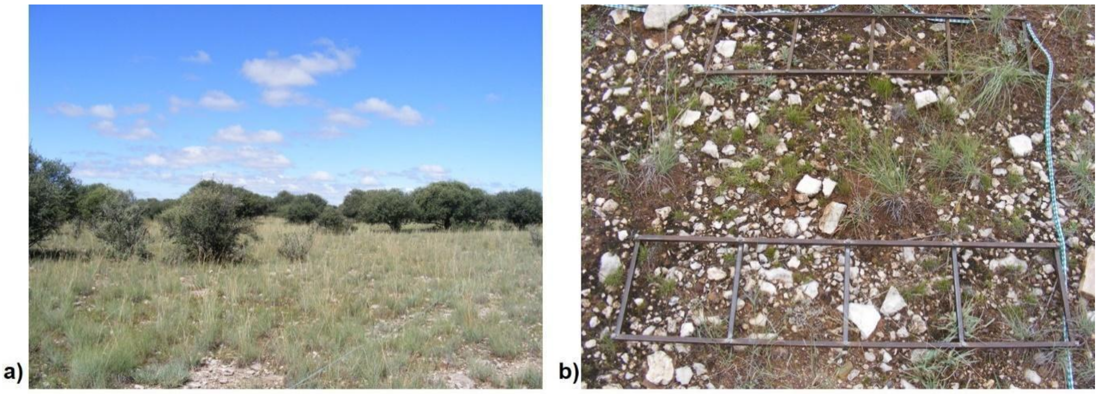

Figure 5.12. The vegetation structure associated with the wetter Ghaap Plateau, a) abundant *Olea europaea* subsp. *africana* individuals in the woody layer and b) exposure of the darker textured bare soil with weathered dolomite pebbles that can be seen together with the presence of the densely populated herbaceous layer consisting of small specimens of *Enneapogon desvauxii* and *Bulbostylis humilis* between rocks.

5.5. Summary

Mountains differed in terms of soil properties and rainfall. Plant community composition was driven by certain edaphic factors as well as rainfall, especially considering that despite being on the same geology, the Kuruman Hills and Asbestos Hills each differed in their composition. Plant diversity, frequency of grasses, lignified forbs, trees, woody plant height and -canopy area of mountain plant communities were driven by soil properties *per se.* In contrast, a combination of rainfall and soil properties driven herbaceous density, -plant height, cover and shrub frequencies between mountain ecosystems. The two ironstone mountain ecosystems hosted the most diverse plant communities, whilst the dolomitic Ghaap Plateau was the most species rich. The quartzite plant community of the Langberg harboured less species. Thus, edaphic filtering effects are evident with plant species that are adapted to flourish in associated edaphic conditions of each geological substrate. As a result, calcicolous flora was associated with the dolomites, and calcifugous with ironstone and quartzite. Mountains in GW, with their specific geologies, are indeed functioning as edaphic islands, which harbour unique plant communities with a specific set of structural characteristics. Grass-, and herbaceous forb cover increased on the wetter mountains while shrub frequencies increased on the drier mountains. It can therefore be concluded that spatial turnover associated with the mountain plant communities, within a semi-arid savanna landscape, are driven by rainfall and geology.

This study was the first to disentangle plant-soil-climate relationships in the mountain plant communities in GW. Results from this study have the potential to serve as a baseline for future long-term monitoring studies on the distinct plant communities of the mountains of GW. Ecological modelling studies can be conducted to establish how these edaphic floras of each mountain system will be impacted by direct and/or indirect climate change impacts. Lastly, management and conservation policies can be informed in order to maintain the unique diversity of these systems to safeguard ecosystem functioning and services provided by these mountains in GW.

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Chapter 6

Diversity-biomass relationships

6.1. Introduction

Mountain ecosystems are increasingly becoming vulnerable to effects of global change as they are fragile, high diversity ecosystems (Gottfried *et al.*, 2012; Chakraborty, 2019; Niu *et al.*, 2019; Pringle, 2019), which differ from lower altitude valleys in terms of vegetation structure and function (Carter & Floyd, 2013; Bai *et al*., 2014; Cassardo *et al*., 2018). Plant species growing mountain ecosystems are particularly sensitive to seasonal shifts and variation in intensity of rainfall and temperature patterns which could lead to drought- and thermal stress (Rutherford *et al.*, 1999; Rutherford *et al.*, 2000). According to the insurance hypothesis, diversity buffers ecosystems against environmental fluctuations (Yachi & Loreau, 1999) and diversity contributes to ecosystem productivity and the provisioning of important ecosystem services (Grêt-Regamey *et al.*, 2012; Egan & Price, 2017; Tito *et al*., 2020). Sustainable management of species diversity, particularly in these ecologically important mountainous ecosystems is therefore considered valuable and necessary. Global climate change has adverse effects on herbaceous species and functional diversity, which inherently leads to reduced plant productivity (Xu *et al.,* 2018). Such patterns are particularly evident under increased temperatures, inter-annual variability and lower mean annual precipitation (MAP) which have been reported for semi-arid savanna rangelands (Lohmann *et al.,* 2012). Climate-induced reductions in diversity and biomass and, hence in livestock forage stability, may lead to increased economic pressure on human livelihoods (Egan & Price, 2017).

The Northern Cape province in South Africa was declared a disaster area due to a prolonged extreme drought event in 2018 (Tandwa, 2018). Future climate scenarios predict increased temperatures combined with lower rainfall (DEA, 2013). To assist rangeland management and promote rangeland stability under variable future climates (DEA, 2013; Van Wilgen *et al*., 2016; Tfwala *et al*., 2018; Tokura *et al*., 2018), it is important to understand diversity-biomass relationships in drought-prone ecosystems. Semi-arid savanna rangelands along mountain ecosystems in Griqualand West (GW) are underrepresented in African ecological studies. Yet, these systems largely contribute to the overall phytodiversity of the area and maintain numerous commercial and rural livestock farmers. Griqualand West mountain rangelands represent a soil nutrient- and rainfall gradient from the dystrophic, drier west to the eutrophic, moister east. Soil nutrients and rainfall are considered important drivers and/or environmental filters on species pools within these mountain rangelands (Van Staden *et al.*, 2020), and are known to strongly influence diversity and ecosystem productivity (Loreau *et al.*, 2001; Kahmen *et al.*, 2005; YuKun *et al.*, 2009; Zuo *et al.*, 2012).

The aim of this chapter was therefore to assess whether soil properties and rainfall act as drivers of biomass production and diversity-biomass relationships at regional (all mountains combined as a representation of the GW region) and local (each mountain alone) scale for GW mountain rangelands. Since herbaceous life-forms are known to respond differently to rainfall and soil (Van Coller *et al.*, 2018), we furthermore present plant functional group (PFG)-specific diversity-biomass relationships with species-specific dominance at different biomass productivity levels. The objectives were to (i) test for differences in total biomass production (above ground green plant material and debris), live biomass production (only live green above ground plant material) and respective PFG biomass production between the four mountain rangelands, (ii) relate differences in biomass production between mountain rangelands to specific soil properties and rainfall as to identify the strongest driver of biomass production, (iii) investigate diversity-biomass relationships for total plant species and for species representing different PFGs and (iv) present an optimal range of biomass production at which herbaceous species diversity can be maintained at regional scale.

6.2. Materials and methods

Please refer to Chapter 2 (Sections 2.6 and 2.7) for detailed information regarding biomass sampling, collection of soil samples and laboratory analysis thereof.

6.2.1. Data analysis

Weighed biomass was converted from g/m^2 to kg/ha. Total species counts per 1 m^2 subplot were used to calculate species richness, Pielou's evenness, Shannon Diversity index (hereafter referred to as Shannon diversity or diversity) and Simpson Diversity index in PRIMER 6 (2012) for each Modified Whittaker plot for total species and PFGs. Diversity measures for total species, PFGs, biomass production (total, live and per PFG) and environmental data (rainfall and soil properties) were tested for normality, using the Lilliefors and Shapiro-Wilk tests. If data violated assumptions of normality, data was log-transformed [log(x+1)]. Where assumptions of normality were met, one-way Analysis of Variance (ANOVA) was conducted to test for significant variance among mountain ranges. To test for significant differences in variables between mountain ranges, Tukey's post-hoc Honestly Significant Difference (HSD) test was performed. When assumptions of normality were still violated despite transformations, non-parametric Kruskal-Wallis ANOVA by Ranks, followed by post-hoc tests for two-tailed multiple comparisons of mean ranks for multiple independent groups were performed.

To determine relationships between biomass production, soil characteristics and rainfall as drivers across mountain ranges, multiple linear regression models with forward selection procedures were performed on log-transformed data, with the exception of pH. Relationships were tested by performing separate regression models for total-, live and PFG biomass. These relationships were then visualised using redundancy analysis (RDA) in CANOCO version 5 (Šmilauer & Lepš, 2014).

Relationships between biomass and each diversity measure for total species and for each respective PFG were analysed using linear correlation matrices. When relationships were non-linear and followed a curve linear relationship, Locally Weighted Scatterplot Smoothing (LOWESS) was fitted to the data. LOWESS is a non-parametric regression analysis that combines least-square regression and non-linear regressions to examine relationships between two variables (Trexler & Travis, 1993; Gijbels & Prosdocimi, 2010). The stiffness of LOWESS regression lines was set to 0.35 to improve the visual representation of the relationship. Biomass data were square transformed ($BIOM^2$) ensuring equal variance between dependent and independent variables, and to account for heterogeneity. Thus, linearity was ultimately improved (Axmanová *et al.*, 2012). All other analyses were performed in STATISTICA version 13.3 (TIBCO Software Inc., 2017).

Where PFG diversity measures peaked at certain biomass production levels, subplots with the highest grass, herbaceous forb and lignified forb biomass were extracted from the main abundance dataset. Species within each PFG of the extracted subplots were subsequently sorted based on their abundance to identify dominant species associated with such biomass peaks. To establish the contribution of each PFG to biomass and species richness (total number of species sampled per mountain ecosystem, i.e. cumulative species richness), the values of these two variables were calculated separately for each respective PFG.

6.3. Results

6.3.1. Biomass production across mountain rangelands

Significant differences were revealed for total biomass (including live herbaceous biomass and debris) ($F=8.9$, $p<0.001$; Table 6.1) and live biomass (only live and green plant material) ($F=5.0$, $p=0.004$; Table 6.1) between mountain ecosystems. Similarly, to results discussed in Chapter 5 (Figure 5.3), a clear rainfall gradient could be observed along the mountain rangelands with a decreasing aridity gradient from the Langberg to the Ghaap Plateau. The two driest mountain ecosystems (i.e. the Langberg and Asbestos Hills) differed in total biomass production and debris. The drier Langberg was characterised by plant communities with higher total biomass ($p=0.001$; Table 6.1) and debris production ($p<0.001$; Table 6.1) than the Asbestos Hills. Contrary to what was expected, the wettest system (i.e. the Ghaap Plateau) was associated with lower total biomass ($p<0.001$; Table 6.1) and debris ($p<0.001$; Table 6.1) than the dry Langberg. In contrast, when debris was excluded, live biomass production on the Kuruman Hills was significantly higher than the dry Langberg ($p=0.0018$;

Table 6.1) and Ghaap Plateau (p=0.005; Table 6.1). Therefore, for further analyses, only live biomass (hereafter referred to as biomass) was considered to compare the same season's production, except for the regional diversity-biomass relationships. The inclusion of debris was problematic as stocking rate and fire histories could not be determined accurately.

Grass and lignified forb biomass largely contributed to higher biomass levels on the ironstone hills (Table 6.2), whereas herbaceous forb biomass was significantly higher on the wetter Kuruman Hills and Ghaap Plateau compared to the drier Langberg and Asbestos Hills (Table 6.2). Grasses and lignified forbs contributed mostly to biomass production on the two drier mountain rangelands (Table 6.2). Generally, lignified forbs contributed the most to species richness in each mountain rangeland, followed by grasses and herbaceous forbs (Table 6.2), which contributed only a small proportion of total biomass (Table 6.2).

6.3.2. Environmental drivers of biomass patterns

Soil physiochemical properties varied significantly across GW mountain ranges (see Chapter 5, Table 5.1). Multiple regression models which included MAP and soil characteristics revealed that live biomass correlated positively with MAP (p=0.045, Table D1; Appendix D) and negatively with pH (p<0.001, Table D1). This suggests that as rainfall increased, biomass also increased whereas with increasing pH, biomass decreased. These two explanatory variables accounted for 32.1% of the total variation in the RDA. The first axis was correlated with biomass production and soil pH, whereas the second was associated with rainfall (Figure 6.1). Higher and lower biomass production associated with the Kuruman Hills and Langberg, respectively, was confirmed by RDA analysis which was linked to rainfall (Figure 6.1). The alkaline Ghaap Plateau (pH>7) and acidic Langberg (pH<5) clustered separately from the ironstone hills since the former and latter were associated with low yet similar biomass production.

Table 6.1. Mean biomass production (kg/ha) and species diversity measures (total and within PFGs) (mean±SD) of mountain rangelands. Different lowercase letters in the same line denote significant differences as determined by pairwise tests ($p<0.05$).

	Langberg	Asbestos Hills	Kuruman Hills	Ghaap Plateau	F	χ^2	P
Total	7805.2±4843.3^{a}	3818.4±2223.9^{b,c}	6451.6±3578.9^{a,c}	2782.8±1081.4^{b}	8.9		<0.001
Debris	6935.0±4534.7^{a}	2692.3±1896.2^{b,c}	5043.3±3308.1^{a,c}	1991.5±850.2^{b}	9.2		<0.001
Live	870.2±537.7^{a}	1126.2±634.4^{ab}	1408.3±429.3^{b}	791.3±346.9^{a}	5.0		0.004
Grasses	733.7±475.7^{a}	816.4±565.2^{ab}	1052.4±391.6^{b}	623.7±221.2^{a}	3.1		0.034
Lignified forbs	126.8±231.1^{a}	302.0±337.2^{b}	303.1±±246.8^{b}	134.8±293.2^{a}		15.6	0.001
Herbaceous forbs	9.7±15.5^{a}	7.7±7.3^{a}	52.8±42.0^{b}	32.5±41.8^{b}	9.4		<0.001

Table 6.2. Summary of proportions of each PFGs (%) contribution to total herbaceous species biomass (kg/ha) and richness (number of species) per mountain ecosystem.

	Langberg	Asebestos Hills	Kuruman Hills	Ghaap Plateau
Biomass (cumulative)				
All	13 923.2	18 017.6	22 532.3	12 655.4
Grass	11 738.4 (84.3%)	13 063.1 (72.5%)	16 837.7 (74.7%)	9 978.7 (78.9%)
Lignified forbs	2 029.2 (14.6%)	4 832.0 (26.8%)	4 849.2 (21.5%)	2 156.1 (17.0%)
Herbaceous forbs	155.6 (1.1%)	122.5 (0.7%)	845.4 (3.8%)	520.6 (4.1%)
Species richness (cumulative)				
All	55	70	69	76
Grass	19 (34.6%)	19 (27.1%)	23 (33.3%)	23 (30.3%)
Lignified forbs	26 (47.3%)	39 (55.7%)	36 (52.2%)	34 (44.7%)
Herbaceous forbs	10 (18.2%)	12 (17.1%)	10 (14.5%)	19 (25.0%)

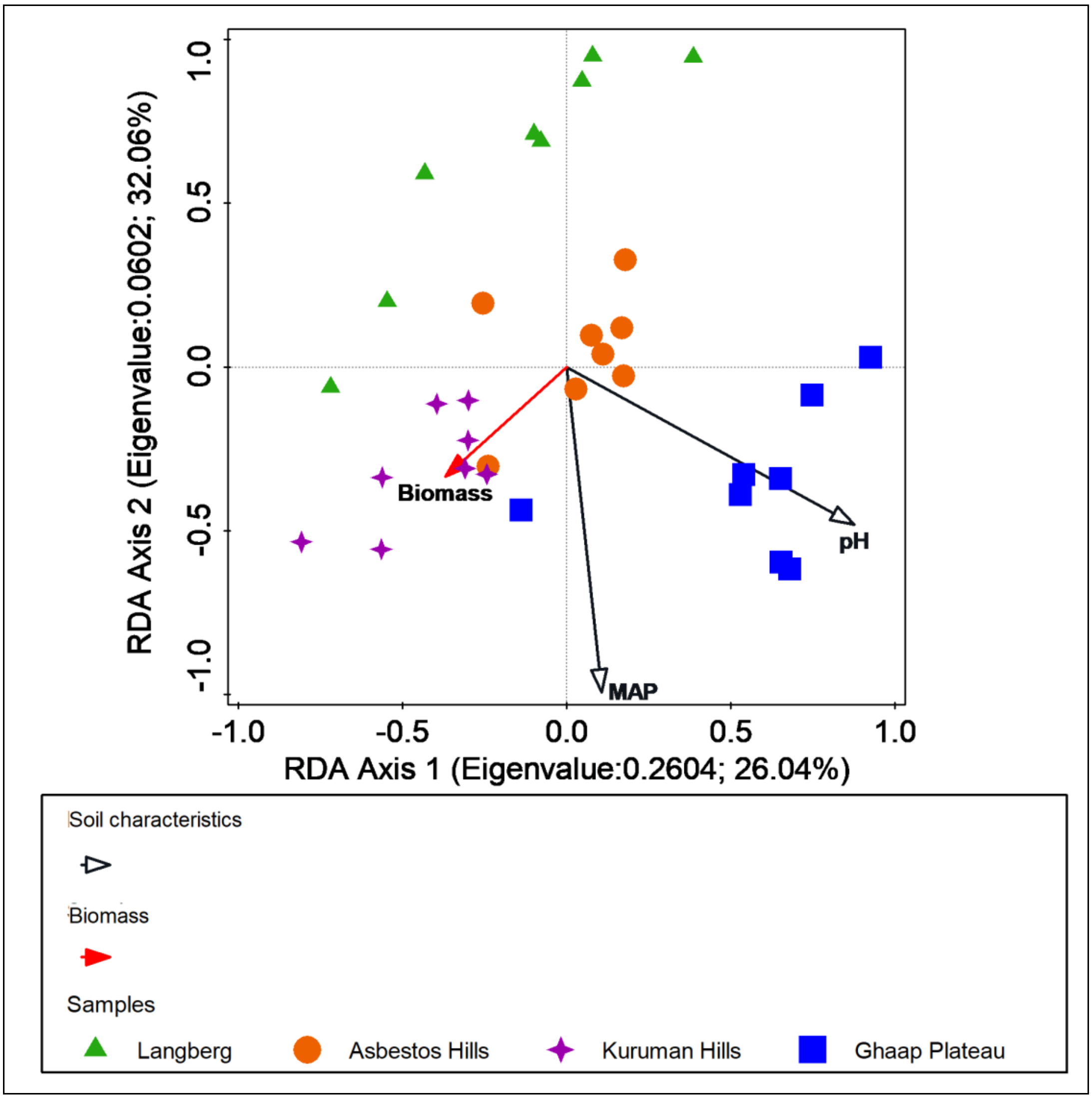

Figure 6.1. Redundancy analysis (RDA) of live biomass with significant soil characteristics. *MAP,* Mean annual precipitation.

Rainfall correlated positively and highly significantly with grass- (p=0.001; Table D1) and herbaceous forb biomass (p=0.002; Table D1). Soil pH correlated strongly with the biomass production of these two PFGs, however this these correlations were negative (p<0.05; Table D1). Lignified forb biomass revealed different responses and was not correlated with rainfall, but rather with CEC (p=0.012, Table D1) and pH (p=0.025; Table D1). With increasing CEC, lignified forb biomass increased, whereas biomass decreased as pH increased. The RDA consisting of a combination of PFG biomass and their drivers explained 18.3% of the total variation (Figure 6.2). The first axis of the RDA was associated with an aridity gradient and grass biomass production, whilst the second with CEC and lignified forb biomass. High grass- and lignified forb biomass associated with the Kuruman Hills seemed to be driven by higher rainfall and CEC (Figure 6.2). The decrease associated with grass and lignified forb production revealed for the Langberg is linked to the drier climate and lower CEC associated with this rangeland ecosystem (Figure 6.2). Low biomass production of grasses and lignified forbs revealed for the Ghaap Plateau is suggested to be associated with alkalinity. From the results, it is evident that herbaceous forb biomass is strongly linked to higher rainfall on the Ghaap Plateau (Figure 6.2).

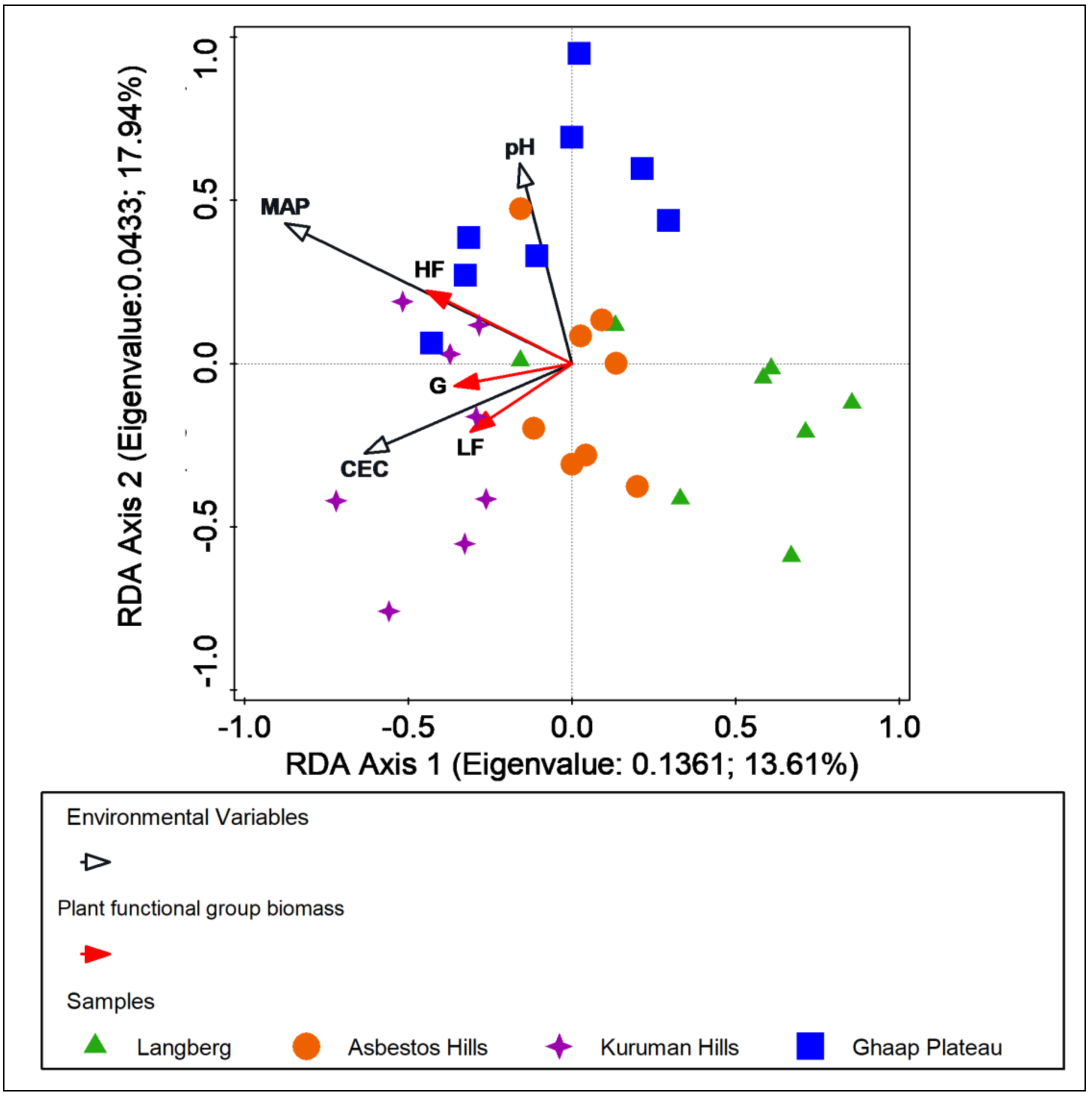

Figure 6.2. Redundancy analysis (RDA) of PFG biomass with significant soil characteristics. G - grass; HF - herbaceous forb; LF - lignified forb. of live biomass with significant soil characteristics. *MAP,* Mean annual precipitation; *CEC*, Cation Exchange Capacity.

6.3.3. Diversity-biomass relationships at regional and local scales

At a regional scale, total species richness- and evenness- biomass relationships were non-linear for both live- and total biomass (Figures 6.3 a-d; Table D2). Total species richness increased from 200 kg/ha reaching a peak at 600 kg/ha (Figure 6.3a). Between these biomass levels, each mountain rangeland displayed positive linear relationship between total richness and biomass production and, hence contributed to the regional relationship (Figures D1a, D2a, D3a and D4a; Table D3; Appendix D). The decrease in species richness above 600 kg/ha up to approximately 800 kg/ha (Figure 6.3a) could be linked to the decrease in species richness revealed for the Langberg (Figure D1a). The linear increase above 1 800 kg/ha was related to the positive linear species richness-biomass relationship of the Kuruman Hills (Figure D3a). Furthermore, considering total biomass, peaks were identified for all four diversity measures that increased from 2 000 kg/ha, reaching peaks at approximately 3000 kg/ha, after which a steady decline up to 5 000 kg/ha was evident (Figure 6.3). At a total biomass production of 5 000 kg/ha and above diversity measures reached a plateau and declined above 10 000 kg/ha. In addition, species diversity measures within PFGs were also associated with similar decreasing trends in diversity measures at total biomass levels of 10 000 kg/ha (Figures 6.4-6.6).

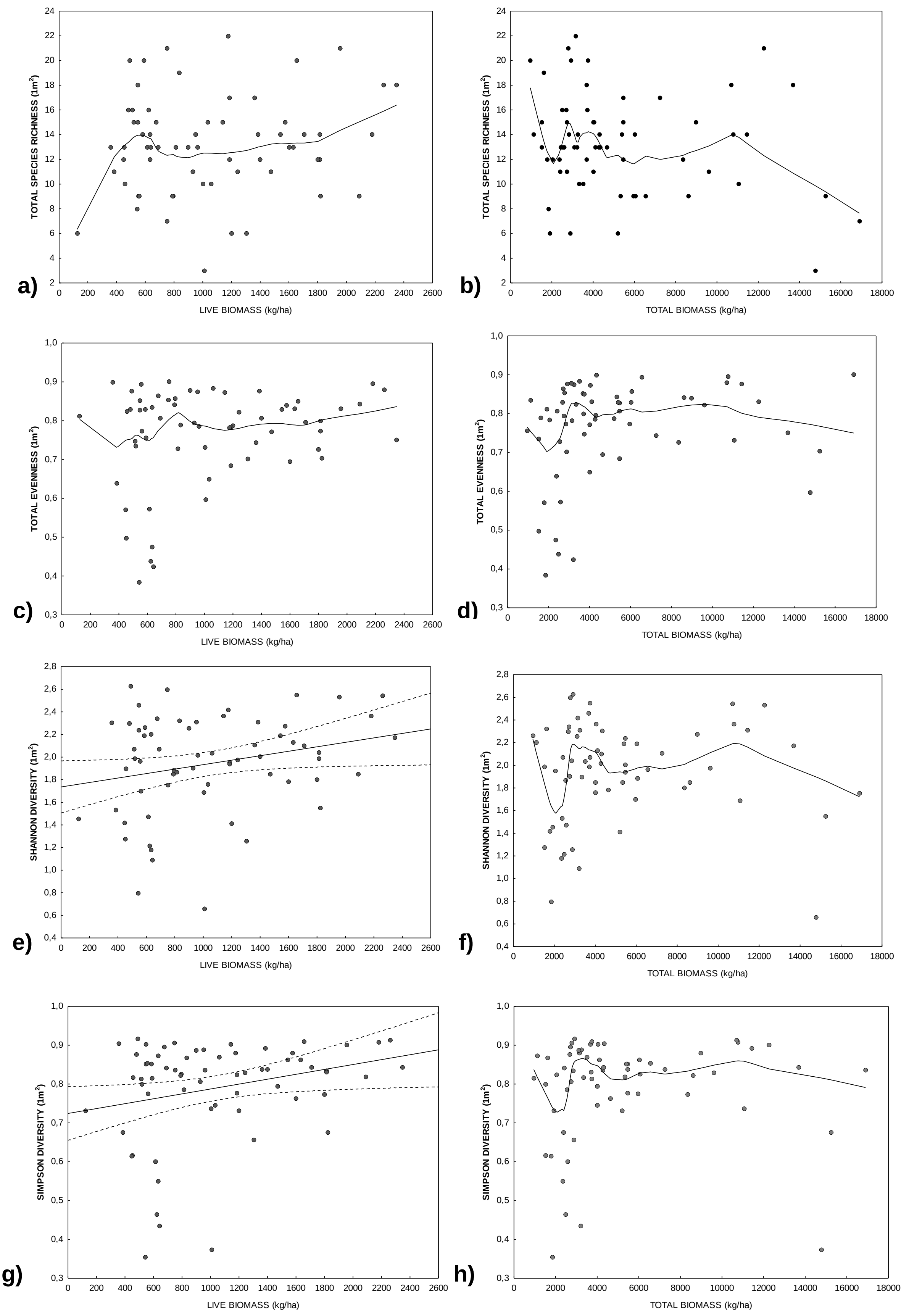

Figure 6.3. Live- (a, c, e, g) and total biomass (b, d, f, g) diversity relationships for Griqualand West.

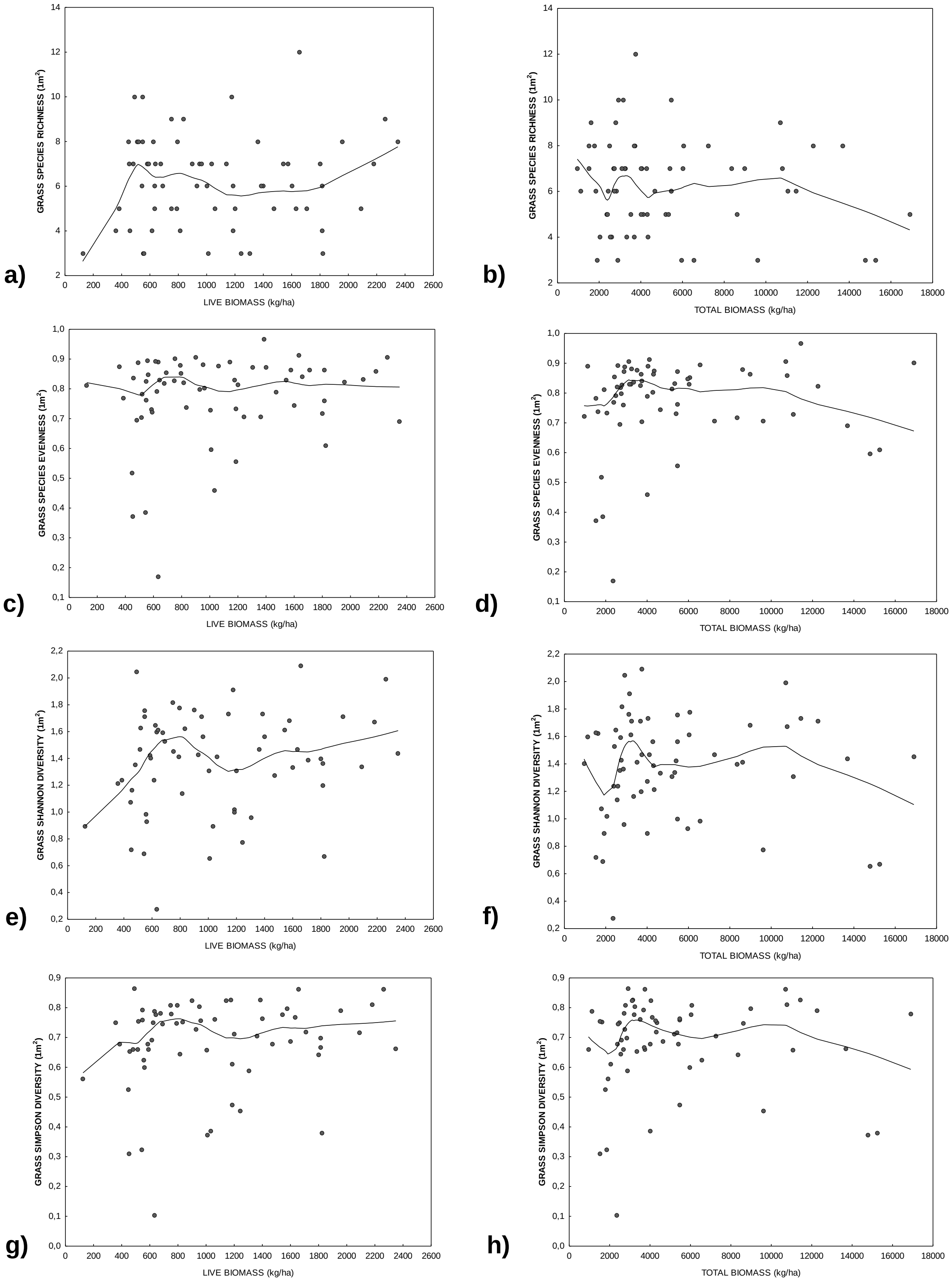

Figure 6.4. Regional grass diversity-biomass relationships associated with live- (a, c, e, g) and total biomass (b, d, f, g) production for Griqualand West.

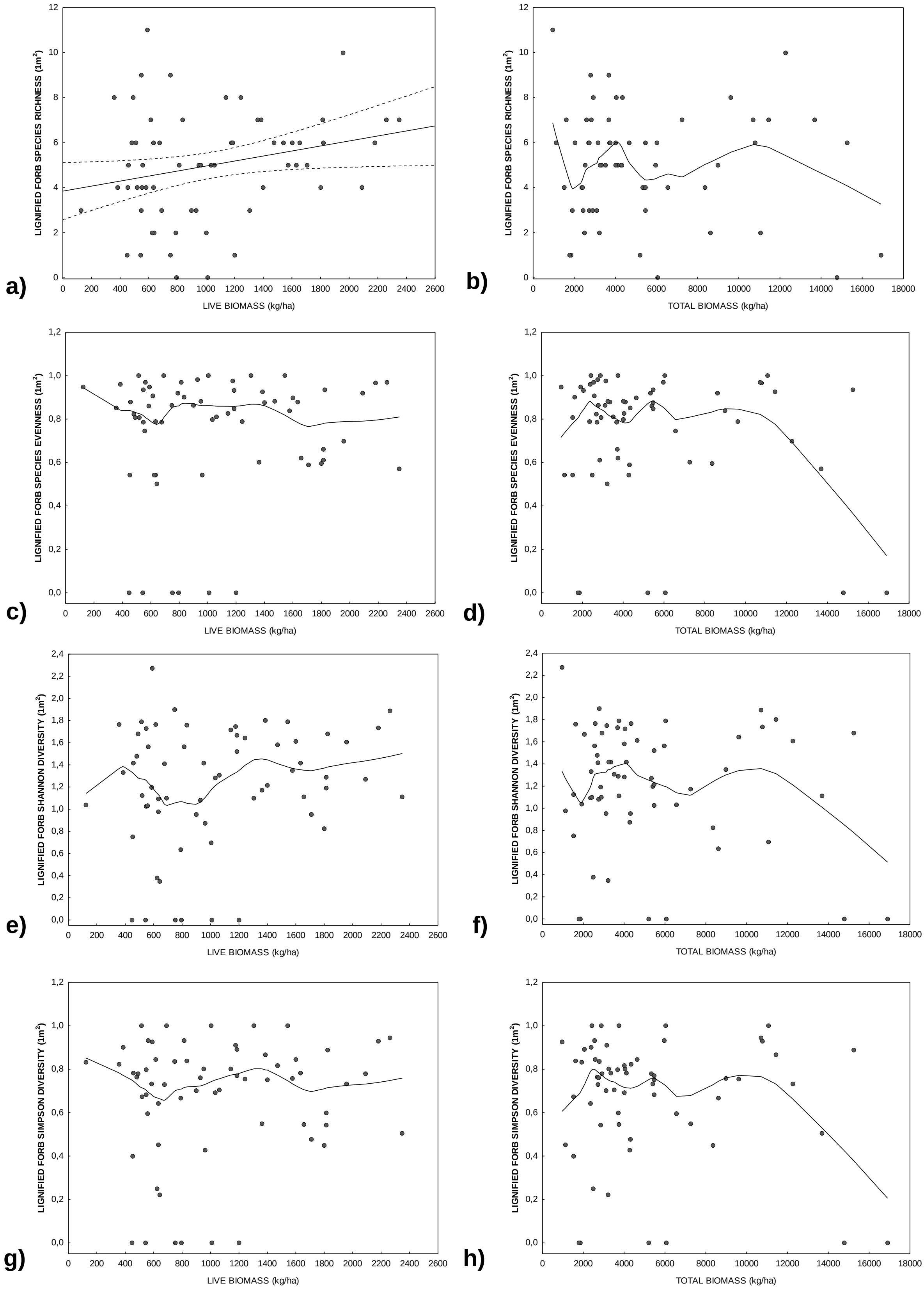

Figure 6.5. Regional lignified forb diversity-biomass relationships associated with live- (a, c, e, g) and total biomass (b, d, f, g).

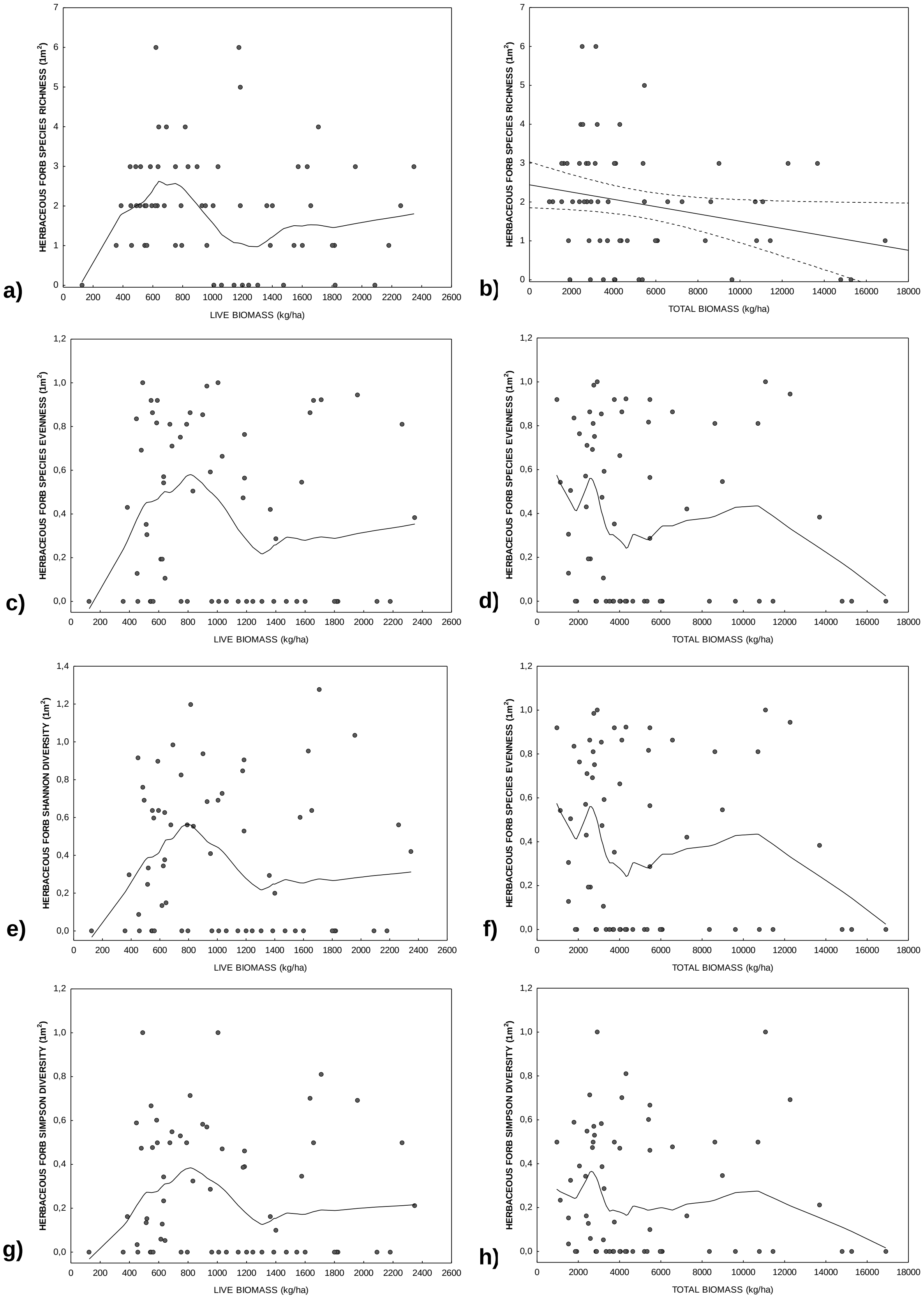

Figure 6.6. Herbaceous forb diversity-biomass relationships comparing live- (a, c, e, g) and total biomass (b, d, f, g) for Griqualand West.

Diversity-biomass relationships for PFGs and live biomass at a regional scale were primarily non-linear (Figures 6.4-6.6), with the exception of lignified forb species richness (Figure 6.5a). Locally, all diversity measures within PFGs and their relationship towards live biomass, within each mountain rangeland, responded more dynamically than at regional scale (Table D3; Figures D5-D16).

Plant communities with lower live biomass associated with the Langberg, Asbestos Hills and Ghaap Plateau (above 200-500 kg/ha) were rich in grass species. Peaks in grass evenness (Figure 6.4c), Shannon- (Figure 6.4e) and Simpson Diversity (Figure 6.4g) were revealed at 800 kg/ha. Grass Shannon Diversity increased linearly until it peaked between 650 and 800 kg/ha (Figure 6.4e), after which diversity decreased until biomass reached approximately 1 100 kg/ha. PFG-specific observations revealed that annual grasses dominated mountain rangelands when biomass levels were below 800 kg/ha (Figure 6.7), whereas perennial grass species dominated between 800 and 1 200 kg/ha (54%). Biomass production between 1 200 and 1 600 kg/ha revealed (95%) dominance of perennial grass species. Grass richness (Figure 6.4b), evenness (Figure 6.4d), Shannon- (Figure 6.4f) and Simpson Diversity (figure 6.4h) for total biomass increased from 2 000 kg/ha and peaked at approximately 3 000 kg/ha.

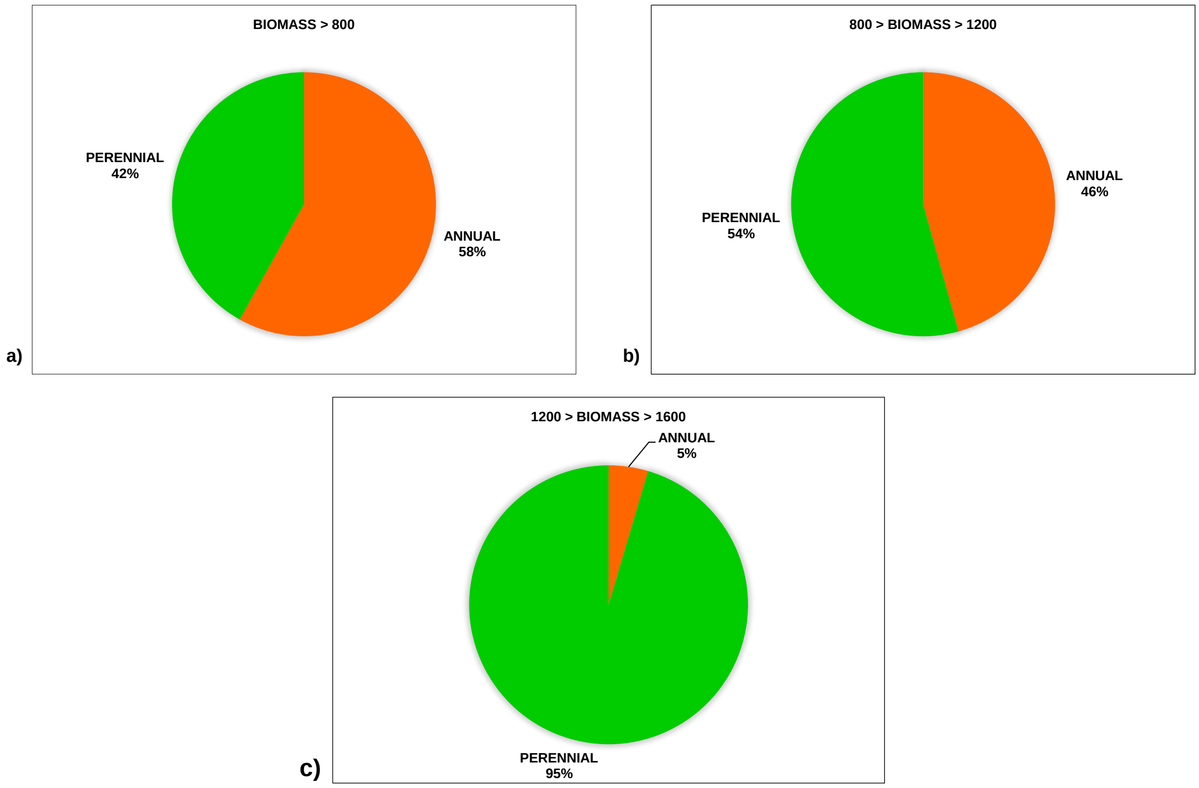

Figure 6.7. Proportion of annual and perennial grass species at a) low (125.7-795.5 kg/ha), b) intermediate (815.5-1 199.2 kg/ha) and c) high (1 242.7-1 575.3 kg/ha) biomass levels.

Lignified forb species richness in response to live biomass, was associated with a positive linear relationship, suggesting that species richness within this PFG increased with increasing live biomass yield (Figure 6.5a), whereas lignified forb richness reached peaks at 4 000 and 11 000 kg/ha when total biomass was considered (Figure 6.5b). Relationships between evenness as well as Simpson Diversity and live biomass, displayed less prominent peaks compared to those of total biomass (Figure 6.5). Decreasing relationships were associated with lignified forb evenness from 150 to 640 kg/ha. Thereafter evenness in this PFG remained relatively constant between 800-1 400 kg/ha (Figure 6.5c). For total biomass, lignified forb evenness peaked firstly at approximately 2 050 kg/ha followed by a second peak at 5 080 kg/ha (Figure 6.5d). Lignified forb diversity reached a peak at 400 kg/ha with a slightly higher second peak at 1 300 kg/ha live biomass (Figure 6.5e). In contrast, the highest diversity peak for lignified forbs and total biomass was reached at 4 000 kg/ha followed by a lower diversity peak at 11 000 kg/ha (Figure 6.5f). Similar to evenness, Simpson Diversity of lignified forbs revealed decreases between 150 and 640 kg/ha followed by an increase up to 1 380 kg/ha (Figure 6.5g). When compared to total biomass, Simpson Diversity increased between 1 000 and 2 080 kg/ha, and also displayed a slight peak at approximately 5 070 kg/ha (Figure 6.5h).

Herbaceous forb diversity-biomass relationships associated with live biomass, were hump-shaped at regional scale, whereas with regards to total biomass, linear and non-linear relationships were revealed (Figure 6.6). Richness, evenness, Shannon Diversity and Simpson Diversity of herbaceous forbs increased from live biomass levels of 150 kg/ha and upwards. Herbaceous forb richness peaked at 750 kg/ha (Figure 6.6a), whereas the other three diversity measures peaked at 800 kg/ha (Figures 6.6c, e, g). After these peaks, all herbaceous forb diversity measures decreased up to 1 300 kg/ha after which a plateau was reached at higher live biomass levels above 1 700 kg/ha (Figure 6.6c, e, g). The majority of herbaceous forb species exhibited perennial life history traits at both these two diversity peaks (Figure 6.8). Herbaceous forb species richness revealed to be sensitive to increasing total biomass production, since it showed a negative linear relationship (Figure 6.6b). Similar relationships were revealed for herbaceous forb species evenness (Figure 6.6d), Shannon Diversity (Figure 6.6f) and Simpson Diversity (Figure 6.6h) and total biomass. These diversity measures for herbaceous forbs increased from 2 000 kg/ha upward and peaked at approximately 3 000 kg/ha and decreased after this peak. In plant communities with high total biomass production herbaceous forb all diversity measures declined (Figure 6.6b, d, f, h) such as in sites of the Langberg and Kuruman Hills.

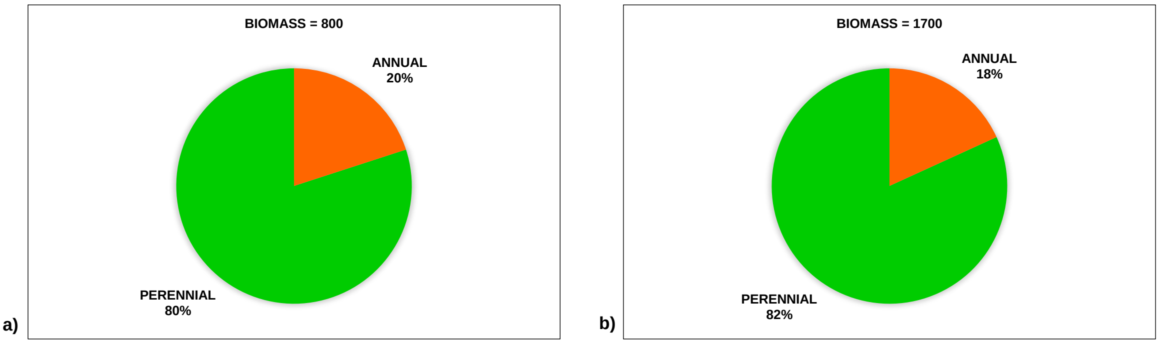

Figure 6.8. Proportion of perennial and annual herbaceous forbs at a) low (800 kg/ha) and b) high (1 700 kg/ha) biomass levels.

6.3.4. Optimum plant diversity for mountain rangelands in GW

Linear regression analysis revealed a positive relationship between biomass and total diversity (Figure 6.9a, Table D4). Species diversity index values of 1.7, 1.9 and 2.1 were maintained at lowest (125 kg/ha), intermediate (1 050 kg/ha) and highest (2 350 kg/ha) recorded biomass, respectively. Variance in regional species diversity as previously revealed within PFGs, resulted in non-linear relationships, and was also evident from the linear regression analysis since no clear linear relationship was revealed for PFGs (Figure 6.9b, c, d). This is an indication that total species diversity measures and those within PFGs respond differently.

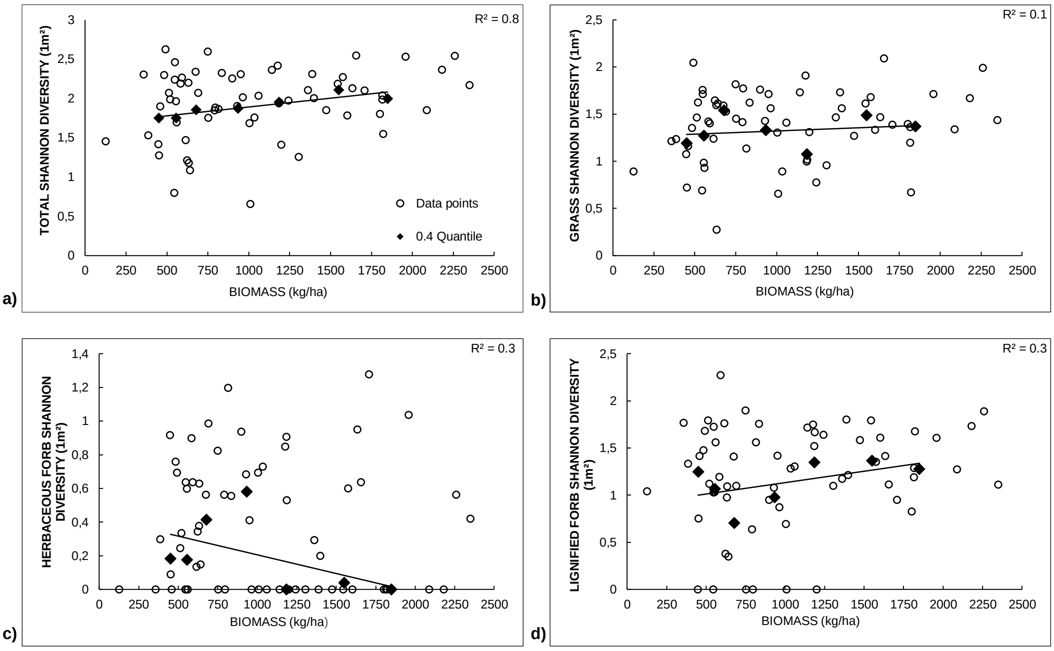

Figure 6.9. Quantile regression scatterplots, representing the 40% quantile models of a) total species-, b) grass-, c) herbaceous forb- and d) lignified forb Shannon diversity against live biomass. Circles represent data points whereas filled diamonds the 0.4 quantiles.

6.4. Discussion

6.4.1. Live biomass production and its environmental drivers

This study revealed that soil pH, which is related to underlying parent material and rainfall interact to drive spatial biomass patterns of semi-arid mountain rangelands of GW. These findings are in accordance with previous studies (Lane *et al.*, 1998; Siefert *et al.*, 2012; Smit *et al.*, 2013; Guo *et al.*, 2018) which highlighted the role of similar environmental factors acting as drivers of biomass patterns.

Soils associated with quartz, such as the Langberg, are known to be acidic and thus considered dystrophic (Wild *et al.*, 1963; Cowling *et al.*, 1994; Schmiedel *et al.*, 2015). These characteristics are considered to limit biomass yield in quartzitic environments (Benites *et al.*, 2007; Neina, 2019; Abrahão *et al.*, 2020). Accumulation of debris on the Langberg is unexpected since it is a xeric system. It has been reported that production of organic matter increased with increasing precipitation (Alvarez & Lavado, 1998; Epstein *et al.*, 2002). However, a study conducted by Benites *et al.* (2007) on quartzitic mountains in Brazil, found that organic matter accumulates due to unfavourable environmental conditions (i.e. coarse sandy texture, high aluminium content, low nutrient levels, nutrient leaching) that prevent decomposition by microbes. In addition, organic plant material has also been found to decay at slower rates in drier environments (Guo *et al.,* 2006). Yet, accumulation of organic matter promotes vegetation establishment by means of soil feedback mechanisms that enhance soil nutrients such as nitrogen (N), phosphor (P) and sulphur (S) (Russell, 1977; Kowalenko, 1978; Veen *et al.*, 2019), as well as water holding capacity in quartzitic plant communities (Benites *et al.*, 2007). Therefore, the higher levels of P associated with the Langberg compared to the Asbestos Hills, may be ascribed to the higher production of debris on the former than the latter. Furthermore, in savanna systems, fire reduces accumulation of moribund plant material (Frost & Robertson, 1985; Garnier & Dajoz, 2001; Van Coller *et al.*, 2018). From field notes it was further established that two Langberg transects had a fire history (sites where it burnt within two years before sampling) while six transects of the ironstone hills burned more frequently due to anthropogenic or wild fires. This suggests that fire contributed to a high level of debris accumulation associated with the Langberg. In contrast to the Langberg, low production of total biomass associated with the Asbestos Hills (mean 3 815 kg/ha) and Ghaap Plateau (mean 2 783 kg/ha) is ascribed to lower debris production. This is due to the negative relationship between soil pH and debris production, since decomposition of organic matter is enhanced through increased solubility of organic compounds and enhanced microbial activity on soils with higher soil pH (Neina, 2019). Live biomass reached optimum levels on the less acidic Kuruman Hills. Based on a study conducted by Gentili *et al.* (2018), pH values near 5 are considered to promote plant growth. Additionally, biodegradation rates of organic matter are enhanced under these slightly acidic conditions (Neina, 2019), suggesting that nutrient cycling is sufficient on the Kuruman Hills and would promote biomass production. Furthermore, due to higher vegetation cover, soil erosion and nutrient leaching will be limited (Materechera *et al.*, 1998), despite the Kuruman Hills system being characterised by steep slopes.

Since the dominant soils on the Ghaap Plateau are of the Coega soil form (Soil Classification Working Group, 1991), a shallow responsive soil (Van Tol & Le Roux, 2019) with limited water infiltration, it tends to become waterlogged after a rapid and intense rainfall event (Herman, 1999). Waterlogging is a characteristic feature of carbonate soils, which contributes to changes in soil chemistry and structure due to anoxic conditions (Dixon, 1996; Adhami *et al.*, 2012; Choudhury *et al.*, 2016). Consequently, soil redox potential is reduced (Naidoo & Naidoo, 1992). Under lower soil redox potential, hydrogen sulphide (H_2S) has the potential to become toxic to plants and consequently limit growth (Trudinger, 1986; Zhao *et al.*, 2008). Additionally, the alkaline nature of carbonate soils contributes to the reduction of plant growth (Gentili *et al.*, 2018; Neina, 2019; Robles-Aguilar *et al.*, 2019). Hence, the Ghaap Plateau, despite its higher rainfall, is less productive based on biomass production, which is in accordance with a study conducted by Gamoun *et al.* (2010) on limestone plant communities.

Biomass levels are dependent on the ability of species within each respective PFG to tolerate locally adverse environmental conditions of semi-arid savannas (Siebert *et al.*, In press). Grass- and herbaceous forb biomass increased along the rainfall gradient. This finding reinforces the role of rainfall in structuring herbaceous vegetation dynamics in semi-arid savanna landscapes (Buitenwerf *et al.*, 2011; O'Connor, 2015; Zerbo *et al.*, 2018). The known ability of herbaceous forbs to withstand competition from tall grass species (Grime, 1973; Bond & Parr, 2010; Van Coller & Siebert, 2015) was evident at sites on the Kuruman Hills. This suggests that some savanna herbaceous forb species of the Kuruman Hills are either shade tolerant (Ludwig *et al.*, 2004), or equipped with traits to avoid and/or tolerate competition. Graminoid species associated with the Ghaap Plateau are small in stature and are considered to be adapted to the alkaline and seasonally waterlogged soil (Patrick & Mahapatra, 1968; Setter *et al.*, 2009; Adhami *et al.*, 2012). Such species included *Bulbostylis humilis* (Kunth) C.B.Clarke, *Enneapogon. desvauxii* P.Beauv. and *Oropetium capense* Stapf, which follow the C4 photosynthetic pathway (Rubin *et al.*, 2001; Bruhl & Wilson, 2007), a physiological trait that provides these species with higher water- and CO_2-use efficiencies, especially under waterlogged conditions (Pearcy & Ehleringer, 1984; Naidoo & Naidoo, 1992; Ueno, 1996). Lignified forbs were found to be sensitive to soil pH and CEC. Biomass yield of this group was lower on soils associated with the most acidic Langberg and most alkaline Ghaap Plateau (Neina, 2019). Acidic soils generally have a low CEC, and hence develop nutrient deficiencies through leaching (Brown & Lemon, 2020). Despite the soil of the Ghaap Plateau being more alkaline with higher available cations, soils derived from sedimentary carbonates are associated with deficiencies in soil P (Cowling & Witkowski, 1994) due to dominance of Ca phosphates (Von Wandruszka, 2006), which are unavailable to plants. Lignified forbs may also be sensitive to such soil conditions in combination with higher soil pH, resulting in lower biomass production by this PFG. The ironstone hills are more fertile (higher CEC) than the Langberg, which therefore explains the high lignified forb biomass above 300 kg/ha. Since the soils of the ironstone hills are also rich in manganese, the high biomass yield of lignified forbs suggest metal tolerance (Faucon *et al.*, 2009).

6.4.2. Diversity-biomass relationships and role of PFGs

This study revealed linear, non-linear and unimodal diversity-biomass relationships at both regional and local scales, emphasising the importance of scale when studying diversity-biomass relationships (Guo & Berry, 1998; Huston, 1999; Waide *et al.*, 1999; Mittelbach *et al.*, 2001). Linear diversity-biomass relationships identified by this study are related to the positive relationship between productivity and species richness (Zheng *et al.*, 2010). This explains the increase in productivity (live herbaceous biomass) of the species rich ironstone hills and productivity decrease in the species poor Langberg. Moreover, resource supply in local species pools contributes to biomass production (Cardinale *et al.*, 2009). Under low (i.e. Langberg) or high (i.e. Ghaap Plateau) resource supply (i.e. low CEC, high CEC which indicates availability of nutrients), communities are subjected to stress conditions resulting in low productivity. In these plant communities, competition among plant species is weak while germination and tolerance of species determines which species will be successful colonisers (Guo & Berry, 1998). When resources are sufficiently available (intermediate CEC) (i.e. Kuruman Hills), coexistence allows for resources to be utilised in a complementary manner (Huston, 1997; Loreau & Hector, 2001). Furthermore, non-linear relationships are linked to species coexistence due to different population growth rates of species (Graham & Duda, 2011), suggesting that at regional and local levels herbaceous species respond dynamically to the associated environmental conditions in combination with biomass production. Consequently, colonisation-competition trade-offs are evident (Dos Santos *et al.*, 2010), especially at smaller local scales (Guo & Berry, 1998), along environmental gradients (Pausas & Austin, 2001). Locally, each mountain ecosystem was characterised by its own unique diversity-biomass relationship. Consequently, diversity-biomass relationships differed between local and regional scales. This finding is ascribed to the contribution of regional (i.e. evolutionary history, speciation, topography, climate, dispersal limitation) and local (i.e. disturbance, resource availability, micro-climate, competition, adaptation) processes that shape plant communities (Ricklefs, 1987). Thus, diversity-biomass relationships are influenced by these processes (Cardinale *et al.*, 2004; Fayiah *et al.*, 2019; Wang *et al.*, 2019) and interactions of species in response to rainfall and edaphic factors (Tilman *et al.*, 1997; Fridley, 2001). Non-linear relationships at a regional scale with regards to total biomass, revealed loss in all diversity measures for total species and within PFGs. These findings are in accordance with studies reporting that plant litter accumulation affects community structure and ecosystem functioning since seedling recruitment, growth and colonisation abilities of herbaceous plants are constrained by debris build up (Knapp & Seastedt, 1986; Facelli & Pickett, 1991; Foster & Gross, 1998)

Unimodal trends were primarily associated with regional herbaceous forb diversity-biomass relationships. These patterns for herbaceous forbs are linked to habitat heterogeneity across environmental gradients associated with mountain ecosystems (Gough *et al.*, 1994; Guo & Berry, 1998; Pausas & Austin, 2001; Ma *et al.*, 2010). This may be ascribed to the filtering effect of environmental conditions on species pools which drives species composition and, as a result thereof, diversity and productivity of plant communities. (Loreau *et al.*, 2001a; Kahmen *et al.*, 2005; YuKun *et al.*, 2009; Zuo *et al.*, 2012). The unimodal trend revealed for herbaceous forbs suggests the dynamic nature of species within this PFG due to non-equilibrium ecosystem processes within communities (Graham & Duda, 2011) and competitive exclusion effects (Grime, 1973; Abrams, 1995).

This study revealed a positive, linear diversity-biomass relationship, suggesting that herbaceous plant diversity, at regional scale, will be maintained at higher live biomass levels, suggesting optimal ecosystem functioning (Tilman *et al.*, 1997; Zheng *et al.*, 2010; Grace *et al.*, 2016). Plant functional group diversity-biomass relationships were primarily non-linear and diversity within PFGs tended to peak at certain biomass production levels. This suggests that biomass had a limited effect on diversity trends of separate PFGs and might be better explained by habitat heterogeneity within mountain ecosystems of GW (Gough *et al.*, 1994; Guo & Berry, 1998; Pausas & Austin, 2001; Ma *et al.*, 2010; Guo *et al.*, 2018).

Biomass levels below 800 kg/ha promoted diversity peaks for annual grasses and herbaceous forbs, while lower diversity was reported for lignified forbs at this lower productivity. Sites with lowest biomass yield were mostly associated with the Ghaap Plateau, where high soil alkalinity was reported to have a negative effect on lignified forb biomass production. Dominant and indicator grass and herbaceous species of the Ghaap Plateau are *E. desvauxii* and *B. humilis* (Van Staden *et al.*, 2020). These small, annual plants are ruderal species with strategies developed to exploit resources through rapid resource acquisition traits (Roumet *et al.*, 2006), especially after a rainfall event when competition levels are low (Buitenwerf *et al.*, 2011). Ruderal plant species produce high numbers of viable seeds and have a short life cycle (Pianka, 1970; Grime, 1973). The investment in a dormant viable seedbank under unfavourable conditions serves as a drought avoidance strategy (Siebert *et al.*, 2020). After the first rainfall event following a drought, these species have a greater post-drought recovery rate, since they can germinate rapidly and continue their life cycle for the next season (Tielbörger *et al.*, 2012; Ruppert *et al.*, 2015; Siebert *et al.*, 2020). The dominant grass *E. desvauxii* is known to appear swiftly after a rainfall event (Fouché *et al.*, 2014). As a pioneer grass species, it fulfils important ecosystem functions on bare soil systems, i.e. soil stabilisation and prevention of erosion (Fouché *et al.*, 2014). However, communities dominated by annual plants may be more vulnerable to ecosystem degradation and desertification under future climate change scenarios (Ruppert *et al.*, 2015). Future predictions suggest that intensities and frequencies of droughts may become more severe and lengthly resulting in declines in biomass production and, hence, depletion of seed banks in combination with overgrazing (Kinloch & Friedel, 2005; Golodets *et al.*, 2015).

Lignified forb diversity peaked between 150-400 kg/ha and again at 900-1 300 kg/ha. Sites associated with these peaks were not restricted to a single mountain ecosystem. Dominant lignified forb species within the lower peak included *Aptosimum lugardiae* (N.E.Br. ex Hemsl. & Skan) E.Phillips, *Chascanum pinnatifidum* (L.f.) E.Mey., *Evolvulus alsinoides* (L.) L., *Indigofera charlieriana* Schinz, *Lophiocarpus polystachyus* Turcz. and *Sida chrysantha* Ulbr. At higher biomass, *E. alsinoides*, *Kyphocarpa angustifolia* (Moq.) Lopr., *L. argute-carinatum*, *Phyllanthus parvulus* Sond., *S. chrysantha* and *Tephrosia longipes* Meisn. were dominant. In contrast to these two peaks, an intermediate diversity peak at 700 kg/ha was associated with sites of the Ghaap Plateau and Asbestos Hills that were dominated by *Glossochillus burchellli* Nees, *L. fenestratum* (Fenzl) Heimerl, *P. parvulus* and *S. chrysantha*. Since lignified forb species were widespread across mountain ecosystems with different biomass levels, it indicates that these species are adapted to various habitat and environmental conditions (Foden & Potter, 2005; Koekemoer *et al.*, 2014; Van Rooyen & Van Rooyen, 2019). This may be attributed to their lignified stems, an indication of slower growth and nutrient storage in roots and/or buds, providing these plants with a functional advantage (Laliberté, 2017; Pausas *et al.*, 2018). Lignified forbs are thus provided with disturbance-tolerant traits through long-term resource acquisition under unfavourable conditions (Sun *et al.*, 2016; Pausas *et al.*, 2018; Wigley *et al.*, In press). Furthermore, lignified forbs have the potential to provide nursing sites for herbaceous forbs, such as *B. hispidula* (Vahl) R.W.Haines, *B. humilis* and *Moraea polystachya* (Thunb.) Ker Gawl., the dominant species at 800 kg/ha where herbaceous forb diversity peaked (Withgott, 2000; Ren *et al.*, 2008; Gonzalez & Ghermandi, 2019; Madrigal-González *et al.*, 2020).

In general, grass and lignified forb diversity were characterised by similar diversity-biomass relationship patterns, especially considering similar diversity peaks at around 800- and 1 200 kg/ha. These peaks were dominated by a combination of perennial grass species. The two most dominant grasses were *Diheteropogon amplectens* (Nees) Clayton and *Eragrostis nindensis* Ficalho & Hiern. *Diheteropogon amplectens* is a tufted climax grass species which is abundant on the Asbestos- and Kuruman Hills where it is an indicator of good rangeland condition (Fouché *et al.*, 2014). *Eragrostis nindensis* is a small tufted sub-climax grass that has the ability to rehydrate rapidly after a rainfall event (Van Oudtshoorn, 2009). Hence these perennial grass species are stress-tolerant and also good competitors (Grime, 1977) since they allocate and conserve nutrients in their roots (Mapfumo *et al.*, 2002; Roumet *et al.*, 2006). Dominant lignified forbs included those with erect growth forms such as *P. parvulus*, as well as prostrate growing taxa such as *L. argute-carinatum* Wawra ex Wawra & Peyr. (Van Rooyen & Van Rooyen, 2019). Due to their growth forms, erect species can compete with taller growing and tufted grass species for light, whereas prostrate growth forms are adapted to high light intensity habitats and have been found to avoid shade (Bonser & Geber, 2005; Fazlioglu *et al.*, 2016). The shade-avoidance trait displayed by prostrate plants was found to be an advantageous strategy to maximise early life resource acquisition as well as reproduction efficiency under competition (Fazlioglu *et al.*, 2016). This suggests that *L. argute-carinatum*, an annual herbaceous species with limited lignification, can colonize patches between tufted grasses and avoid the shade conditions by elongation of the stems to ensure optimum exposure to sunlight.

Similar to other semi-arid savannas (Van Coller *et al.*, 2018), grasses and forbs (herbaceous and lignified) were also found to co-dominate in GW. However, above 1 800 kg/ha, only perennial grasses and lignified forbs persisted. Abundant grass species (*Anthephora pubescens* Nees, *Aristida diffusa* Trin., *Brachiaria serrata* (Thunb.) Stapf, *D. amplectens* and *Elionurus muticus* (Spreng.) Kunth) were all tufted and produced high biomass, suggesting that herbaceous forbs are outcompeted due to competitive exclusion effects ascribed to an increase in competition for light (Grime, 1973; Van Coller *et al.*, 2018; Siebert *et al.*, 2020). Based on dominance of palatable grass species such as *A. pubescens* and *B. serrata*, suitable rangeland conditions seem to prevail in GW mountain communities where biomass is high (Fouché *et al.*, 2014). These rangelands should be managed to maintain these grass species (Walker *et al.*, 1981; Van Oudtshoorn, 2009), especially where *A. diffusa* and *E.*

muticus, both unpalatable perennials, become more abundant under overgrazed conditions (Van Oudtshoorn, 2009). Regardless of its unpalatability, *E. muticus*, in combination with *A. pubescens*, *D. amplectens* and *Themeda triandra* Forssk*.,* contributes to the climax component in sweet veld of the ironstone hills (Fouché *et al.*, 2014). Despite being potentially overtopped and over shaded, the lignified forbs *C. adenostachyum*, *E. alsinoides, K. angustifolia*, *P. parvulus* and *Sutera halimnifolia* (Benth.) Kuntze were abundant. This suggests that these lignified forb species are well adapted to compete with perennial grasses for resources (Grime, 1977). In high biomass mountain rangelands within GW, these lignified forb species may also be grazing indicators and require further investigation, especially considering the dominance of species from families that are known to be palatable, such as Amaranthaceae and Convolvulaceae (Siebert & Scogings, 2015).

Griqualand West forms part of the Savanna Biome, which is characterised by a well-developed grassy layer, therefore the large contribution of grasses to total herbaceous biomass was expected (Skarpe, 1992; Scholes & Archer, 1997; Rutherford *et al.*, 2006). Forbs (both herbaceous and lignified) also contributed to herbaceous biomass production. Herbaceous forbs provide additional forage to livestock and wild mammalian herbivores (Holechek, 1984; Grant *et al.*, 1985; Siebert & Scogings, 2015; Morris & Scott-Shaw, 2019). Herbaceous forbs are nutritious forage sources during dry seasons when grass biomass decreases (Kelly & Walker, 1976; Van Coller *et al.*, 2018). However, under conditions of water stress and/or increased grazing pressure, availability of grasses and herbaceous forbs decreases, and livestock becomes dependent on woodier plant species (Ratovonamana *et al.*, 2013). Therefore, lignified forbs, which had the second highest biomass yield, is an important PFG of semi-arid mountain plant communities to sustain forage provision during drought events.

Herbaceous- and lignified forbs not only contributed to biomass production, but also to species diversity and richness in this savanna mountain landscape, similar to what was recorded in other semi-arid savannas in South Africa (Jacobs & Naiman, 2008; Van Coller *et al.*, 2013; Siebert & Scogings, 2015; Siebert *et al.*, 2020). These findings suggest that rangeland management in GW should not only consider grass species, but also the non-grassy components of the herbaceous layer. Together, all these PFG components can provide ecosystem stability for rangeland production in semi-arid mountain rangelands and an alternative forage during dry spells.

6.5. Summary

Differences in herbaceous biomass production across mountain rangelands in GW are driven by complex interactions between rainfall and soil properties, specifically soil pH and CEC, which are largely determined by underlying parent material. Grasses contributed the most to biomass followed by lignified forbs and lastly herbaceous forbs. Additionally, lignified forbs were the most species rich PFG across mountain ecosystems followed by grasses. Co-dominance of PFGs in the herbaceous layer of GW mountain ecosystems suggest that, apart from a diverse suite of perennial palatable grasses for forage production, the diversity and hence, overall ecosystem functioning, is largely dependent on the herbaceous and lignified forb richness. An improved understanding of herbaceous- and lignified forb dominance across a rainfall gradient is needed to assist in the identification of potential indicators of rangeland condition. Forage quality assessments (based on leaf nutrient- and crude protein contents) and how it varies across a rainfall gradient in semi-arid mountain ecosystems, would also add value to current knowledge on management for a changing climate.

This study revealed that most diversity-biomass relationships were predominantly non-linear, at both regional and local scales, with and without the inclusion of debris. The detected non-linearity of species diversity measures in response to biomass production, were related to historical and/or evolutionary processes as well as biotic and abiotic interactions that shape plant communities through the response of species to their locally adverse environmental conditions. However, with regards to total herbaceous plant diversity, a positive linear relationship was revealed at a regional scale. This suggests that in GW mountain rangelands, herbaceous plant diversity is maintained at higher levels of biomass yield due to competition trade-offs and/or tolerance to certain soil characteristics. Thus, management should manage rangelands for high diversity that will lead to increased biomass production. In the GW ecosystem, communities with low biomass productivity were dominated by ruderal herbaceous species that have rapid resource acquisition traits or abilities to invest in a viable seedbank, securing post-drought recovery. Communities with intermediate levels of biomass were dominated by a combination of mainly perennial grasses, herbaceous forb- and lignified forb species. This was related to resource conservation abilities associated with perennial grass and lignified forb species. Additionally, lignified forbs may act as nurse plants for herbaceous forbs. Despite the loss of herbaceous forbs in high biomass communities, tussock perennial grasses and lignified forbs dominated these rangelands that are in good condition, based on the presence of palatable grass indicators. Furthermore, herbaceous forb diversity was sensitive to increasing biomass and moribund plant material, and perennial tussock grasses that outcompete and over shade herbaceous forbs. Hence, effects of competitive exclusion in higher biomass communities was evident.

This first attempt to investigate diversity-biomass relationships in mountain rangelands of the semi-arid savanna landscape of GW suggests that mountain rangelands serve as natural sites at which biomass production under future climate change can be explored in further detail. Long-term monitoring of these sites are envisaged to contribute to guidelines for land managers to safeguard diversity and forage production under drought events in GW. Future studies must increase sampling effort per mountain rangeland to investigate local optimum diversity for each mountain system.

6.6. References

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Chapter 7
Conclusion and recommendations

7.1. Summary of research

This thesis investigated the effects of geology, through soil properties related to the underlying geological parent material, and rainfall as drivers of floristic patterns, plant diversity and structure, as well as biomass production and the relationships between diversity and biomass of mountain ecosystems in Griqualand West (GW). The relevant objectives and hypotheses for each results chapter are briefly stated, followed by a summary of the most important findings.

7.1.1. Chapter 4

The objectives of this chapter were to (i) redefine the borders of Griqualand West Centre of plant endemism (GWC) to establish which main mountain ranges fall within the centre by using a MaxEnt spatial model based on geology, climate and topography in combination with distribution data of GWC endemics and, (ii) describe flora within the newly redefined borders of GWC based on dominant plant families and -species, indicator plant species, endemic species and species composition. It was hypothesised that each mountain plant community will be characterised by unique assemblages associated with particular indicator plant species (Hypothesis 1).

The major findings from this chapter are listed below:

- The spatial model revealed that GWC endemic plant species are restricted to the mountains due to their unique geology and cooler climate than the low-lying valleys.
- The mountain ecosystems of GWC are thus suggested to be hotspots within a centre of endemism as a result of topographical heterogeneity, geology and climate.
- The refined borders of GWC, which specifically include the mountains, are considered a priority conservation area.
- The most species-rich and dominant plant families across the studied mountain ecosystems include the Asteraceae, Fabaceae, Malvaceae and Poaceae. The Cyperaceae is dominant on the wetter Kuruman Hills and Ghaap Plateau, whereas the Scrophulariaceae is more dominant on the drier Langberg and Asbestos Hills.
- Mountain ecosystems of the GWC are characterised by distinct indicator plant species, driven by rainfall and soil properties.
- Indicator plant species associated with the Ghaap Plateau prefer alkaline soil with high Ca:Mg ratios. Those of the Kuruman Hills are adapted to slightly acidic soils with high iron (Fe) content. Indicator species of the Langberg and Asbestos Hills are associated

with low rainfall conditions. Moreover, indicator species of the Langberg seem to be adapted to low soil nutrient availability and sandy soils.

- Occurrence of indicator plant species is related to niche partitioning, environmental filtering and habitat specialisation across nutrient- and rainfall gradients.
- Each mountain system is characterised by unique herbaceous assemblages due to the unique underlying geologies, i.e. dolomite and limestone, banded ironstone and quartzite. However, despite occurring on ironstone, the wetter Kuruman Hills differed from their drier southern counterparts, the Asbestos Hills. This finding highlights the role of rainfall in driving compositional differences in savanna ecosystems.
- The Ghaap Plateau hosts the highest number of GWC endemic plant species, followed by the ironstone hills (i.e. the Kuruman Hills and Asbestos Hills combined).
- Of the 24 endemic plant species, six are restricted to a specific mountain range, and are considered narrow endemic plant species. Three species namely *Deverra rapaletsa*, *Nerine hesseoides* and *Pentzia stellata* are narrow endemics of the Ghaap Plateau. *Lithops aucampiae* subsp. *euniceae* is restricted to the Asbestos Hills, whereas *Brachiaria dura* var. *pilosa* and *Lithops bromfieldii* are found only on the Langberg. Since these species are restricted to certain geologies and distribution ranges within GWC, they are considered highly specialised and edaphic specialists.
- Each mountain plant community was characterised by unique herbaceous plant communities (i.e. herbaceous assemblages) with specific indicator plant species, driven by soil properties and rainfall. Therefore, **Hypothesis 1** is accepted.

7.1.2. Chapter 5

Objectives of this chapter included a comparison of soil properties, rainfall, plant diversity and structure between mountain ecosystems to test whether mountains, within the defined borders identified in Chapter 4, differed significantly from each other. Additionally, it was determined whether soil properties, rainfall or a combination of these acted as drivers of plant diversity and structural differences between mountains. It was hypothesised that a combination of soil properties and rainfall will act as drivers of herbaceous species composition, plant diversity and vegetation structure across mountain ecosystems (Hypothesis 2).

The major findings from this chapter include:

- Mountains differ in chemical and physical soil properties which is a clear indication of the influence of underlying geological heterogeneity. The ironstone hills are characterised by high Fe content, Ghaap Plateau with high calcium (Ca), Ca:Mg ratio and alkaline soils and, Langberg with acidic and sandy soils with a low Ca:Mg ratio.
- A rainfall gradient with increasing aridity towards the Langberg can be observed. The Langberg is the driest system followed by the Asbestos Hills. The Kuruman Hills and Ghaap Plateau are the wettest mountain ecosystems with the Ghaap Plateau receiving the highest mean annual precipitation.
- Each mountain system harbours distinct plant communities that were driven by specific soil properties. Compositional changes are driven by Ca on the dolomitic Ghaap Plateau, Fe on the ironstone hills and low Ca:Mg ratio on the quartzitic Langberg. These soil properties are considered environmental filters determining herbaceous composition. Thus, a clear plant-soil interaction effect is evident.
- Since Ca and Fe levels are high on the Ghaap Plateau and ironstone hills, respectively, plant species growing here are considered to have ecological tolerances enabling them to survive under the associated edaphic conditions.
- The quartzitic Langberg is species-poor, with less diverse plant communities, yet with high evenness. This finding can be related to the dystrophic acidic and sandy soils which act as drivers of herbaceous diversity on the quartzitic Langberg.
- Herbaceous forbs were underrepresented in the herbaceous layer on the Langberg due to the aridity of the system. Lignified forbs, shrubs and trees are considered adapted to the harsh and stressful environmental conditions, since these life form groups were larger in stature i.e. taller with wide canopy areas.
- Generally, the ironstone hills harbour species rich and diverse plant communities with high evenness. These patterns are driven by Fe, CEC and Al content.
- Based on community structure, the ironstone hills are different due to rainfall effects. The herbaceous layer of the drier Asbestos Hills is shorter whereas the wetter Kuruman Hills have a taller and more developed herbaceous layer. In addition to rainfall, Al content is lower on the Kuruman Hills and, since this system has a favourable soil pH for plant growth, Al toxicity is considered to be limited. As a result, these conditions are additional factors that contributed to plant growth on the Kuruman Hills. In contrast, the Asbestos Hills had a lower soil pH with higher Al content, suggesting Al toxicity that resulted in dwarfism of the herbaceous layer.
- Similar to the Langberg, the less arid Asbestos Hills also revealed low cover and frequency values of herbaceous forbs. Tall lignified forbs with wide canopy areas

characterised the Kuruman Hills. This finding can be related to higher rainfall conditions which favour grass growth and hence competition for sunlight between tall-growing grasses and lignified forbs. In contrast to the Asbestos Hills, lignified forbs are smaller with narrower canopy areas. Shrubs are more frequently encountered on the Asbestos hills and hence, this mountain system has a more developed shrub layer than its northern counterpart (Kuruman Hills).

- The dolomitic Ghaap Plateau harbours species rich plant communities driven mainly by soil pH and Ca. Diversity is lower on the Ghaap Plateau due to the dominance of certain herbaceous plant species which are adapted to rocky, shallow alkaline soils with a high lime content.
- Lignified forbs on the Ghaap Plateau are short with narrow canopy areas due to high Ca content, alkalinity and nutrient deficiencies that reduced plant growth of this life form group. Herbaceous forbs have higher cover and frequencies on both the Ghaap Plateau and Kuruman Hills, since these two systems are less arid with moister conditions that favour this life form group. Similar to lignified forbs, shrubs display reduced plant height and canopy areas. However, the tree layer is highly developed with tall tree species, especially *Olea europaea* subsp. *africana* with wide canopies. Tree species are furthermore considered adapted to grow on Ca- and Mg-rich soils.
- From this, **Hypothesis 2** is partially supported. Plant community composition, herbaceous plant density, -plant height, -cover and shrub frequencies are driven by a combination of soil properties and rainfall. However, soil properties are the main driver of plant diversity, frequency of grass, lignified forbs and trees, and woody plant height and -canopy area.

7.1.3. Chapter 6

This chapter firstly tested for differences in total biomass production (above ground green plant material and debris), live biomass production (only live green above-ground plant material) and respective plant functional group (PFG) biomass production between the four mountain rangelands. Secondly, differences in biomass were related to specific soil properties and rainfall to identify the strongest drivers of biomass production in GW. Thirdly, diversity-biomass relationships for total plant species and species representing different PFGs were investigated at local and regional scales. Lastly, an optimal range of biomass production at which herbaceous species diversity can be maintained at a regional scale was provided. Here, we hypothesised that diversity-biomass relationships will be unimodal at regional scale and non-linear at a local scale (Hypothesis 3).

The major findings from this chapter is summarised below:

- Total biomass (live herbaceous biomass and debris) and live biomass (live, green plant material) production differ between mountain rangelands.
- Grasses and lignified forbs contribute mostly to biomass production (live biomass) of the two drier rangelands, i.e. Langberg and Asbestos Hills, whereas herbaceous forb biomass is higher on the wetter rangelands, i.e. Kuruman Hills and Ghaap Plateau.
- Generally, lignified forbs contribute to species richness in each mountain rangeland, followed by grasses and herbaceous forbs.
- Soil pH and rainfall are interacting drivers of spatial biomass patterns in mountain rangelands. The acidic and arid Langberg has the lowest biomass yield, whilst the less acidic and -arid Asbestos Hills have slightly higher biomass whereas optimum biomass production is reached on the wetter Kuruman Hills since the pH value is considered to promote plant growth. The Ghaap Plateau with its high rainfall is less productive (based on biomass production) due to shallow, seasonally waterlogged and alkaline soil that contribute to reduced plant growth and hence, low biomass.
- Linear, non-linear and unimodal diversity-biomass relationships prevail at both regional and local scales.
- Linear diversity-biomass relationships can be linked to the positive relationship between productivity and species richness. Thus, the less species rich Langberg had lower biomass production whereas the species rich Kuruman Hills had high biomass yield.
- Resource supply (based on CEC values, an indicator of soil nutrients) contributed to low biomass production associated with the Langberg and Ghaap Plateau. Under low resource supply (i.e. Langberg) or too high resource supply (i.e. Ghaap Plateau), plant growth is restricted, and hence low biomass levels occur. In these two plant communities, competition among plant species are considered to be weak, while germination and tolerance of species determined which species will be successful colonisers that contributed to biomass. Under sufficient resource supply (i.e. Kuruman Hills with intermediate CEC) coexistence allowed for resources to be utilised in a complementary manner.
- Non-linear relationships are linked to the coexistence of species as a result of different population growth rates of plant species. Therefore, at regional and local scales, herbaceous plant species respond dynamically to environmental conditions in combination with biomass production. Consequently, colonisation-competition trade-offs are evident, especially at a local scale.
- At local scale, each mountain ecosystem is characterised by unique diversity-biomass relationships.

- Diversity-biomass relationships differ at regional and local scales due to different regional and local processes responsible to shape plant communities.
- Unimodal trends are primarily identified for regional herbaceous forb diversity-biomass relationships due to habitat heterogeneity across environmental gradients across mountain rangelands. This unimodal trend suggests that forb species respond dynamically as a result of non-equilibrium processes and competitive exclusion effects within plant communities.
- A positive, linear diversity-biomass relationship is revealed at regional scale. Thus, diversity will be maintained at higher levels of biomass thereby ensuring optimal ecosystem functioning. Species diversity index (Shannon Diversity) values of 1.7, 1.9 and 2.1 were maintained at lowest (125 kg/ha), intermediate (1 050 kg/ha) and highest (2 350 kg/ha) recorded biomass, respectively.
- Diversity-biomass relationships for PFGs are non-linear. Therefore, diversity within PFGs peaked at certain biomass production levels. This finding suggests that biomass has a limited effect on PFG diversity patterns and habitat heterogeneity is considered to better explain these patterns.
- Plant functional groups contribute to biomass production. Lignified- and herbaceous forbs are considered to provide additional forage to livestock, especially during dry spells when availability of grasses decreases.
- **Hypothesis 3** is partially supported. At the regional scale, diversity-productivity relationships were primarily non-linear with some positive linear trends. Hypothesis 3 is primarily supported at local scale.

7.2. Recommendations

7.2.1. Conservation and management

The four mountain ecosystems studied in this thesis, i.e. Langberg, Asbestos Hills, Kuruman Hills and Ghaap Plateau, were revealed to be hotspots of endemic plant species. Therefore, these mountain ranges are proposed as conservation priority areas. Since the Ghaap Plateau and ironstone hills harboured the most endemic plant species, these three mountains are of particular conservation significance in GW. Conservation managers should aim to focus specifically on the narrow endemics (those that were restricted to a specific geology and mountain) and those endemic species that are listed as vulnerable, rare, critically rare, data deficient and or near threatened. *Deverra rapaletsa*, which is not yet assessed, should be assessed for a conservation status on the National Red List of South Africa.

Conservation and management policies should be developed to conserve the unique diversity and species richness of the mountain ecosystems. The Ghaap Plateau and ironstone hills are emphasised as conservation target areas based on their diversity. Plant-soil interactions were the main driver of herbaceous diversity of GW mountain plant communities, whereas herbaceous composition and -structure by a combination of soil properties and rainfall. It is worrisome that not one of the studied mountain ranges is currently included in formally protected areas. Therefore, future reserve planning should aim to include parts of the mountain ranges to ensure optimum conservation of not only endemic plant species but also their unique herbaceous composition and diversity by conserving the underlying factors acting as drivers thereof.

The studied mountain rangelands have the potential to serve as natural sites at which biomass production and diversity-productivity relationships can be further investigated and explored. For example, long-term experiments can be conducted to investigate the effects of herbivore inclusion and/exclusion or under various livestock densities as well as with and without fire. If such experiments can be initiated, data can also be captured regarding rainfall patterns in the region. Consequently, vegetation dynamics in response to drought or a drought release year can be studied in combination with livestock grazing and fire. This will aid the development of land management strategies and will ensure that subsistence and commercial farmers will apply appropriate grazing management especially after a fire or drought. Consequently, diversity will be safeguarded as well as forage production. Grasses should also not be the main target group to conserve and manage. Herbaceous forbs and lignified forbs should also be conserved since these two functional groups provide additional forage to livestock during droughts. To provide optimum forage production in mountain rangelands in GW, herbaceous plant species diversity must be managed to be maintained at high levels. Thus, the livelihood of subsistence and commercial farmers can be safeguarded.

It is necessary to follow a holistic, multi-disciplinary conservation and management approach and to build relationships with subsistence and commercial farmers. Conservation managers will need to collaborate with farmers to ensure optimum conservation of GWC. It is proposed that community-based resource management can be implemented in collaboration with subsistence farmers, such as the Griqua community near Groenwater, to educate farmers regarding appropriate land- and grazing strategies. Community engagement is further encouraged, e.g. the primary school situated in Groenwater, to educate children from a young age to conserve natural resources and to respect their environment. If they learn that when we look after nature, nature will provide for us, a difference will be made for the future farmers among the school children. Furthermore, farmer association days can be attended by environmental officers and/or conservation managers to gain the farmers' trust and to build good relationships. Research can then also be presented to farmers at these events to have understandable informative sessions that will aid farmers with their land management strategies. Results from this study can also be included in environmental impact assessments by mines as well as development plans and identification of sites appropriate for sun and/or wind farms.

7.2.2. Future studies

Results from this thesis can be used to guide future once-off and long-term monitoring studies in GW. It is advised that future botanical studies should focus research within the new refined borders of the GWC. Ecological modelling studies are encouraged to determine how vegetation dynamics will respond to future climate change scenarios to ensure proper land management strategies under especially droughts. Additionally, our understanding of the special edaphic floras of the four mountain ecosystems should be expanded. Specifically, such studies could help predict how distribution ranges of endemic plant species and biomass yield will be affected by climate- and/or land use change in the future. Future studies should also increase sampling efforts per mountain system to ensure that optimum diversity for each mountain system can be determined at which biomass levels will be maintained.

Appendix A

Supplementary tables and figures relating to Chapter 3

PRISMA 2009 Flow Diagram

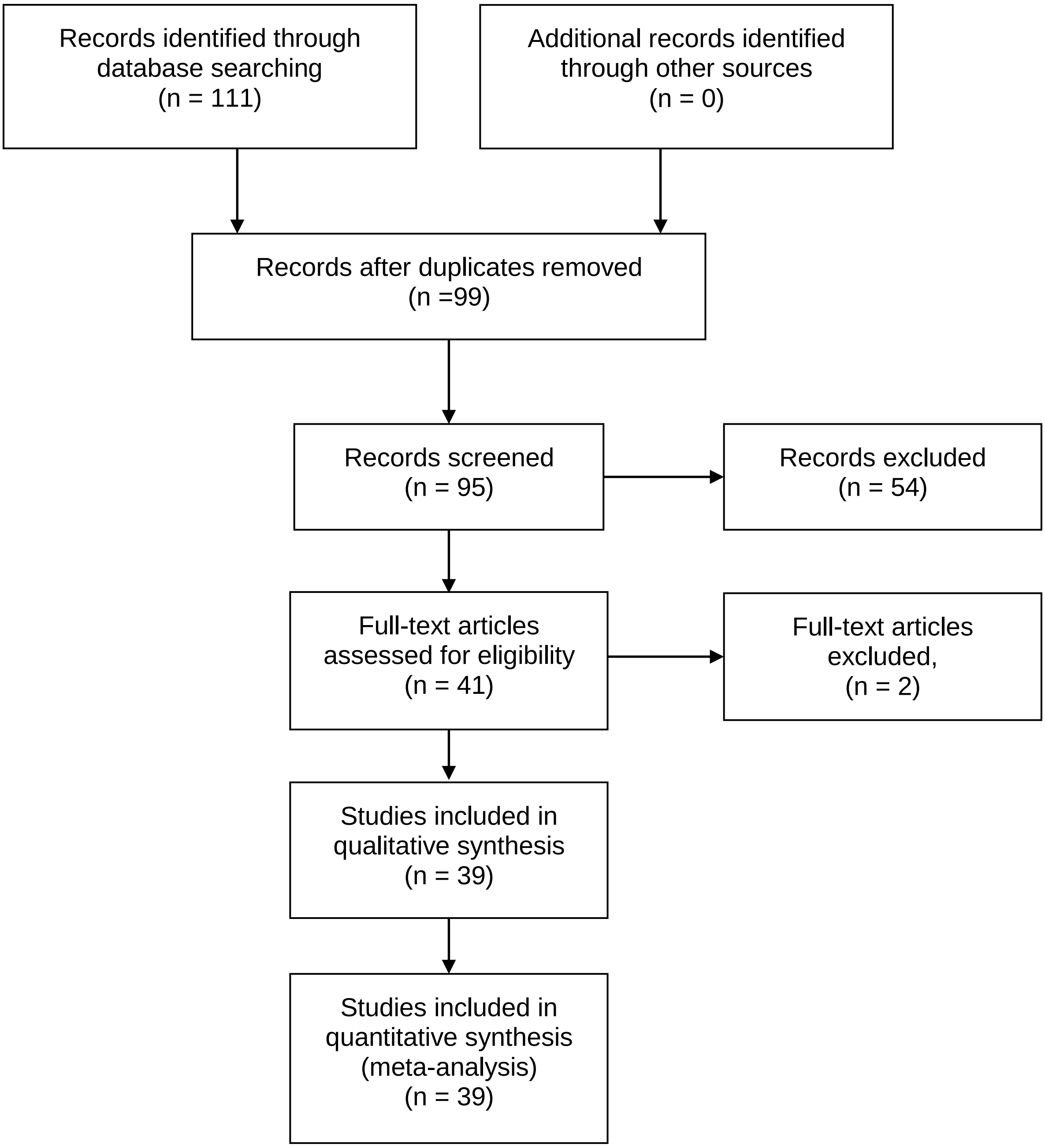

Figure A1. Flow diagram of screening and inclusion of relevant literature following the criteria (described in-text). The final relevant studies were classified into eight major themes.

From: Moher. D., Liberati, A,. Tetzlaff, J. and Altman, D.G. The PRISMA Group. 2009. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLoS Med*, 6(7): e1000097. doi:10.1371/journal.pmed1000097. For more information, visit www.prisma-statement.org.

Table A1. List of 39 publications included in this review. Scopus search strings for October 2018 and August 2019 are indicated. Where search strings for 2019 are absent, studies were irrelevant or already included in the initial search.

First author	Year	Publication title	Journal
Search string: October 2018 **(TITLE-ABS-KEY (africa*) AND TITLE-ABS-KEY (dolo*) AND TITLE-ABS-KEY (plant*) OR TITLE-ABS-KEY (vegetation) OR TITLE-ABS-KEY (flor*)) AND (LIMIT-TO (DOCTYPE , "ar") AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (AFFILCOUNTRY , "South Africa") OR LIMIT-TO (AFFILCOUNTRY , "Algeria") OR LIMIT-TO (AFFILCOUNTRY ,"Burkina Faso" OR LIMIT-TO (AFFILCOUNTRY , "Egypt") OR LIMIT-TO (AFFILCOUNTRY , "Ghana") OR LIMIT-TO (AFFILCOUNTRY , "Namibia") OR LIMIT-TO (AFFILCOUNTRY , "Nigeria") OR LIMIT-TO (AFFILCOUNTRY , "Tunisia")) AND (EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "CHEM") OR EXCLUDE (SUBJAREA , "ENGI") OR EXCLUDE (SUBJAREA , "ENER") OR EXCLUDE (SUBJAREA , "MATE") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "PHAR")) AND (EXCLUDE (LANGUAGE , "Spanish"))**			
Pule, H.T.	2018	The effects of abiotic factors in South African semi-arid grassland communities on *Seriphium plumosum* L density and canopy size	*PLoS One*
Van Jaarsveld, E.J.	2016	*Dracaena transvaalensis* Bak.,(Dracaenaceae) the dragon tree of the Limpopo Province, South Africa	*Bradleya*
Goldblatt, P.	2013	New taxa of *Hesperantha* (Iridaceae: Crocoideae) from the southern African winter rainfall region and a review of the *H. pilosa* complex	*Bothalia*
Magee, A.R.	2011	*Gazania lanata* and *G. splendidissima*: Two new species of Asteraceae (tribe Arctotideae) from the Greater Capensis, with an updated key for the genus	*South African Journal of Botany*
Siebert, F.	2005	Dolomitic vegetation of the Sterkfontein Caves World Heritage Site and its	*Koedoe*

		importance in the conservation of Rocky Highveld Grassland.	
Burke, A	2001	Classification and ordination of plant communities of the Naukluft Mountains, Namibia	*Journal of Vegetation Science*
Bezuidenhout, H.	1994	A classification of the vegetation of the western Transvaal dolomite and chert grassland, South Africa	*South African Journal of Botany*
Matthews, W.S.	1993	Endemic flora of the north-eastern Transvaal escarpment, South Africa.	*Biological Conservation*
Search string: June 2019 **(TITLE-ABS-KEY (africa*) AND TITLE-ABS-KEY (dolo*) AND TITLE-ABS-KEY (plant*) OR TITLE-ABS-KEY (vegetation) OR TITLE-ABS-KEY (flor*)) AND (LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018)) AND (LIMIT-TO (SUBJAREA , "AGRI")) AND (LIMIT-TO (AFFILCOUNTRY , "South Africa"))**			
Frisby, A.W.	2019	Plant endemism in Griqualand West, South Africa.	*South African Journal of Botany*
Search string: October 2018 **(TITLE-ABS-KEY (africa*) AND TITLE-ABS-KEY (calcareous*) AND TITLE-ABS-KEY (plant*) OR TITLE-ABS-KEY (vegetation) OR TITLE-ABS-KEY (flor*)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (AFFILCOUNTRY , "South Africa") OR LIMIT-TO (AFFILCOUNTRY , "Egypt") OR LIMIT-TO (AFFILCOUNTRY , "Tunisia") OR LIMIT-TO (AFFILCOUNTRY , "Malawi") OR LIMIT-TO (AFFILCOUNTRY , "Morocco") OR LIMIT-TO (AFFILCOUNTRY , "Algeria") OR LIMIT-TO (AFFILCOUNTRY , "Cameroon") OR LIMIT-TO (AFFILCOUNTRY , "Libyan Arab Jamahiriya") OR LIMIT-TO (AFFILCOUNTRY , "Namibia") OR LIMIT-TO (AFFILCOUNTRY , "Nigeria") OR LIMIT-TO (AFFILCOUNTRY , "Senegal") OR LIMIT-TO (AFFILCOUNTRY , "Uganda")) AND (EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "NURS") OR EXCLUDE (SUBJAREA , "SOCI")) AND (EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "EART"))**			

Visser, M.	2012	*Argyrolobium uniflorum* seedlings respond strongly to small doses of phosphorus: Consequences for rehabilitating degraded arid fallows in Presaharian Tunisia.	*Arid Land Research and Management*
Gamoun, M.	2010	Effects of grazing and trampling on primary production and soil surface in North African rangelands	*Ekológia*
Retief, E.	2008	A new species of *Euclea* (Ebenaceae) from ultramafic soils in Sekhukhuneland, South Africa, with notes on its ecology	*Bothalia*
Abd El-Ghani, M.M.	2007	Environment and vegetation of *Randonia africana*: An endangered desert plant in Egypt	*African Journal of Ecology*
Zietsman, M.M.	2006	Dune vegetation and coastal thicket plant communities in threatened limestone fynbos of Andrew's Field and Tsaba-Tsaba Nature Reserve, Struisbaai, Western Cape	*Koedoe*
Abd El-Ghani, M.M.	2005	The coastal roadside vegetation and environmental gradients in the arid lands of Egypt	*Community Ecology*
Cowling, R.M.	1994	Convergence and non-convergence of plant traits in climatically and edaphically matched sites in Mediterranean Australia and South Africa	*Australian Journal of Ecology*
Bredenkamp, G.J.	1991	The *Eucleo divinori - Acacietum nigricentis*, a new association from the calcareous bottomland clays of the Manyeleti Game Reserve, Eastern Transvaal Lowveld, Gazankulu, South Africa	*Vegetatio*

Pierce, S.M.	1991	Disturbance regimes as determinants of seed banks in coastal dune vegetation of the southeastern Cape	*Journal of Vegetation Science*

Search string: October 2018

(TITLE-ABS-KEY (africa*) AND TITLE-ABS-KEY (limestone) AND TITLE-ABS-KEY (plant*) OR TITLE-ABS-KEY (vegetation) OR TITLE-ABS-KEY (flor*)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (EXCLUDE (SUBJAREA , "ENGI") OR EXCLUDE (SUBJAREA , "SOCI") OR EXCLUDE (SUBJAREA , "BUSI") OR EXCLUDE (SUBJAREA , "CENG") OR EXCLUDE (SUBJAREA , "MATE") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "COMP") OR EXCLUDE (SUBJAREA , "ENER") OR EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "MATH") OR EXCLUDE (SUBJAREA , "NEUR")) AND (EXCLUDE (SUBJAREA , "EART") OR EXCLUDE (SUBJAREA , "BIOC")) AND (LIMIT-TO (AFFILCOUNTRY , "South Africa") OR LIMIT-TO (AFFILCOUNTRY , "Tunisia") OR LIMIT-TO (AFFILCOUNTRY , "Congo") OR LIMIT-TO (AFFILCOUNTRY , "Egypt") OR LIMIT-TO (AFFILCOUNTRY , "Madagascar") OR LIMIT-TO (AFFILCOUNTRY , "Undefined"))

Chimphango, S.B.M.	2015	Differentiation of the biogeochemical niches of legumes and non-legumes in the Cape Floristic Region of South Africa	*Plant Ecology*
Gamoun, M.	2013	Vegetation change in variable rangeland environments: The relative contribution of drought and soil type in arid rangelands	*Ekológia*
Ratovonamana, Y.R.	2013	Impact of livestock grazing on forest structure, plant species composition and biomass in Southwestern Madagascar	*Scripta Botanica Belgica*
Goldblatt, P.	2012	Systematics of the hypervariable *Moraea tripetala* complex (Iridaceae: Iridoideae) of the southern African winter rainfall zone	*Bothalia*

Radloff, F.G.T.	2010	Strontium isotope analyses of large herbivore habitat use in the Cape Fynbos region of South Africa	*Oecologia*
Magee, A.R.	2010	Two new species of Asteraceae (tribe Anthemideae, subtribe Pentziinae) from the Cape Floristic Region of South Africa	*South African Journal of Botany*
Van Wyk, B.E.	2010	A revision of the genus *Glia* (Apiaceae, tribe Heteromorpheae)	*South African Journal of Botany*
Hall, A.R.	2003	Recovery of thicket in a revegetated limestone mine	*South African Journal of Botany*
Laurie, H.	1997	A shared niche? The case of the species pair *Protea obtusifolia* - *Leucadendron meridianum*	*Oikos,*
Willis, C.K.	1996	Patterns of endemism in the limestone flora of South African lowland fynbos	*Biodiversity & Conservation*
Willis, C.K.	1996	Reserve systems for limestone endemic flora of the cape lowland fynbos: Iterative versus linear programming	*Biological Conservation*
Mustart, P.J.	1994	Reproductive traits of two closely related species-pairs on adjacent, different soil types in South African Fynbos	*Vegetatio*
Cowling, R.M.	1994	Taxonomic, edaphic and biological aspects of narrow plant endemism on matched sites in mediterranean South Africa and Australia	*Journal of Biogeography*
Cowling, R.M.	1992	Endemism and speciation in a lowland flora from the Cape Floristic Region	*Biological Journal of the Linnean Society*
Cowling, R.M.	1991	How small can reserves be? An empirical approach in Cape Fynbos, South Africa.	*Biological Conservation*

Raitt, L.M.	1987	The cation status of some indigenous plants from a Cango valley limestone-sandstone transition, South Africa	*Plant and Soil*

Search string: June 2019

(TITLE-ABS-KEY (limestone) AND TITLE-ABS-KEY (endemic) AND TITLE-ABS-KEY (species)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (AFFILCOUNTRY , "South Africa") OR LIMIT-TO (AFFILCOUNTRY , "Ethiopia") OR LIMIT-TO (AFFILCOUNTRY , "Egypt") OR LIMIT-TO (AFFILCOUNTRY , "Eritrea") OR LIMIT-TO (AFFILCOUNTRY , "Kenya") OR LIMIT-TO (AFFILCOUNTRY , "Tunisia")) AND (EXCLUDE (SUBJAREA , "EART") OR EXCLUDE (SUBJAREA , "BIOC")) AND (EXCLUDE (AFFILCOUNTRY , "United Kingdom") OR EXCLUDE (AFFILCOUNTRY , "United States") OR EXCLUDE (AFFILCOUNTRY , "Australia") OR EXCLUDE (AFFILCOUNTRY , "Denmark") OR EXCLUDE (AFFILCOUNTRY , "France") OR EXCLUDE (AFFILCOUNTRY , "Ireland") OR EXCLUDE (AFFILCOUNTRY , "Luxembourg") OR EXCLUDE (AFFILCOUNTRY , "Netherlands") OR EXCLUDE (AFFILCOUNTRY , "Portugal") OR EXCLUDE (AFFILCOUNTRY , "Switzerland") OR EXCLUDE (AFFILCOUNTRY , "Thailand"))

Van Munster, S.	2019	*Deverra rapaletsa* (Apiaceae), a new limestone endemic species from the Ghaap Plateau, Northern Cape, South Africa.	*South African Journal of Botany*
Magee, A.R.	2010	*Annesorhiza calcicola* (Apiaceae), a new limestone endemic species from the Western Cape Province of South Africa.	*South African Journal of Botany*
Zietsman, M.M.	2007	Threatened Limestone Fynbos plant communities of Andrew's Field and Tsaba-Tsaba Nature Reserve, Western Cape.	*Bothalia*

Search string: August 2019 **(TITLE-ABS-KEY (Africa*) AND TITLE-ABS-KEY (calcrete) AND TITLE-ABS-KEY (vegetation) OR TITLE-ABS-KEY (plant*) OR TITLE-ABS-KEY (flor*)) AND (EXCLUDE (SUBJAREA , "EART") OR EXCLUDE (SUBJAREA , "ENGI") OR EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "SOCI") OR EXCLUDE (SUBJAREA , "ARTS") OR EXCLUDE (SUBJAREA , "MULT"))**			
Van Rooyen, M.W.	2008	Landscapes in the Kalahari Gemsbok National Park, South Africa	*Koedoe*
Herman, P.P.J.	1999	Synopsis of the genus *Rennera* Merxm. (Asteraceae, Anthemideae) with the description of a new species from South Africa	*Botanical Journal of the Linnean Society*

Table A2. Results from Scopus search with reasons why certain studies were excluded, for October 2018.

Scopus search string	Number of articles	Year	Included	Excluded	Motivation for exclusion
(TITLE-ABS-KEY (africa*) AND TITLE-ABS-KEY (dolo*) AND TITLE-ABS-KEY (plant*) OR TITLE-ABS-KEY (vegetation) OR TITLE-ABS-KEY (flor*)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (AFFILCOUNTRY , "South Africa") OR LIMIT-TO (AFFILCOUNTRY , "Algeria") OR LIMIT-TO (AFFILCOUNTRY , "Burkina Faso") OR LIMIT-TO (AFFILCOUNTRY , "Egypt") OR LIMIT-TO (AFFILCOUNTRY , "Ghana") OR LIMIT-TO (AFFILCOUNTRY , "Namibia") OR LIMIT-TO (AFFILCOUNTRY , "Nigeria") OR LIMIT-TO (AFFILCOUNTRY , "Tunisia")) AND (EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "CHEM") OR EXCLUDE (SUBJAREA , "ENGI") OR EXCLUDE (SUBJAREA , "ENER") OR EXCLUDE (SUBJAREA , "MATE") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "PHAR")) AND (EXCLUDE (LANGUAGE , "Spanish"))	**38**	**1993-2018**	**8**	**30**	
The effects of abiotic factors in South African semi-arid grassland communities on *Seriphium plumosum* L density and canopy size		2018	1		
First survey of the fungi from the bakwena cave in South Africa suggests low human disturbance		2017		1	No plant-soil interactions. Study focuses on fungi.
Down, but not out: Recent decline of Berg-Breede river whitefish (*Barbus andrewi*) in the upper Hex River, South Africa		2017		1	No plant-soil interactions. Study focuses on fish.
Spatial extent and consequences of black bass (*Micropterus* spp.) invasion in a Cape Floristic Region river basin		2016		1	No plant-soil interactions. Study focuses on fish.
Dracaena transvaalensis Bak., (Dracaenaceae) the dragon tree of the Limpopo Province, South Africa		2016	1		

Using tournament angler data to rapidly assess the invasion status of alien sport fishes (*Micropterus* spp.) in Southern Africa		2015		1	No plant-soil interactions. Study focuses on fish.
Silicon reduces impact of plant nitrogen in promoting stalk borer (*Eldana saccharina*) but not sugarcane thrips (*Fulmekiola serrata*) infestations in sugarcane		2014		1	Pest management. Stem borer on sugarcane.
Cretaceous (Albian-early Santonian) palynology and stratigraphy of the Abu Tunis 1x borehole, northern Western Desert, Egypt		2014		1	No plant-soil interactions. Study focuses on palynology.
Using impacts of deep-level mining to research karst hydrology—a Darcy-based approach to predict the future of dried-up dolomitic springs in the Far West Rand goldfield (South Africa). Part 2: predicting inter-compartmental flow and final groundwater tables		2014		1	No plant-soil interactions. Hydrogeological approach.
Analysis of active rotenone concentration during treatment of the Rondegat River, Cape Floristic Region, South Africa		2014		1	No plant-soil interactions. Study focuses on fish.
Preliminary evaluation of the impact of invasive smallmouth bass *Micropterus dolomieu* on native fish abundance in the Witte River, Cape Floristic Region, South Africa		2014		1	No plant-soil interactions. Study focuses on fish.
Determining the minimum effective dose of rotenone for eradication of alien smallmouth bass *Micropterus dolomieu* from a South African river		2013		1	No plant-soil interactions. Study focuses on fish.
Comparison of medium-term organic and inorganic fertiliser application on leaf nutrient concentration and yield of maize in rural agriculture in the Mbizana area, Eastern Cape province, South Africa		2013		1	Comparisons of different fertilisers on maize yield
Fish distributions in the Rondegat River, Cape Floristic Region, South Africa, and the immediate impact of rotenone treatment in an invaded reach		2013		1	No plant-soil interactions. Study focuses on fish.
New taxa of *Hesperantha* (Iridaceae: Crocoideae) from the southern African winter rainfall region and a review of the *H. pilosa* complex		2013	1		
Effects of liming and inorganic fertiliser application on soil properties and maize growth and yield in rural agriculture in the Mbizana area, Eastern Cape province, South Africa		2012		1	Liming on maize yield.

Liming improves herbage yield, essential oil yield and nutrient uptake of rose-scented geranium (*Pelargonium capitatum* × *P. radens*) on acidic soils		2011		1	Liming on rose-scented geranium on acidic soil
Gazania lanata and *G. splendidissima*: Two new species of Asteraceae (tribe Arctotideae) from the Greater Capensis, with an updated key for the genus		2011	1		
Present status and historical changes in the fish fauna of the Berg River, South Africa		2009		1	No plant-soil interactions. Study focuses more on mining pollution on water and soil
The Oued Mellègue: Mining activity, stream sediments and dispersion of base metals in natural environments, North-western Tunisia		2009		1	No plant-soil interactions. Study focuses on fish.
Late Pleistocene stalagmite growth in Wolkberg Cave, South Africa		2009		1	No plant-soil interactions. Study focuses on formation of stalagmites
Water and fertilizer influence on yield of grain sorghum varieties produced in Burkina Faso		2009		1	No plant-soil interactions. Study focuses on the production of a beer called dolo that is made from Sorghum
The impact of invasive fish and invasive riparian plants on the invertebrate fauna of the Rondegat River, Cape Floristic Region, South Africa		2008		1	No plant-soil interactions. Study focuses on invasive plants and fish.
Cattle manure and grass residues as liming materials in a semi-subsistence farming system		2008		1	No plant-soil interactions. Study focuses on different liming materials

Soil properties and processes driving the leaching of nitrate in the forested catchments of the eastern escarpment of South Africa		2006		1	No plant-soil interactions. Study focuses on soil properties forested vs grassland soils
Dolomitic vegetation of the Sterkfontein Caves World Heritage Site and its importance in the conservation of Rocky Highveld Grassland		2005	1		
The predatory impact of invasive alien smallmouth bass, *Micropterus dolomieu* (Teleostei: Centrarchidae), on indigenous fishes in a Cape Floristic Region mountain stream		2005		1	No plant-soil interactions. Study focuses on fish.
Origin and evolution of major salts in the Darling pans, Western Cape, South Africa		2004		1	No plant-soil interactions. Study focuses on formation of salts in pans
A geological comparison of the Sishen and Sishen South (Welgevonden) iron ore deposits, Northern Cape Province, South Africa		2003		1	No plant-soil interactions. Study focuses on iron ore deposits and the development of sinkholes
Nutrient cycling in a *Pinus patula* plantation in the Mpumalanga Province, South Africa		2002		1	No plant-soil interactions. Study focuses on nutrient cycling in plantations
Classification and ordination of plant communities of the Naukluft Mountains, Namibia		2001	1		
The occurrence of sinkholes and subsidence depressions in the far West Rand and Gauteng province, South Africa, and their engineering implications		2001		1	No plant-soil interactions. Study focuses on sinkholes
Post-Gondwana pedogenic ferromanganese deposits, ancient soil profiles, African land surfaces and palaeoclimatic change on the Highveld of South Africa		1999		1	No plant-soil interactions. Study has a geological approach

Post Gondwana African land surfaces and pedogenetic ferromanganese deposits on the Witwatersrand at the West Wits Gold Mine, South Africa		1999		1	No plant-soil interactions. Study has a geological approach
87Sr/86Sr ratios in modern and fossil food-webs of the Sterkfontein Valley: Implications for early hominid habitat preference		1998		1	No plant-soil interactions. Study focuses on potential contribution of strontium isotopes to the reconstruction of early hominid behaviour
Earliest laterites and possible evidence for terrestrial vegetation in the Early Proterozoic		1998		1	No plant-soil interactions. Study has a geological approach
A classification of the vegetation of the western Transvaal dolomite and chert grassland, South Africa		1994	1		
Endemic flora of the north-eastern Transvaal Escarpment, South Africa		1993	1		
(TITLE-ABS-KEY (africa*) AND TITLE-ABS-KEY (calcareous*) AND TITLE-ABS-KEY (plant*) OR TITLE-ABS-KEY (vegetation) OR TITLE-ABS-KEY (flor*)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (AFFILCOUNTRY , "South Africa") OR LIMIT-TO (AFFILCOUNTRY , "Egypt") OR LIMIT-TO (AFFILCOUNTRY , "Tunisia") OR LIMIT-TO (AFFILCOUNTRY , "Malawi") OR LIMIT-TO (AFFILCOUNTRY , "Morocco") OR LIMIT-TO (AFFILCOUNTRY , "Algeria") OR LIMIT-TO (AFFILCOUNTRY , "Cameroon") OR LIMIT-TO (AFFILCOUNTRY , "Libyan Arab Jamahiriya") OR LIMIT-TO (AFFILCOUNTRY , "Namibia") OR LIMIT-TO (AFFILCOUNTRY , "Nigeria") OR LIMIT-TO (AFFILCOUNTRY , "Senegal") OR LIMIT-TO (AFFILCOUNTRY , "Uganda")) AND (EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "NURS") OR EXCLUDE (	**20**	**1991-2016**	**10**	**10**	

SUBJAREA , "SOCI")) AND (EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "EART"))					
Performance of 'Subirana' flat peach cultivar budded on different Prunus rootstocks in a warm production area in North Africa		2016		1	No plant-soil interactions. Study evaluated the performance and fruit yield of different peach cultivars
Distribution of calcareous nannoplankton in surface sediments along the northern KwaZulu-Natal Bight, South Africa		2016		1	No plant-soil interactions. Study focuses on nannoplankton
Soil type influences crop mineral composition in Malawi		2015		1	No plant-soil interactions. Study has agricultural approach
Argyrolobium uniflorum Seedlings Respond Strongly to Small Doses of Phosphorus: Consequences for Rehabilitating Degraded Arid Fallows in Presaharian Tunisia		2012	1		
Enhancing white lupin (*Lupinus albus* L.) adaptation to calcareous soils through selection of lime-tolerant plant germplasm and *Bradyrhizobium* strains		2012		1	No plant-soil interactions. Study has agricultural approach
Effects of grazing and trampling on primary production and soil surface in North African rangelands		2010	1		

Effects of 5-year application of municipal solid waste compost on the distribution and mobility of heavy metals in a Tunisian calcareous soil		2009		1	No plant-soil interactions. Study focuses on the accumulation of heavy metals in calcareous soils and seems to be more an agricultural approach
Obtaining the parameters required to model labile phosphorus for south african soils		2009		1	No direct plant-soil interactions. Focuses more on soil classification
A new species of *Euclea* (Ebenaceae) from ultramafic soils in Sekhukhuneland, South Africa, with notes on its ecology		2008	1		
Environment and vegetation of *Randonia africana*: An endangered desert plant in Egypt		2007	1		
Vegetation associates of the endangered *Randonia africana* Coss. and its soil characteristics in an arid desert ecosystem of western Egypt		2006	1		Duplicate study
Dune vegetation and coastal thicket plant communities in threatened limestone fynbos of Andrew's Field and Tsaba-Tsaba Nature Reserve, Struisbaai, Western Cape		2006	1		
The coastal roadside vegetation and environmental gradients in the arid lands of Egypt		2005	1		
Soil characteristics and vegetation associates of the endangered *Randonia africana* Coss. in arid desert ecosystem of Western Egypt		2005		1	The same study published in another journal in another year. Google Scholar only provides the 2006 publication.
The effect of irrigated rice cropping on the alkalinity of two alkaline rice soils in the Sahel		2004		1	Agricultural perspective, rice cropping and alkaline soils

Acidic iron oxide waste as a conditioner for calcareous soils		2002		1	Agricultural perspective. Study addresses the potential to use acid iron waste on agricultural soils.
Recent ecosystem dynamics in nine North African lakes in the CASSARINA Project		2001		1	No plant-soil interactions. Study follows an aquatic ecology perspective.
Convergence and non-convergence of plant traits in climatically and edaphically matched sites in Mediterranean Australia and South Africa		1994	1		
The *Eucleo divinori - Acacietum nigricentis*, a new association from the calcareous bottomland clays of the Manyeleti Game Reserve, Eastern Transvaal Lowveld, Gazankulu, South Africa		1991	1		
Disturbance regimes as determinants of seed banks in coastal dune vegetation of the southeastern Cape		1991	1		
(TITLE-ABS-KEY (africa*) AND TITLE-ABS-KEY (limestone) AND TITLE-ABS-KEY (plant*) OR TITLE-ABS-KEY (vegetation) OR TITLE-ABS-KEY (flor*)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (EXCLUDE (SUBJAREA , "ENGI") OR EXCLUDE (SUBJAREA , "SOCI") OR EXCLUDE (SUBJAREA , "BUSI") OR EXCLUDE (SUBJAREA , "CENG") OR EXCLUDE (SUBJAREA , "MATE") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "COMP") OR EXCLUDE (SUBJAREA , "ENER") OR EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "MATH") OR EXCLUDE (SUBJAREA , "NEUR")) AND (EXCLUDE (SUBJAREA , "EART") OR EXCLUDE (SUBJAREA , "BIOC")) AND (LIMIT-TO (AFFILCOUNTRY , "South Africa") OR LIMIT-TO (AFFILCOUNTRY , "Tunisia") OR LIMIT-TO (AFFILCOUNTRY , "Congo") OR LIMIT-TO (AFFILCOUNTRY , "Egypt") OR LIMIT-TO (AFFILCOUNTRY , "Madagascar") OR LIMIT-TO (AFFILCOUNTRY , "Undefined")	**31**	**2018-1987**	**17**	**14**	

Effect of soil- and foliar-applied nitrogen fertiliser on growth, yield and protein content of spring wheat (*Triticum aestivum* L.) under glasshouse conditions		2018		1	Agricultural approach. Liming.
Effect of phosphorus and nitrogen sources on essential nutrient concentration and uptake by maize (*Zea mays* L.) during early growth and development		2017		1	Agricultural approach. Liming.
Evaluation of the effects of phosphorus and nitrogen source on aerial and subsoil parameters of maize (*Zea mays* L.) during early growth and development		2016		1	Agricultural approach. Liming.
Predicting bat distributions and diversity hotspots in Southern Africa		2016		1	No plant-soil interactions. Study focuses on bats
Differentiation of the biogeochemical niches of legumes and non-legumes in the Cape Floristic Region of South Africa		2015	1		
Three years of phytostabilisation experiment of bare acidic soil extremely contaminated by copper smelting using plant biodiversity of metal-rich soils in tropical Africa (Katanga, DR Congo)		2015		1	Application of limestone and compost on acidic soil contaminated by copper-smelting. Phytostabilisation on the wrong substrate…
Risk assessment of the *Acacia cyclops* dieback pathogen, *Pseudolagarobasidium acaciicola*, as a mycoherbicide in South African strandveld and limestone fynbos		2015		1	No plant-soil interactions. Study focuses on the use of a mycoherbicide controlling an invasive weed species in limestone fynbos.
Vegetation change in variable rangeland environments: The relative contribution of drought and soil type in arid rangelands		2013	1		
Insights and lessons learned from the long-term rehabilitation of an iron ore mine		2013		1	Rehabilitation of mine dumps with limestone as a fertiliser
Impact of livestock grazing on forest structure, plant species composition and biomass in Southwestern Madagascar		2013	1		

New taxa of *Hesperantha* (Iridaceae: Crocoideae) from the southern African winter rainfall region and a review of the *H. pilosa* complex		2013		1	Already included
Effect of tillage systems and nitrogen application rates on selected physical and biological properties of a clay loam soil in KwaZulu-Natal, South Africa		2012		1	Agricultural approach. Ferilizing with limestone ammonium nitrate.
Systematics of the hypervariable *Moraea tripetala* complex (Iridaceae: Iridoideae) of the southern African winter rainfall zone		2012	1		
Liming improves herbage yield, essential oil yield and nutrient uptake of rose-scented geranium (*Pelargonium capitatum* × *P. radens*) on acidic soils		2011		1	Horticultural/agricultural approach. Liming
Strontium isotope analyses of large herbivore habitat use in the Cape Fynbos region of South Africa		2010	1		
Two new species of Asteraceae (tribe Anthemideae, subtribe Pentziinae) from the Cape Floristic Region of South Africa		2010	1		
A revision of the genus *Glia* (Apiaceae, tribe Heteromorpheae)		2010	1		
Effects of grazing and trampling on primary production and soil surface in North African rangelands		2010		1	Already included
Dissolution rate of South African calcium-based materials at constant pH		2009		1	No plant-soil interactions
Dune vegetation and coastal thicket plant communities in threatened limestone fynbos of Andrew's Field and Tsaba-Tsaba Nature Reserve, Struisbaai, Western Cape		2006		1	Already included
Recovery of thicket in a revegetated limestone mine		2003	1		
Plant communities in two vegetation transects in the extreme desert of western Egypt		2003	1		Could not be retrieved through the internet or library services.
A shared niche? The case of the species pair *Protea obtusifolia-Leucadendron meridianum*		1997	1		
Patterns of endemism in the limestone flora of South African lowland fynbos		1996	1		
Reserve systems for limestone endemic flora of the Cape lowland fynbos: Iterative versus linear programming		1996	1		
Reproductive traits of two closely related species-pairs on adjacent,		1994	1		

different soil types in South African Fynbos					
Taxonomic, edaphic and biological aspects of narrow plant endemism on matched sites in mediterranean South Africa and Australia		1994	1		
Convergence and non-convergence of plant traits in climatically and edaphically matched sites in Mediterranean Australia and South Africa		1994		1	Already included
Endemism and speciation in a lowland flora from the Cape Floristic Region		1992	1		
How small can reserves be? An empirical approach in Cape Fynbos, South Africa		1991	1		
The cation status of some indigenous plants from a Cango valley limestone-sandstone transition, South Africa		1987	1		
Number of studies included			**35**		

Table A3. Results from Scopus search with reasons why certain studies were excluded, for August 2019.

Scopus search string	Number of articles	Year	Included	Excluded	Motivation for exclusion
(TITLE-ABS-KEY (africa*) AND TITLE-ABS-KEY (dolo*) AND TITLE-ABS-KEY (plant*) OR TITLE-ABS-KEY (vegetation) OR TITLE-ABS-KEY (flor*)) AND (LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018)) AND (LIMIT-TO (SUBJAREA , "AGRI")) AND (LIMIT-TO (AFFILCOUNTRY , "South Africa"))	**2**	**2018-2019**			
Plant endemism in Griqualand West, South Africa		2019	1		
The effects of abiotic factors in South African semi-arid grassland communities on *Seriphium plumosum* L density and canopy size		2018		1	Already included
(TITLE-ABS-KEY (africa*) AND TITLE-ABS-KEY (calcareous*) AND TITLE-ABS-KEY (plant*) OR TITLE-ABS-KEY (vegetation) OR TITLE-ABS-KEY (flor*)) AND (LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (AFFILCOUNTRY , "Cameroon") OR LIMIT-TO (AFFILCOUNTRY , "South Africa")) AND (LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "AGRI"))	**2**				
Reaction of South African rye, triticale and barley forage cultivars to stem and leaf rust		2019		1	Agricultural approach
Cretaceous-Tertiary Foraminifera and Palynomorphs from Djega Section and Inferred Paleodepositional Environments, Rio Del Rey Basin, Cameroon, West Africa		2018		1	Paleontology

(TITLE-ABS-KEY (africa*) AND TITLE-ABS-KEY (limestone) AND TITLE-ABS-KEY (plant*) OR TITLE-ABS-KEY (vegetation) OR TITLE-ABS-KEY (flor*)) AND (LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (AFFILCOUNTRY , "South Africa") OR LIMIT-TO (AFFILCOUNTRY , "Ethiopia")) AND (EXCLUDE (SUBJAREA , "EART") OR EXCLUDE (SUBJAREA , "SOCI") OR EXCLUDE (SUBJAREA , "ARTS") OR EXCLUDE (SUBJAREA , "COMP") OR EXCLUDE (SUBJAREA , "ENER") OR EXCLUDE (SUBJAREA , "MATE") OR EXCLUDE (SUBJAREA , "MATH"))	**3**				
Plant endemism in Griqualand West, South Africa		2019		1	Already included
The Gerire Hills, a SE Ethiopian outpost of the transitional semi-evergreen bushland: vegetation, endemism and three new species, *Croton elkerensis* (Euphorbiaceae), *Gnidia elkerensis* (Thymelaeaceae), and *Plectranthus spananthus* (Lamiaceae)		2018		1	Endemics mostly on sandstone. The authors refer to similar plant species that are endemic to limestone soils.
Effect of soil- and foliar-applied nitrogen fertiliser on growth, yield and protein content of spring wheat (*Triticum aestivum* L.) under glasshouse conditions		2018		1	Agricultural approach

(TITLE-ABS-KEY (limestone) AND TITLE-ABS-KEY (endemic) AND TITLE-ABS-KEY (species)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (AFFILCOUNTRY , "South Africa") OR LIMIT-TO (AFFILCOUNTRY , "Ethiopia") OR LIMIT-TO (AFFILCOUNTRY , "Egypt") OR LIMIT-TO (AFFILCOUNTRY , "Eritrea") OR LIMIT-TO (AFFILCOUNTRY , "Kenya") OR LIMIT-TO (AFFILCOUNTRY , "Tunisia")) AND (EXCLUDE (SUBJAREA , "EART") OR EXCLUDE (SUBJAREA , "BIOC")) AND (EXCLUDE (AFFILCOUNTRY , "United Kingdom") OR EXCLUDE (AFFILCOUNTRY , "United States") OR EXCLUDE (AFFILCOUNTRY , "Australia") OR EXCLUDE (AFFILCOUNTRY , "Denmark") OR EXCLUDE (AFFILCOUNTRY , "France") OR EXCLUDE (AFFILCOUNTRY , "Ireland") OR EXCLUDE (AFFILCOUNTRY , "Luxembourg") OR EXCLUDE (AFFILCOUNTRY , "Netherlands") OR EXCLUDE (AFFILCOUNTRY , "Portugal") OR EXCLUDE (AFFILCOUNTRY , "Switzerland") OR EXCLUDE (AFFILCOUNTRY , "Thailand"))	**9**				
Plant endemism in Griqualand West, South Africa		2019		1	Already included
Deverra rapaletsa (Apiaceae), a new limestone endemic species from the Ghaap Plateau, Northern Cape, South Africa		2019	1		
Two new species of Asteraceae (tribe Anthemideae, subtribe Pentziinae) from the Cape Floristic Region of South Africa		2010		1	Already included
Annesorhiza calcicola (Apiaceae), a new limestone endemic species from the Western Cape Province of South Africa		2010	1		
A revision of the genus *Glia* (Apiaceae, tribe Heteromorpheae)		2010		1	Already included
Threatened Limestone Fynbos plant communities of Andrew's Field and Tsaba-Tsaba Nature Reserve, Western Cape		2007	1		
Dune vegetation and coastal thicket plant communities in threatened limestone fynbos of Andrew's Field and Tsaba-Tsaba Nature Reserve, Struisbaai, Western Cape		2006		1	Already included
Patterns of endemism in the limestone flora of South African lowland fynbos		1996		1	Already included

Endemism and speciation in a lowland flora from the Cape Floristic Region		1992		1	Already included
(TITLE-ABS-KEY (africa*) AND TITLE-ABS-KEY (calcrete) AND TITLE-ABS-KEY (vegetation) OR TITLE-ABS-KEY (plant*) OR TITLE-ABS-KEY (flor*)) AND (EXCLUDE (SUBJAREA , "EART") OR EXCLUDE (SUBJAREA , "ENGI") OR EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "SOCI") OR EXCLUDE (SUBJAREA , "ARTS") OR EXCLUDE (SUBJAREA , "MULT"))	**4**				
The influence of fire frequency on the structure and botanical composition of savanna ecosystems		2019		1	No plant-soil interactions investigated
Growing islands and sinking solutes: Processes maintaining the endorheic Okavango Delta as a freshwater system		2008		1	No plant-soil interactions investigated
Landscapes in the Kalahari Gemsbok National Park, South Africa		2008	1		
Synopsis of the genus *Rennera* Merxm. (Asteraceae, Anthemideae) with the description of a new species from South Africa		1999	1		
Number of studies included	**20**		**6**	**14**	

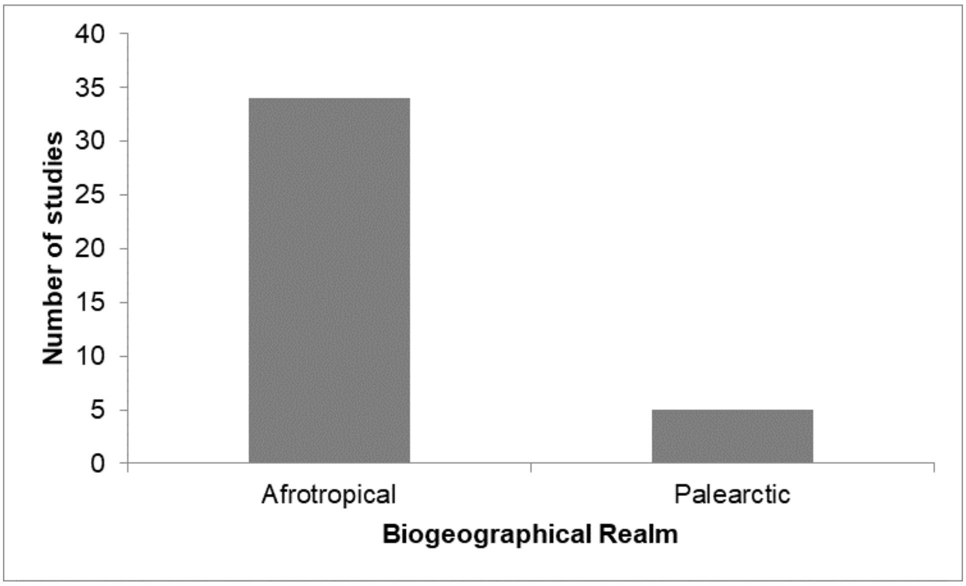

Figure A2. Biogeographical Realms that were included in publications.

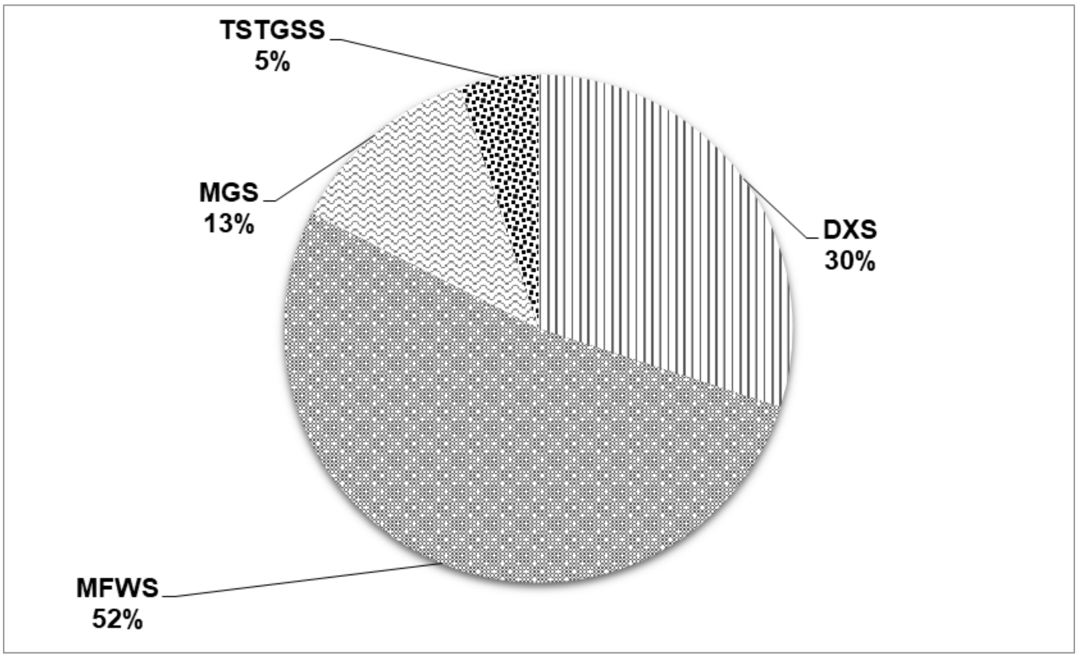

Figure A3. Percentage of studies within World Biomes. DXS - Deserts and Xeric Shrublands; MFWS - Mediterranean Forests, Woodlands and Scrub; MGS - Montane Grasslands and Shrublands; TSTGSS -Tropical and Subtropical Grasslands, Savannas and Shrublands.

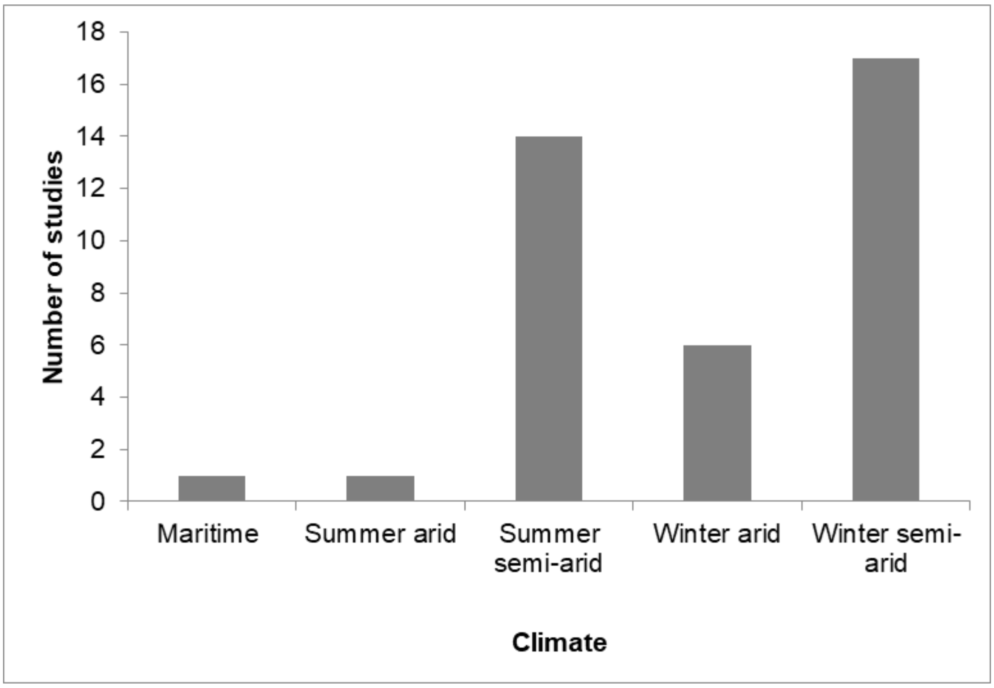

Figure A4. Climate associated with carbonate plant community studies in Africa.

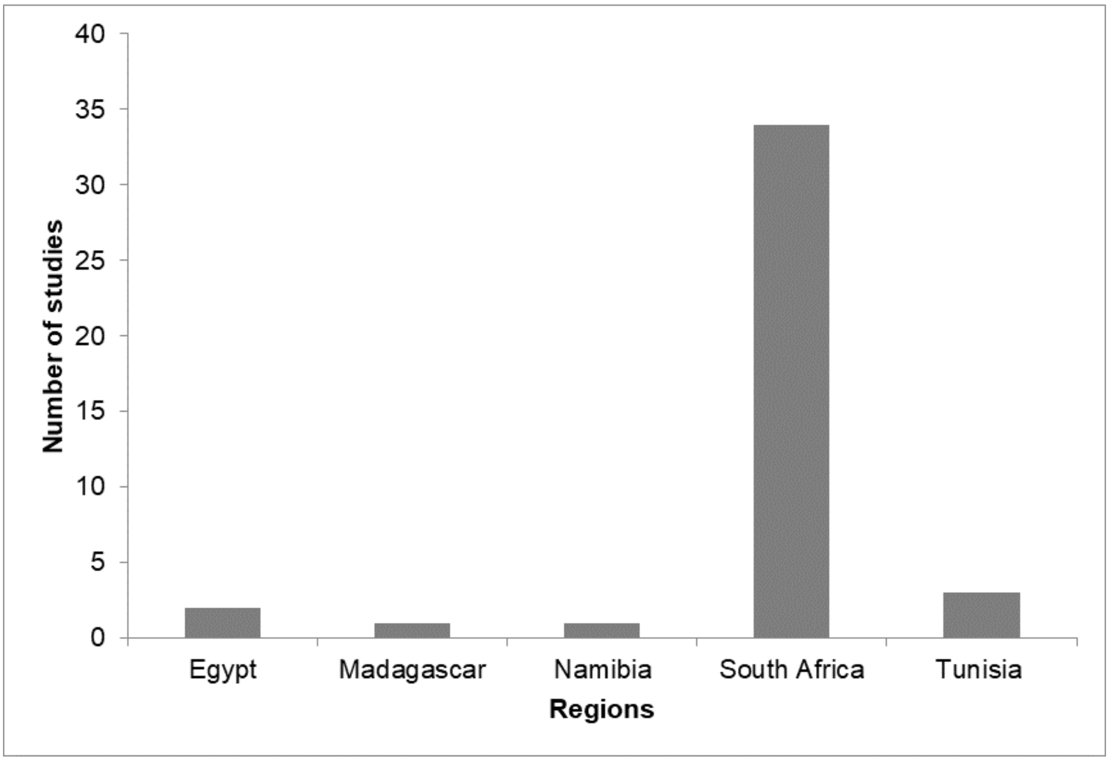

Figure A5. Geographical regions (study areas) that harboured researched calcicolous flora in Africa.

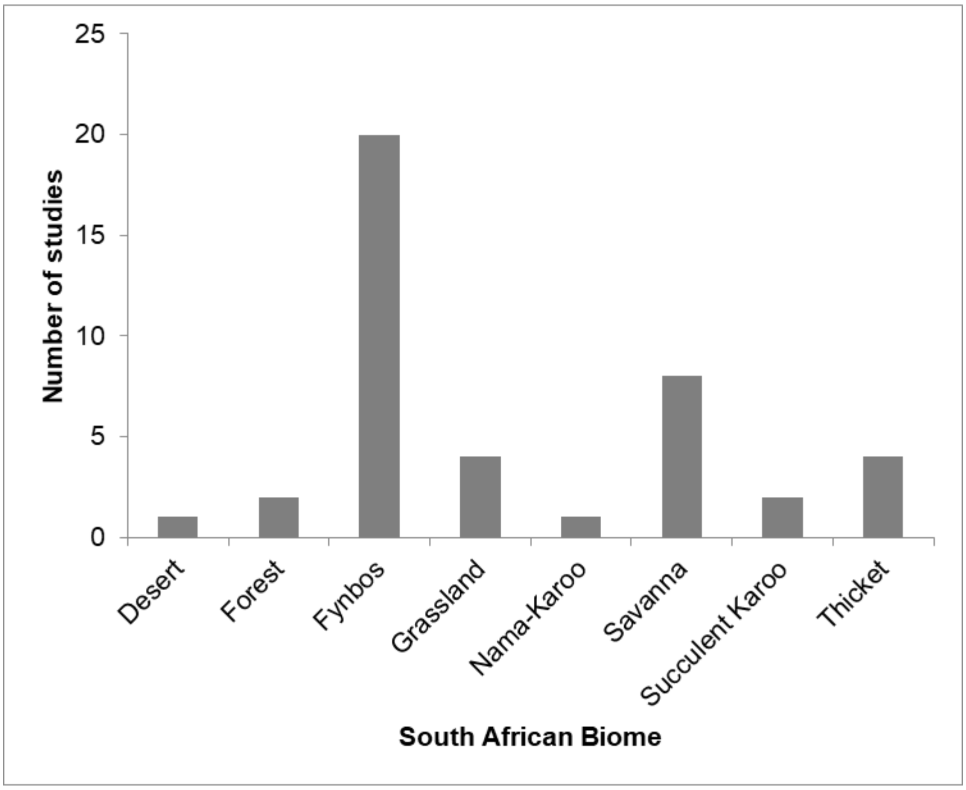

Figure A6. Publications within biomes of South Africa.

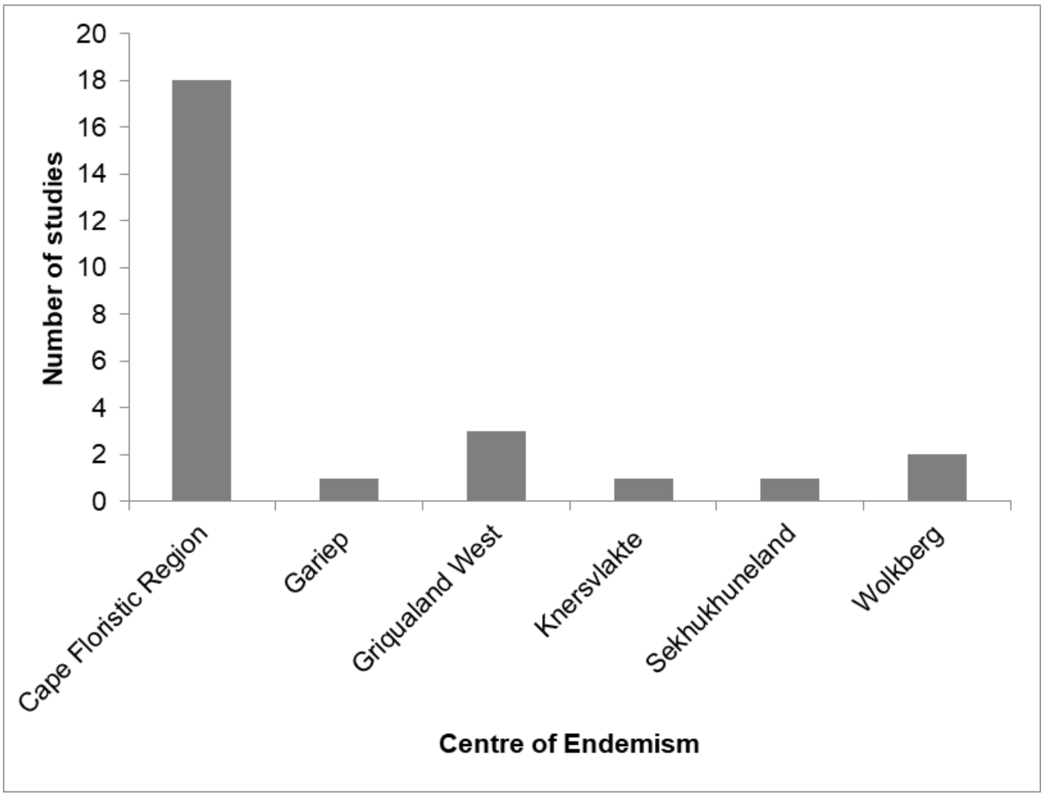

Figure A7. Studies within centres of endemism in South Africa.

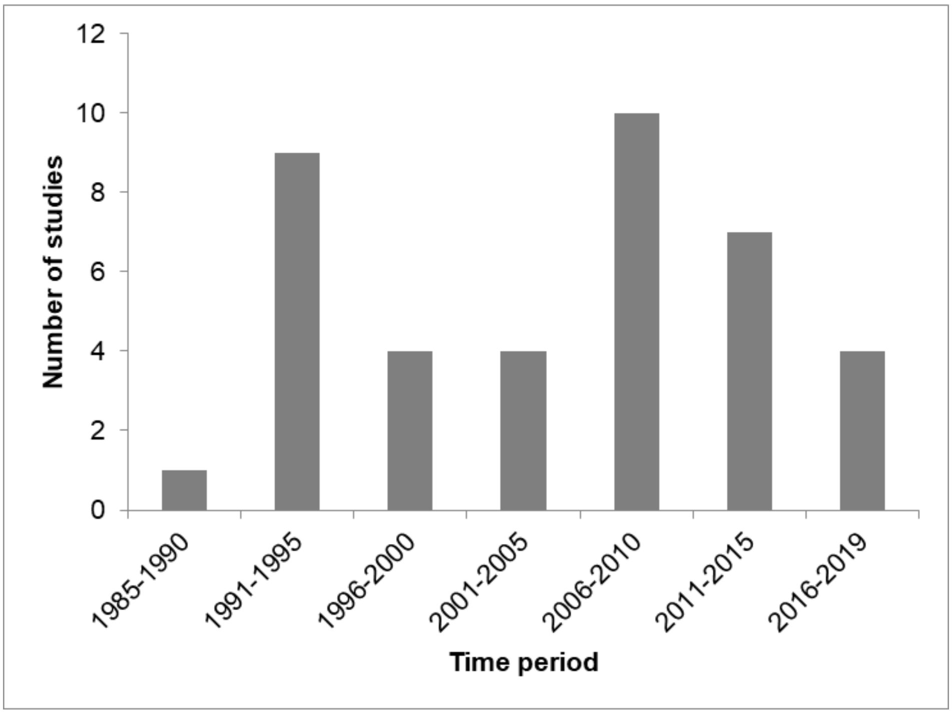

Figure A8. Number of studies conducted in Africa during certain time periods.

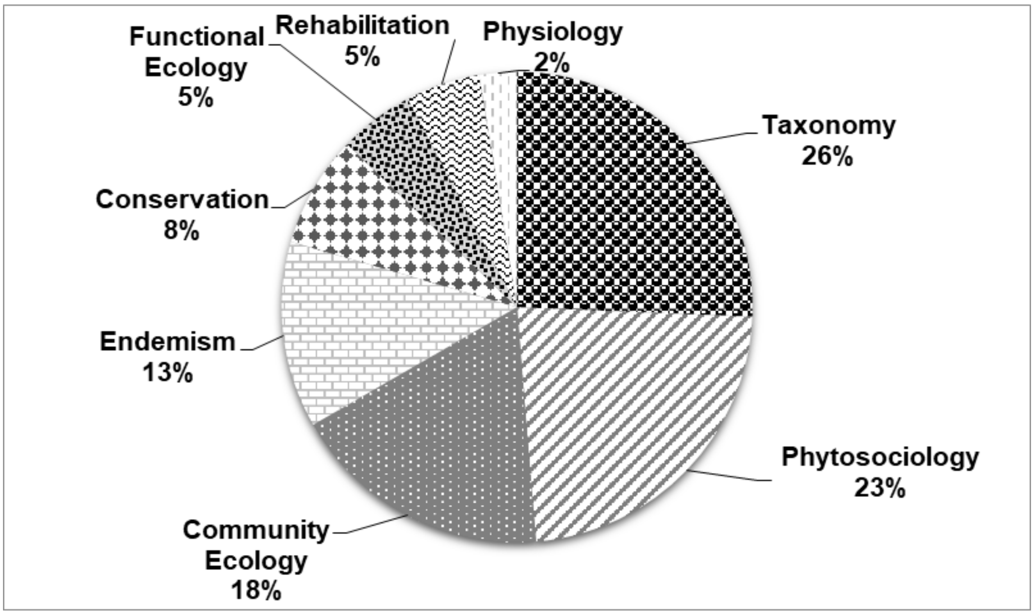

Figure A9. Percentage of studies included within broad themes.

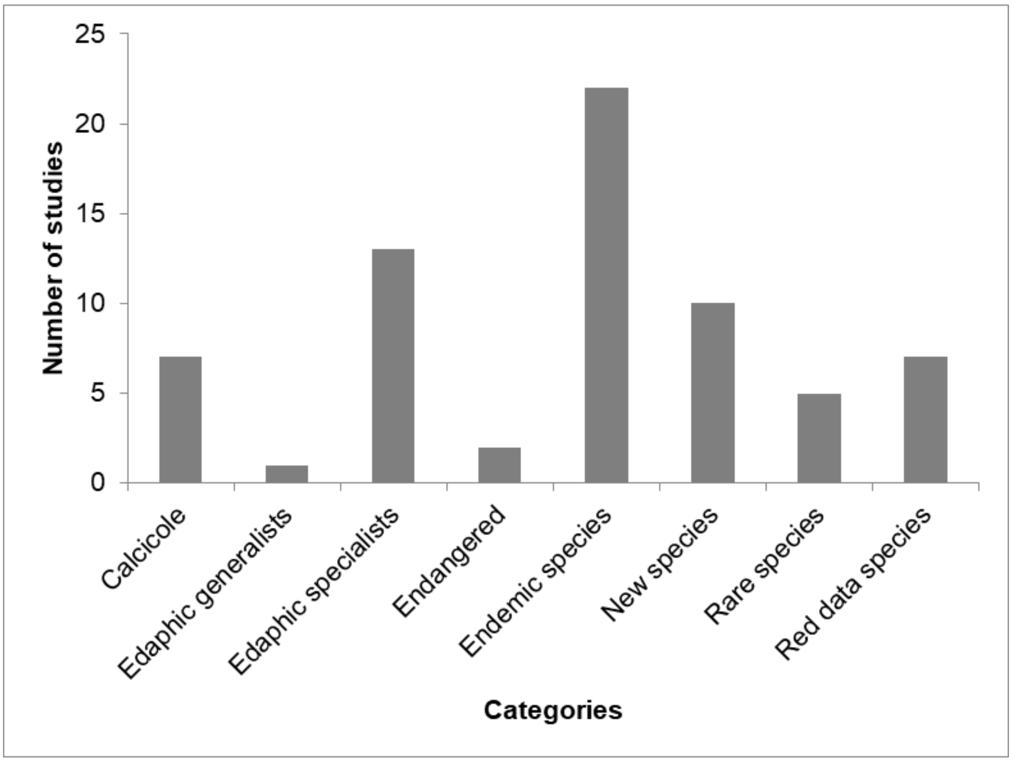

Figure A10. Plant species categories that were addressed in publications.

Appendix B

Supplementary tables and figures relating to Chapter 4

Table B1. Bioclimatic variables (WorldClim - Global Climate Data, 2016; Fick & Hijmans, 2017) used for the construction of the refined borders of GWC.

BIO1	Annual Mean Temperature
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO3	Isothermality (BIO2/BIO7) (*100)
BIO4	Temperature Seasonality (standard deviation *100)
BIO5	Max Temperature of Warmest Month
BIO6	Min Temperature of Coldest Month
BIO7	Temperature Annual Range (BIO5-BIO6)
BIO8	Mean Temperature of Wettest Quarter
BIO9	Mean Temperature of Driest Quarter
BIO10	Mean Temperature of Warmest Quarter
BIO11	Mean Temperature of Coldest Quarter
BIO12	Annual Precipitation
BIO13	Precipitation of Wettest Month
BIO14	Precipitation of Driest Month
BIO15	Precipitation Seasonality (Coefficient of Variation)
BIO16	Precipitation of Wettest Quarter
BIO17	Precipitation of Driest Quarter
BIO18	Precipitation of Warmest Quarter
BIO19	Precipitation of Coldest Quarter

Table B2. Geological data used for modelling purposes (Department of Environmental Affairs, 2016).

Variables	*Source*	*Scale*
Geology	E-GIS	1: 50 000

Table B3. Comprehensive plant species list according to herbarium records and field collected data for each mountain. Presence of species is indicated by √. Species names follow nomenclature as indicated by Germishuizen and Meyer (2003).

Family	Species	Herbaria	Field
Langberg			
ACANTHACEAE	*Barleria bechuanensis*	√	
ACANTHACEAE	*Barleria lichtensteiniana*	√	√
ACANTHACEAE	*Barleria rigida*		√
ACANTHACEAE	*Blepharis mitrata*	√	
ACANTHACEAE	*Justicia puberula*	√	√
ACANTHACEAE	*Justicia thymifolia*	√	
ACANTHACEAE	*Monechma divaricatum*	√	√
ACANTHACEAE	*Monechma spartioides*	√	
AIZOACEAE	*Galenia pubescens*	√	
AIZOACEAE	*Plinthus sericeus*	√	
AMARANTHACEAE	*Hermbstaedtia odorata* var.*odorata*	√	
AMARANTHACEAE	*Kyphocarpa angustifolia*		√
AMARANTHACEAE	*Pupalia lappacea*		√
AMARANTHACEAE	*Sericorema remotiflora*	√	
ANACARDIACEAE	*Searsia burchellii*	√	√
ANACARDIACEAE	*Searsia ciliata*	√	
ANACARDIACEAE	*Searsia lancea*	√	
ANACARDIACEAE	*Searsia tridactyla*	√	
ANTHERICACEAE	*Chlorophytum fasciculatum*	√	

APIACEAE	*Deverra denudata* subsp. *aphylla*	√	
APOCYNACEAE	*Fockea angustifolia*	√	
APOCYNACEAE	*Hoodia officinalis* subsp. *officinalis*	√	
APOCYNACEAE	*Huernia longituba*	√	
APOCYNACEAE	*Orthanthera jasminiflora*		√
APOCYNACEAE	*Pergularia daemia* subsp. *daemia*	√	
APOCYNACEAE	*Raphionacme velutina*		√
APOCYNACEAE	*Sarcostemma pearsonii*	√	
APOCYNACEAE	*Sarcostemma viminale* subsp. *viminale*	√	
ASPARAGACEAE	*Asparagus bechuanicus*	√	
ASPARAGACEAE	*Asparagus glaucus*		√
ASPARAGACEAE	*Asparagus laricinus*		√
ASPARAGACEAE	*Asparagus striatus*	√	
ASPARAGACEAE	*Asparagus suaveolens*	√	√
ASPLENIACEAE	*Asplenium cordatum*	√	
ASTERACEAE	*Amphiglossa tecta*	√	
ASTERACEAE	*Arctotheca calendula*	√	
ASTERACEAE	*Arctotis leiocarpa*	√	
ASTERACEAE	*Chrysocoma ciliata*	√	
ASTERACEAE	*Chrysocoma obtusata*	√	
ASTERACEAE	*Cineraria lyratiformis*	√	
ASTERACEAE	*Cineraria vallis-pacis*	√	
ASTERACEAE	*Cotula anthemoides*	√	

ASTERACEAE	*Dicoma capensis*	√	
ASTERACEAE	*Dimorphotheca polyptera*	√	
ASTERACEAE	*Dimorphotheca sinuata*	√	
ASTERACEAE	*Eriocephalus ericoides* subsp. *griquensis*	√	
ASTERACEAE	*Eriocephalus merxmuelleri*	√	
ASTERACEAE	*Euryops multifidus*	√	
ASTERACEAE	*Felicia fascicularis*	√	
ASTERACEAE	*Felicia muricata* subsp. *cinerascens*	√	
ASTERACEAE	*Felicia muricata* subsp*. muricata*	√	√
ASTERACEAE	*Garuleum schinzii* subsp. *schinzii*	√	
ASTERACEAE	*Gazania krebsiana* subsp. *serrulata*	√	√
ASTERACEAE	*Geigeria brevifolia*	√	
ASTERACEAE	*Geigeria filifolia*		√
ASTERACEAE	*Geigeria ornativa* subsp. *ornativa*	√	
ASTERACEAE	*Helichrysum arenicola*	√	
ASTERACEAE	*Helichrysum argyrosphaerum*	√	
ASTERACEAE	*Helichrysum cerastioides* var. *cerastioides*	√	
ASTERACEAE	*Helichrysum spiciforme*	√	
ASTERACEAE	*Helichrysum zeyheri*	√	√
ASTERACEAE	*Hertia kraussii*	√	
ASTERACEAE	*Hertia pallens*	√	
ASTERACEAE	*Hirpicium echinus*	√	
ASTERACEAE	*Ifloga glomerata*	√	

ASTERACEAE	*Kleinia longiflora*	√	
ASTERACEAE	*Leysera gnaphalodes*	√	
ASTERACEAE	*Lopholaena cneorifolia*	√	
ASTERACEAE	*Nolletia annetjieae*	√	
ASTERACEAE	*Nolletia arenosa*	√	
ASTERACEAE	*Nolletia ciliaris*	√	√
ASTERACEAE	*Nolletia gariepina*	√	
ASTERACEAE	*Osteospermum microphyllum*	√	
ASTERACEAE	*Osteospermum muricatum* subsp*. muricatum*	√	
ASTERACEAE	*Pechuel-Loeschea leubnitziae*		√
ASTERACEAE	*Pegolettia retrofracta*	√	√
ASTERACEAE	*Pentzia calcarea*	√	
ASTERACEAE	*Pentzia incana*	√	
ASTERACEAE	*Pseudognaphalium oligandrum*	√	
ASTERACEAE	*Psiadia punctulata*	√	
ASTERACEAE	*Pteronia glauca*	√	
ASTERACEAE	*Senecio consanguineus*	√	
ASTERACEAE	*Tarchonanthus camphoratus*	√	√
ASTERACEAE	*Tarchonanthus obovatus*	√	
ASTERACEAE	*Troglophyton capillaceum* subsp*. capillaceum*	√	
ASTERACEAE	*Ursinia nana* subsp*. nana*	√	
BIGNONIACEAE	*Rhigozum obovatum*	√	
BORAGINACEAE	*Heliotropium ciliatum*	√	

BRASSICACEAE	*Heliophila trifurca*	√	
BRASSICACEAE	*Sisymbrium burchellii* var. *burchellii*	√	
BUDDLEJACEAE	*Buddleja saligna*	√	
CAMPANULACEAE	*Wahlenbergia nodosa*		√
CAPPARACEAE	*Boscia albitrunca*		√
CAPPARACEAE	*Boscia microphylla*	√	
CAPPARACEAE	*Cleome kalachariensis*	√	
CAPPARACEAE	*Cleome monophylla*	√	
CAPPARACEAE	*Cleome rubella*		√
CARYOPHYLLACEAE	*Corrigiola litoralis* subsp. *litoralis* var.*litoralis*	√	
CELASTRACEAE	*Gymnosporia polycantha*		√
CELASTRACEAE	*Maytenus ilicina*	√	
CELASTRACEAE	*Maytenus undata*	√	
CELASTRACEAE	*Putterlickia pyracantha*	√	
CELASTRACEAE	*Putterlickia saxatilis*	√	√
CHENOPODIACEAE	*Salsola marginata*	√	
CHENOPODIACEAE	*Salsola rabieana*	√	
CHENOPODIACEAE	*Suaeda fruticosa*	√	
COLCHICACEAE	*Ornithoglossum dinteri*		√
COLCHICACEAE	*Ornithoglossum vulgare*	√	
COMBRETACEAE	*Terminalia sericea*	√	
COMMELINACEAE	*Commelina africana*		√
COMMELINACEAE	*Commelina africana* var. *lancispatha*	√	

CONVOLVULACEAE	*Evolvulus alsinoides*		√
CONVOLVULACEAE	*Ipomoea bolusiana*	√	
CONVOLVULACEAE	*Ipomoea magnusiana*	√	
CONVOLVULACEAE	*Ipomoea obscura*		√
CONVOLVULACEAE	*Ipomoea oenotheroides*	√	
CONVOLVULACEAE	*Merremia verecunda*	√	
CONVOLVULACEAE	*Seddera suffruticosa*		√
CONVOLVULACEAE	*Xenostegia tridentata* subsp. *angustifolia*	√	
CRASSULACEAE	*Kalanchoe paniculata*		√
CUCURBITACEAE	*Acanthosicyos naudinianus*	√	
CUCURBITACEAE	*Coccinia rehmannii*	√	
CUCURBITACEAE	*Cucumis africanus*	√	
CUCURBITACEAE	*Cucumis heptadactylis*		√
CUCURBITACEAE	*Cucumis myriocarpus*		√
CUCURBITACEAE	*Momordica balsamina*	√	
CUCURBITACEAE	*Peponium caledonicum*	√	
CYPERACEAE	*Bulbostylis burchellii*	√	
CYPERACEAE	*Bulbostylis hispidula* subsp. *pyriformis*	√	√
CYPERACEAE	*Bulbostylis humilis*		√
CYPERACEAE	*Cyperus atriceps*	√	
CYPERACEAE	*Cyperus congestus*	√	
CYPERACEAE	*Cyperus margaritaceus* var. *margaritaceus*	√	√
CYPERACEAE	*Cyperus rupestris* var. *rupestris*	√	

CYPERACEAE	*Cyperus usitatus*	√	
CYPERACEAE	*Isolepis sepulcralis*	√	
CYPERACEAE	*Isolepis setacea*	√	
CYPERACEAE	*Kyllinga alba*	√	
CYPERACEAE	*Schoenoplectus muriculatus*	√	
EBENACEAE	*Diospyros lycioides* subsp. *lycioides*	√	
EBENACEAE	*Euclea undulata*	√	√
EUPHORBIACEAE	*Croton gratissimus* var. *gratissimus*	√	√
EUPHORBIACEAE	*Euphorbia avasmontana* var. *avasmontana*	√	
EUPHORBIACEAE	*Euphorbia duseimata*	√	
EUPHORBIACEAE	*Euphorbia ephedroides* var. *ephedroides*	√	
EUPHORBIACEAE	*Euphorbia gariepina* subsp. *gariepina*	√	
EUPHORBIACEAE	*Euphorbia mauritanica* var. *mauritanica*	√	√
EUPHORBIACEAE	*Euphorbia rectirama*	√	
EUPHORBIACEAE	*Jatropha erythropoda*	√	
EUPHORBIACEAE	*Phyllanthus incurvus*		√
EUPHORBIACEAE	*Phyllanthus parvulus*		√
FABACEAE	*Calobota spinescens*	√	
FABACEAE	*Coelidium muraltioides*	√	
FABACEAE	*Crotalaria griquensis*		√
FABACEAE	*Crotalaria sphaerocarpa* subsp. *sphaerocarpa*	√	
FABACEAE	*Crotalaria virgultalis*	√	
FABACEAE	*Cullen tomentosum*	√	

FABACEAE	*Cyamopsis serrata*	√	
FABACEAE	*Elephantorrhiza elephantina*		√
FABACEAE	*Indigastrum argyraeum*	√	
FABACEAE	*Indigofera bainesii*		√
FABACEAE	*Indigofera charlieriana* var. *lata*	√	
FABACEAE	*Indigofera daleoides* var. *daleoides*	√	
FABACEAE	*Indigofera damarana*	√	
FABACEAE	*Indigofera heterotricha*	√	
FABACEAE	*Indigofera sordida*		√
FABACEAE	*Indigofera vicioides*		√
FABACEAE	*Lessertia macrostachya* var. *macrostachya*	√	
FABACEAE	*Lessertia pauciflora* var. *pauciflora*	√	
FABACEAE	*Lotononis crumanina*	√	
FABACEAE	*Lotononis listii*	√	
FABACEAE	*Lotononis parviflora*	√	
FABACEAE	*Melolobium calycinum*	√	
FABACEAE	*Melolobium candicans*	√	
FABACEAE	*Pomaria burchellii* subsp. *burchellii*	√	
FABACEAE	*Rhynchosia confusa*		√
FABACEAE	*Rhynchosia totta*		√
FABACEAE	*Senegalia mellifera* subsp. *detinens*	√	√
FABACEAE	*Senna italica* subsp. *arachoides*	√	
FABACEAE	*Sutherlandia frutescens*	√	

FABACEAE	*Sutherlandia humilis*	√	
FABACEAE	*Tephrosia burchellii*		√
FABACEAE	*Tephrosia longipes*		√
FABACEAE	*Tephrosia pupurea*		√
FABACEAE	*Vachellia erioloba*		√
FABACEAE	*Vachellia erioloba x haematoxylon*	√	
FABACEAE	*Vachellia haematoxylon*	√	
GERANIACEAE	*Monsonia angustifolia*		√
GISEKIACEAE	*Gisekia africana*		√
GISEKIACEAE	*Gisekia pharnacioides*		√
HALORAGACEAE	*Laurembergia repens* subsp. *brachypoda*	√	
HYACINTHACEAE	*Albuca setosa*	√	
HYACINTHACEAE	*Dipcadi marlothii*	√	
HYACINTHACEAE	*Dipcadi rigidifolium*	√	√
HYACINTHACEAE	*Drimia altissima*		√
HYACINTHACEAE	*Drimia intricata*	√	√
HYACINTHACEAE	*Drimia sanguinea*	√	
HYACINTHACEAE	*Ledebouria undulata*	√	
HYPERICACEAE	*Hypericum lalandii*	√	
IRIDACEAE	*Babiana bainesii*	√	
IRIDACEAE	*Freesia andersoniae*	√	
IRIDACEAE	*Gladiolus permeabilis* subsp*. edulis*	√	
IRIDACEAE	*Lapeirousia littoralis* subsp*. caudata*	√	

IRIDACEAE	*Lapeirousia littoralis* subsp. *littoralis*	√	
JUNCACEAE	*Juncus oxycarpus*	√	
LAMIACEAE	*Leucas capensis*		√
LAMIACEAE	*Salvia namaensis*	√	
LAMIACEAE	*Salvia verbenaca*	√	
LAMIACEAE	*Stachys burchelliana*	√	√
LOBELIACEAE	*Lobelia erinus*	√	
LORANTHACEAE	*Septulina glauca*	√	
LORANTHACEAE	*Tapinanthus oleifolius*	√	
MALVACEAE	*Abutilon dinteri*	√	
MALVACEAE	*Grewia flava*	√	√
MALVACEAE	*Hermannia bryoniifolia*	√	
MALVACEAE	*Hermannia burchellii*	√	
MALVACEAE	*Hermannia burkei*	√	
MALVACEAE	*Hermannia comosa*	√	
MALVACEAE	*Hermannia erodioides*	√	
MALVACEAE	*Hermannia minutiflora*	√	
MALVACEAE	*Hermannia modesta*	√	
MALVACEAE	*Hermannia quartiniana*	√	
MALVACEAE	*Hermannia spinosa*	√	
MALVACEAE	*Hermannia tomentosa*	√	
MALVACEAE	*Hibiscus fleckii*	√	
MALVACEAE	*Hibiscus micranthus*		√

MALVACEAE	*Hibiscus pusillus*		√
MALVACEAE	*Melhania damarana*	√	
MALVACEAE	*Melhania prostrata*	√	√
MALVACEAE	*Melhania rehmannii*	√	√
MALVACEAE	*Sida chrysantha*		√
MALVACEAE	*Sida cordifolia* subsp. *cordifolia*	√	
MELIACEAE	*Nymania capensis*	√	
MESEMBRYANTHEMACEAE	*Ebracteola wilmaniae*	√	
MESEMBRYANTHEMACEAE	*Hereroa wilmaniae*	√	
MESEMBRYANTHEMACEAE	*Lithops bromfieldii*	√	
MESEMBRYANTHEMACEAE	*Nananthus aloides*	√	
MESEMBRYANTHEMACEAE	*Psilocaulon coriarium*	√	
MESEMBRYANTHEMACEAE	*Ruschia griquensis*		√
MOLLUGINACEAE	*Hypertelis salsoloides* var. *salsoloides*	√	
MOLLUGINACEAE	*Limeum aethiopicum* var. *intermedium*	√	
MOLLUGINACEAE	*Limeum argute-carinatum*		√
MOLLUGINACEAE	*Limeum argute-carinatum* var. *kwebense*	√	
MOLLUGINACEAE	*Pharnaceum viride*	√	
MORACEAE	*Ficus cordata* subsp. *cordata*	√	
NEURADACEAE	*Grielum humifusum* var. *humifusum*	√	
OLEACEAE	*Olea europaea* subsp. *africana*	√	
OXALIDACEAE	*Oxalis haedulipes*	√	√
PHYTOLACCACEAE	*Lophiocarpus polystachyus*		√

POACEAE	*Agrostis lachnantha* var. *lachnantha*	√	
POACEAE	*Anthephora argentea*	√	
POACEAE	*Anthephora pubescens*	√	√
POACEAE	*Aristida congesta* subsp. *barbicollis*	√	√
POACEAE	*Aristida congesta* subsp. *congesta*	√	√
POACEAE	*Aristida diffusa* subsp. *burkei*	√	√
POACEAE	*Aristida engleri* var. *engleri*	√	
POACEAE	*Aristida meridionalis*	√	
POACEAE	*Aristida stipitata* subsp. *graciliflora*	√	√
POACEAE	*Aristida vestita*	√	
POACEAE	*Brachiaria brizantha*	√	
POACEAE	*Brachiaria dura* var. *pilosa*	√	
POACEAE	*Brachiaria marlothii*	√	
POACEAE	*Brachiaria nigropedata*	√	√
POACEAE	*Brachiaria serrata*	√	√
POACEAE	*Cenchrus ciliaris*	√	
POACEAE	*Centropodia glauca*	√	
POACEAE	*Chloris virgata*	√	
POACEAE	*Cymbopogon caesius*	√	
POACEAE	*Cymbopogon dieterlenii*	√	
POACEAE	*Cymbopogon pospischilii*	√	√
POACEAE	*Cymbopogon prolixus*	√	
POACEAE	*Cynodon dactylon*	√	

POACEAE	*Diandrochloa namaquensis*	√	
POACEAE	*Diandrochloa pusilla*	√	
POACEAE	*Digitaria eriantha*	√	√
POACEAE	*Digitaria polyphylla*	√	√
POACEAE	*Diheteropogon amplectens*		√
POACEAE	*Elionurus muticus*		√
POACEAE	*Enneapogon cenchroides*	√	
POACEAE	*Enneapogon desvauxii*	√	
POACEAE	*Enneapogon scaber*	√	
POACEAE	*Enneapogon scoparius*	√	√
POACEAE	*Eragrostis chloromelas*		√
POACEAE	*Eragrostis curvula*	√	
POACEAE	*Eragrostis echinochloidea*	√	
POACEAE	*Eragrostis gummiflua*	√	
POACEAE	*Eragrostis lehmanniana* var. *lehmanniana*	√	√
POACEAE	*Eragrostis macrochlamys* var. *wilmaniae*	√	
POACEAE	*Eragrostis nindensis*		√
POACEAE	*Eragrostis obtusa*	√	
POACEAE	*Eragrostis pallens*	√	
POACEAE	*Eragrostis porosa*	√	
POACEAE	*Eragrostis rigidior*	√	√
POACEAE	*Eragrostis rotifer*	√	
POACEAE	*Eragrostis superba*		√

POACEAE	*Eragrostis trichophora*	√	√
POACEAE	*Eustachys paspaloides*	√	√
POACEAE	*Heteropogon contortus*	√	√
POACEAE	*Hyparrhenia hirta*	√	
POACEAE	*Imperata cylindrica*	√	
POACEAE	*Melinis nerviglumis*	√	√
POACEAE	*Melinis repens* subsp. *repens*	√	√
POACEAE	*Oropetium capense*	√	
POACEAE	*Panicum gilvum*	√	
POACEAE	*Panicum impeditum*	√	
POACEAE	*Panicum kalaharense*	√	
POACEAE	*Panicum maximum*	√	√
POACEAE	*Panicum schinzii*	√	
POACEAE	*Paspalum scrobiculatum*	√	
POACEAE	*Pogonarthria squarrosa*	√	√
POACEAE	*Schmidtia pappophoroides*	√	√
POACEAE	*Sporobolus albicans*	√	
POACEAE	*Sporobolus fimbriatus*	√	
POACEAE	*Sporobolus ioclados*	√	
POACEAE	*Sporobolus tenellus*	√	
POACEAE	*Stipagrostis amabilis*	√	
POACEAE	*Stipagrostis ciliata* var. *capensis*	√	
POACEAE	*Stipagrostis uniplumis* var. *uniplumis*	√	√

POACEAE	*Themeda triandra*		√
POACEAE	*Tragus koelerioides*	√	
POACEAE	*Tricholaena monachne*	√	
POACEAE	*Trichoneura grandiglumis*	√	
POLYGALACEAE	*Polygala asbestina*	√	
POLYGALACEAE	*Polygala krumanina*		√
POLYGALACEAE	*Polygala leptophylla*	√	
POLYGALACEAE	*Polygala leptophylla* var. *leptophylla*	√	
POLYGONACEAE	*Oxygonum alatum* var. *alatum*	√	
POLYGONACEAE	*Oxygonum delagoense*	√	
PORTULACACEAE	*Portulaca hereroensis*		√
PORTULACACEAE	*Portulaca kermisina*		√
PORTULACACEAE	*Talinum arnotii*		√
PORTULACACEAE	*Talinum tenuissimum*		√
RANUNCULACEAE	*Clematis brachiata*	√	
RHAMNACEAE	*Ziziphus mucronata* subsp. *mucronata*	√	
RUBIACEAE	*Anthospermum rigidum*		√
RUBIACEAE	*Kohautia caespitosa*		√
SANTALACEAE	*Thesium burchellii*	√	
SANTALACEAE	*Thesium goetzeanum*	√	
SANTALACEAE	*Thesium hystricoides*	√	
SANTALACEAE	*Thesium hystrix*	√	
SANTALACEAE	*Thesium lineatum*	√	√

SANTALACEAE	*Thesium utile*		√
SCROPHULARIACEAE	*Aptosimum elongatum*	√	
SCROPHULARIACEAE	*Aptosimum junceum*	√	√
SCROPHULARIACEAE	*Aptosimum lugardiae*		√
SCROPHULARIACEAE	*Aptosimum marlothii*	√	
SCROPHULARIACEAE	*Chaenostoma halimifolium*	√	
SCROPHULARIACEAE	*Hebenstretia integrifolia*	√	
SCROPHULARIACEAE	*Jamesbrittenia atropurpurea* subsp*. pubescens*	√	
SCROPHULARIACEAE	*Jamesbrittenia integerrima*	√	
SCROPHULARIACEAE	*Nemesia hanoverica*	√	
SCROPHULARIACEAE	*Nemesia pubescens* var. *pubescens*	√	
SCROPHULARIACEAE	*Peliostomum leucorrhizum*	√	
SCROPHULARIACEAE	*Selago albida*	√	
SCROPHULARIACEAE	*Selago saxatilis*	√	
SCROPHULARIACEAE	*Selago welwitschii* var*. australis*	√	
SCROPHULARIACEAE	*Sutera griquensis*	√	
SCROPHULARIACEAE	*Sutera halimifolia*		√
SINOPTERIDACEAE	*Cheilanthes eckloniana*	√	√
SINOPTERIDACEAE	*Cheilanthes hirta* var. *brevipilosa*	√	
SINOPTERIDACEAE	*Cheilanthes multifida* var. *multifida*	√	
SINOPTERIDACEAE	*Pellaea calomelanos* var. *calomelanos*	√	√
SOLANACEAE	*Lycium cinereum*	√	
SOLANACEAE	*Lycium hirsutum*	√	

SOLANACEAE	*Lycium horridum*	√	
SOLANACEAE	*Lycium pilifolium*	√	
STERCULIACEAE	*Waltheria indica*		√
THYMELAEACEAE	*Gnidia polycephala*	√	
VAHLIACEAE	*Vahlia capensis* subsp. *ellipticifolia*	√	
VERBENACEAE	*Chascanum pinnatifidum*		√
VERBENACEAE	*Lantana rugosa*	√	√
VIOLACEAE	*Hybanthus densifolius*	√	
VISCACEAE	*Viscum rotundifolium*	√	
ZYGOPHYLLACEAE	*Tribulus terrestris*		√
ZYGOPHYLLACEAE	*Tribulus zeyheri* subsp. *zeyheri*	√	
ZYGOPHYLLACEAE	*Zygophyllum gilfillanii*	√	
Kuruman Hills			
ACANTHACEAE	*Barleria bechuanensis*	√	√
ACANTHACEAE	*Barleria lichtensteiniana*	√	
ACANTHACEAE	*Barleria macrostegia*	√	
ACANTHACEAE	*Barleria media*	√	
ACANTHACEAE	*Blepharis integrifolia* var. *integrifolia*	√	
ACANTHACEAE	*Blepharis marginata*	√	
ACANTHACEAE	*Glossochilus burchellii*	√	
ACANTHACEAE	*Hypoestes forskaolii*	√	
ACANTHACEAE	*Justicia puberula*	√	
ACANTHACEAE	*Monechma divaricatum*	√	

ACANTHACEAE	*Monechma genistifolium* subsp*. australe*	√	
ACANTHACEAE	*Monechma incanum*	√	
AIZOACEAE	*Galenia africana*	√	
AIZOACEAE	*Plinthus sericeus*	√	
AIZOACEAE	*Trianthema parvifolia* var. *parvifolia*	√	
AMARANTHACEAE	*Aerva leucura*	√	
AMARANTHACEAE	*Guilleminea densa*	√	
AMARANTHACEAE	*Hermbstaedtia fleckii*	√	√
AMARANTHACEAE	*Hermbstaedtia odorata* var. *albi-rosea*	√	
AMARANTHACEAE	*Hermbstaedtia odorata* var. *aurantiaca*	√	
AMARANTHACEAE	*Hermbstaedtia odorata* var*. odorata*	√	√
AMARANTHACEAE	*Kyphocarpa angustifolia*	√	√
AMARANTHACEAE	*Pupalia lappacea* var*. lappacea*	√	
AMARANTHACEAE	*Pupalia lappacea* var*. velutina*	√	
AMARANTHACEAE	*Sericorema remotiflora*	√	
AMARYLLIDACEAE	*Boophone disticha*		√
AMARYLLIDACEAE	*Nerine laticoma*	√	
ANACARDIACEAE	*Searsia burchellii*	√	
ANACARDIACEAE	*Searsia ciliata*	√	
ANACARDIACEAE	*Searsia dregeana*	√	
ANACARDIACEAE	*Searsia lancea*	√	
ANACARDIACEAE	*Searsia leptodictya* forma *leptodictya*	√	
ANACARDIACEAE	*Searsia pyroides* var*. pyroides*	√	

ANACARDIACEAE	*Searsia rigida* var. *rigida*	√	
ANACARDIACEAE	*Searsia tridactyla*	√	√
APIACEAE	*Berula thunbergii*	√	
APIACEAE	*Centella asiatica*	√	
APIACEAE	*Deverra burchellii*	√	
APOCYNACEAE	*Brachystelma circinatum*	√	
APOCYNACEAE	*Fockea angustifolia*	√	
APOCYNACEAE	*Gomphocarpus fruticosus* subsp. *fruticosus*	√	
APOCYNACEAE	*Gomphocarpus tomentosus* subsp. *tomentosus*	√	
APOCYNACEAE	*Pachypodium succulentum*	√	
APOCYNACEAE	*Pentarrhinum insipidum*	√	
APOCYNACEAE	*Piaranthus decipiens*	√	
APOCYNACEAE	*Sarcostemma viminale* subsp. *viminale*	√	
APOCYNACEAE	*Sisyranthus randii*		√
ARALIACEAE	*Hydrocotyle verticillata*	√	
ASPARAGACEAE	*Asparagus exuvialis* forma *exuvialis*	√	
ASPARAGACEAE	*Asparagus laricinus*	√	√
ASPARAGACEAE	*Asparagus retrofractus*	√	
ASPARAGACEAE	*Asparagus suaveolens*	√	√
ASPHODELACEAE	*Aloe claviflora*	√	
ASPHODELACEAE	*Aloe grandidentata*	√	
ASPHODELACEAE	*Bulbine abyssinica*	√	
ASPHODELACEAE	*Bulbine frutescens*	√	

ASPHODELACEAE	*Bulbine narcissifolia*	√	
ASPHODELACEAE	*Trachyandra laxa* var. *laxa*	√	
ASPHODELACEAE	*Trachyandra saltii* var*. saltii*	√	
ASPLENIACEAE	*Asplenium adiantum-nigrum* var*. adiantum-nigrum*	√	
ASPLENIACEAE	*Asplenium cordatum*	√	
ASTERACEAE	*Amphiglossa triflora*	√	
ASTERACEAE	*Arctotheca calendula*	√	
ASTERACEAE	*Arctotis arctotoides*	√	
ASTERACEAE	*Berkheya pinnatifida* subsp*. pinnatifida*	√	
ASTERACEAE	*Chrysocoma ciliata*	√	
ASTERACEAE	*Cineraria burkei*	√	
ASTERACEAE	*Cineraria vallis-pacis*	√	
ASTERACEAE	*Conyza pinnata*	√	
ASTERACEAE	*Dicoma anomala* subsp*. gerrardii*	√	√
ASTERACEAE	*Dicoma kurumanii*	√	√
ASTERACEAE	*Dicoma macrocephala*	√	√
ASTERACEAE	*Dicoma schinzii*	√	
ASTERACEAE	*Dimorphotheca cuneata*	√	
ASTERACEAE	*Dimorphotheca zeyheri*	√	
ASTERACEAE	*Eriocephalus ericoides* subsp*. griquensis*	√	
ASTERACEAE	*Eriocephalus glandulosus*	√	
ASTERACEAE	*Erlangea misera*	√	
ASTERACEAE	*Euryops subcarnosus* subsp*. vulgaris*	√	

ASTERACEAE	*Felicia clavipilosa* subsp*. clavipilosa*	√	
ASTERACEAE	*Felicia fascicularis*	√	
ASTERACEAE	*Felicia filifolia* subsp*. filifolia*	√	
ASTERACEAE	*Felicia muricata* subsp*. cinerascens*	√	
ASTERACEAE	*Felicia muricata* subsp*. muricata*	√	√
ASTERACEAE	*Foveolina dichotoma*	√	
ASTERACEAE	*Gazania krebsiana* subsp*. arctotoides*	√	
ASTERACEAE	*Gazania krebsiana* subsp*. serrulata*	√	√
ASTERACEAE	*Geigeria brevifolia*	√	
ASTERACEAE	*Geigeria filifolia*	√	√
ASTERACEAE	*Geigeria ornativa* subsp*. ornativa*	√	
ASTERACEAE	*Gnaphalium englerianum*	√	
ASTERACEAE	*Helichrysum argyrosphaerum*	√	
ASTERACEAE	*Helichrysum caespititium*	√	
ASTERACEAE	*Helichrysum cerastioides* var. *cerastioides*	√	
ASTERACEAE	*Helichrysum lineare*	√	
ASTERACEAE	*Helichrysum nudifolium* var. *nudifolium*	√	
ASTERACEAE	*Helichrysum spiciforme*	√	
ASTERACEAE	*Helichrysum zeyheri*	√	√
ASTERACEAE	*Hirpicium echinus*	√	
ASTERACEAE	*Kleinia longiflora*	√	
ASTERACEAE	*Leysera tenella*	√	
ASTERACEAE	*Litogyne gariepina*	√	

ASTERACEAE	*Lopholaena cneorifolia*	√	
ASTERACEAE	*Nidorella hottentotica*	√	
ASTERACEAE	*Nidorella resedifolia* subsp*. resedifolia*	√	
ASTERACEAE	*Nolletia ciliaris*	√	√
ASTERACEAE	*Osteospermum leptolobum*	√	
ASTERACEAE	*Osteospermum microphyllum*	√	
ASTERACEAE	*Osteospermum muricatum* subsp. *muricatum*	√	
ASTERACEAE	*Pegolettia retrofracta*	√	√
ASTERACEAE	*Pentzia argentea*	√	
ASTERACEAE	*Pentzia calcarea*	√	
ASTERACEAE	*Pentzia oppositifolia*	√	
ASTERACEAE	*Pentzia quinquefida*	√	
ASTERACEAE	*Phymaspermum aciculare*	√	
ASTERACEAE	*Pteronia glauca*	√	
ASTERACEAE	*Pteronia mucronata*	√	
ASTERACEAE	*Pulicaria scabra*	√	
ASTERACEAE	*Rennera stellata*	√	
ASTERACEAE	*Senecio consanguineus*	√	
ASTERACEAE	*Senecio inaequidens*	√	
ASTERACEAE	*Senecio mooreanus*	√	
ASTERACEAE	*Sonchus dregeanus*	√	
ASTERACEAE	*Tagetes minuta*		√
ASTERACEAE	*Tarchonanthus camphoratus*	√	√

ASTERACEAE	*Tarchonanthus obovatus*	√	√
ASTERACEAE	*Tolpis capensis*	√	
ASTERACEAE	*Tripteris aghillana* var. *aghillana*	√	
ASTERACEAE	*Ursinia nana* subsp. *leptophylla*	√	
ASTERACEAE	*Ursinia nana* subsp. *nana*	√	
ASTERACEAE	*Vernonia galpinii*		√
BEGONIACEAE	*Rhigozum trichotomum*	√	√
BIGNONIACEAE	*Rhigozum obovatum*	√	
BLECHNACEAE	*Blechnum australe* subsp. *australe*	√	
BORAGINACEAE	*Anchusa riparia*	√	
BORAGINACEAE	*Ehretia alba*	√	
BORAGINACEAE	*Ehretia rigida*	√	√
BORAGINACEAE	*Heliotropium ciliatum*	√	
BORAGINACEAE	*Heliotropium ovalifolium*	√	
BORAGINACEAE	*Heliotropium strigosum*	√	
BORAGINACEAE	*Lithospermum cinereum*	√	
BRASSICACEAE	*Erucastrum griquense*	√	
BRASSICACEAE	*Erucastrum strigosum*	√	
BRASSICACEAE	*Erucrastrum griquense*	√	
BRASSICACEAE	*Heliophila suavissima*	√	
BRASSICACEAE	*Rorippa fluviatilis* var. *caledonica*	√	
BUDDLEJACEAE	*Buddleja saligna*	√	
CAMPANULACEAE	*Wahlenbergia androsacea*	√	

CAMPANULACEAE	*Wahlenbergia denticulata* var. *denticulata*	√	
CAMPANULACEAE	*Wahlenbergia denticulata* var. *transvaalensis*	√	
CAMPANULACEAE	*Wahlenbergia nodosa*	√	√
CAMPANULACEAE	*Wahlenbergia undulata*	√	
CAPPARACEAE	*Cleome conrathii*	√	
CAPPARACEAE	*Cleome kalachariensis*	√	
CAPPARACEAE	*Cleome oxyphylla* var. *oxyphylla*	√	
CAPPARACEAE	*Cleome rubella*	√	√
CARYOPHYLLACEAE	*Dianthus namaensis* var. *dinteri*	√	
CARYOPHYLLACEAE	*Herniaria erckertii* subsp. *erckertii* var. *dewetii*	√	
CARYOPHYLLACEAE	*Pollichia campestris*	√	√
CARYOPHYLLACEAE	*Silene undulata* subsp. *undulata*	√	
CELASTRACEAE	*Gymnosporia buxifolia*	√	√
CELASTRACEAE	*Putterlickia pyracantha*	√	
CELASTRACEAE	*Putterlickia saxatilis*	√	√
CHENOPODIACEAE	*Atriplex semibaccata* var. *appendiculata*	√	
CHENOPODIACEAE	*Chenopodium hederiforme* var. *undulatum*	√	
CHENOPODIACEAE	*Salsola rabieana*	√	
CHENOPODIACEAE	*Salsola tuberculata*	√	
COLCHICACEAE	*Ornithoglossum vulgare*	√	
COMMELINACEAE	*Commelina africana* var. *africana*	√	
COMMELINACEAE	*Commelina africana* var. *barberae*	√	
COMMELINACEAE	*Commelina africana* var. *krebsiana*	√	

COMMELINACEAE	*Commelina africana* var. *lancispatha*	√	
COMMELINACEAE	*Commelina livingstonii*	√	
COMMELINACEAE	*Cyanotis speciosa*	√	
CONVOLVULACEAE	*Convolvulus ocellatus* var. *ocellatus*	√	
CONVOLVULACEAE	*Convolvulus sagittatus*	√	
CONVOLVULACEAE	*Evolvulus alsinoides*	√	√
CONVOLVULACEAE	*Ipomoea bolusiana*	√	
CONVOLVULACEAE	*Ipomoea obscura* var. *obscura*	√	
CONVOLVULACEAE	*Ipomoea simplex*	√	
CONVOLVULACEAE	*Ipomoea suffruticosa*	√	
CONVOLVULACEAE	*Seddera suffruticosa*	√	√
CONVOLVULACEAE	*Xenostegia tridentata* subsp. *angustifolia*	√	
CRASSULACEAE	*Crassula lanceolata* subsp. *transvaalensis*	√	
CRASSULACEAE	*Crassula nodulosa* var. *nodulosa* forma *nodulosa*	√	
CRASSULACEAE	*Crassula sarcocaulis* subsp. *rupicola*	√	
CRASSULACEAE	*Kalanchoe brachyloba*	√	
CRASSULACEAE	*Kalanchoe lanceolata*	√	
CRASSULACEAE	*Kalanchoe rotundifolia*	√	
CUCURBITACEAE	*Acanthosicyos naudinianus*	√	
CUCURBITACEAE	*Citrullus lanatus*	√	
CUCURBITACEAE	*Coccinia sessilifolia*	√	
CUCURBITACEAE	*Cucumis africanus*	√	
CUCURBITACEAE	*Cucumis heptadactylus*	√	

CUCURBITACEAE	*Cucumis myriocarpus* subsp. *myriocarpus*	√	
CUCURBITACEAE	*Kedrostis africana*	√	
CYPERACEAE	*Abildgaardia ovata*		√
CYPERACEAE	*Bulbostylis burchellii*	√	
CYPERACEAE	*Bulbostylis hispidula*		√
CYPERACEAE	*Carex burchelliana*	√	
CYPERACEAE	*Cyperus bellus*	√	
CYPERACEAE	*Cyperus capensis*	√	
CYPERACEAE	*Cyperus difformis*	√	
CYPERACEAE	*Cyperus indecorus* var. *namaquensis*	√	
CYPERACEAE	*Cyperus longus* var. *tenuiflorus*	√	
CYPERACEAE	*Cyperus margaritaceus* var. *margaritaceus*	√	√
CYPERACEAE	*Cyperus marginatus*	√	
CYPERACEAE	*Cyperus marlothii*	√	√
CYPERACEAE	*Cyperus rupestris* var. *rupestris*	√	
CYPERACEAE	*Cyperus usitatus*	√	
CYPERACEAE	*Fuirena pubescens* var. *pubescens*	√	
CYPERACEAE	*Kyllinga alba*	√	
CYPERACEAE	*Pycreus betschuanus*	√	
CYPERACEAE	*Schoenoplectus pulchellus*	√	
CYPERACEAE	*Scirpoides burkei*	√	
CYPERACEAE	*Scirpoides dioeca*	√	
DIPSACACEAE	*Scabiosa columbaria*	√	

EBENACEAE	*Diospyros austro-africana* var. *microphylla*	√	√
EBENACEAE	*Diospyros lycioides* subsp. *lycioides*	√	
EBENACEAE	*Euclea crispa* subsp. *ovata*	√	
EBENACEAE	*Euclea undulata*	√	√
ELATINACEAE	*Bergia pentheriana*	√	
ERIOSPERMACEAE	*Eriospermum corymbosum*	√	
EUPHORBIACEAE	*Croton gratissimus* var. *gratissimus*	√	
EUPHORBIACEAE	*Euphorbia duseimata*	√	
EUPHORBIACEAE	*Euphorbia inaequilatera*		√
EUPHORBIACEAE	*Euphorbia mauritanica* var. *mauritanica*	√	√
EUPHORBIACEAE	*Euphorbia mundii*	√	
EUPHORBIACEAE	*Euphorbia rectirama*	√	
EUPHORBIACEAE	*Phyllanthus maderaspatensis*	√	√
EUPHORBIACEAE	*Seidelia triandra*	√	
FABACEAE	*Argyrolobium argenteum*	√	
FABACEAE	*Argyrolobium incanum*	√	
FABACEAE	*Bolusia acuminata*	√	
FABACEAE	*Calobota cuspidosa*	√	√
FABACEAE	*Chamaecrista biensis*	√	
FABACEAE	*Chamaecrista mimosoides*	√	
FABACEAE	*Crotalaria griquensis*	√	
FABACEAE	*Crotalaria leubnitziana*	√	
FABACEAE	*Crotalaria podocarpa*	√	

FABACEAE	*Crotalaria spartioides*	√	
FABACEAE	*Crotalaria sphaerocarpa* subsp. *sphaerocarpa*	√	
FABACEAE	*Crotalaria virgultalis*	√	
FABACEAE	*Dichilus lebeckioides*	√	
FABACEAE	*Dichrostachys cinerea* subsp. *africana* var.*setulosa*	√	
FABACEAE	*Elephantorrhiza elephantina*	√	√
FABACEAE	*Indigofera sessifolia*		√
FABACEAE	*Indigofera alternans* var. *alternans*	√	
FABACEAE	*Indigofera auricoma*	√	
FABACEAE	*Indigofera comosa*	√	√
FABACEAE	*Indigofera cryptantha* var. *cryptantha*	√	
FABACEAE	*Indigofera daleoides* var. *daleoides*	√	
FABACEAE	*Indigofera filipes*	√	
FABACEAE	*Indigofera flavicans*	√	
FABACEAE	*Indigofera heterotricha*	√	
FABACEAE	*Indigofera hololeuca*	√	
FABACEAE	*Indigofera sessilifolia*	√	
FABACEAE	*Indigofera vicioides* var. *vicioides*	√	
FABACEAE	*Leobordea divaricata*	√	
FABACEAE	*Lessertia depressa*	√	
FABACEAE	*Lessertia pauciflora* var. *pauciflora*	√	
FABACEAE	*Lotononis burchellii*	√	√
FABACEAE	*Lotononis crumanina*	√	

FABACEAE	*Lotononis laxa*	√	
FABACEAE	*Melolobium candicans*	√	
FABACEAE	*Melolobium canescens*	√	
FABACEAE	*Melolobium macrocalyx* var. *longifolium*	√	
FABACEAE	*Melolobium macrocalyx* var*. macrocalyx*	√	
FABACEAE	*Melolobium microphyllum*	√	
FABACEAE	*Otoptera burchellii*	√	
FABACEAE	*Parkinsonia africana*	√	
FABACEAE	*Ptycholobium biflorum* subsp*. angolensis*	√	
FABACEAE	*Ptycholobium biflorum* subsp*. biflorum*	√	
FABACEAE	*Requienia sphaerosperma*	√	
FABACEAE	*Rhynchosia confusa*	√	
FABACEAE	*Rhynchosia holosericea*	√	
FABACEAE	*Rhynchosia totta* var*. totta*	√	√
FABACEAE	*Rhynchosia venulosa*	√	
FABACEAE	*Senegalia mellifera* subsp. *detinens*	√	√
FABACEAE	*Senna italica* subsp*. arachoides*	√	
FABACEAE	*Sutherlandia frutescens*	√	
FABACEAE	*Tephrosia burchellii*	√	
FABACEAE	*Tephrosia longipes* subsp*. longipes* var*. longipes*	√	√
FABACEAE	*Tephrosia lupinifolia*	√	
FABACEAE	*Tephrosia purpurea* subsp. *leptostachya* *var.leptostachya*	√	√

FABACEAE	*Vachellia erioloba*	√	
FABACEAE	*Vachellia haematoxylon*	√	
FABACEAE	*Vachellia hebeclada* subsp*. hebeclada*	√	
FABACEAE	*Vachellia hereroensis*	√	
FABACEAE	*Vachellia karroo*	√	
FABACEAE	*Vigna unguiculata* subsp. *unguiculata* var. *unguiculata*	√	
GENTIANACEAE	*Chironia palustris* subsp. *palustris*	√	
GERANIACEAE	*Monsonia angustifolia*	√	√
GERANIACEAE	*Monsonia burkeana*	√	
GERANIACEAE	*Pelargonium myrrhifolium* var. *myrrhifolium*	√	
GERANIACEAE	*Pelargonium senecioides*	√	
GISEKIACEAE	*Gisekia africana* var. *africana*	√	
GISEKIACEAE	*Gisekia pharnacioides*		√
HYACINTHACEAE	*Dipcadi marlothii*	√	
HYACINTHACEAE	*Drimia sanguinea*	√	
HYACINTHACEAE	*Ledebouria luteola*	√	
HYACINTHACEAE	*Massonia jasminiflora*	√	
HYACINTHACEAE	*Ornithogalum seineri*	√	
HYACINTHACEAE	*Schizocarphus nervosus*	√	
IRIDACEAE	*Babiana bainesii*	√	
IRIDACEAE	*Babiana hypogaea*	√	
IRIDACEAE	*Freesia andersoniae*	√	

IRIDACEAE	*Gladiolus permeabilis* subsp*. edulis*	√	
IRIDACEAE	*Lapeirousia erythrantha*	√	
IRIDACEAE	*Lapeirousia plicata* subsp*. longifolia*	√	
IRIDACEAE	*Lapeirousia plicata* subsp*. plicata*	√	
IRIDACEAE	*Lapeirousia sandersonii*	√	
IRIDACEAE	*Moraea falcifolia*	√	
IRIDACEAE	*Moraea pallida*	√	
IRIDACEAE	*Moraea polystachya*	√	
IRIDACEAE	*Psilosiphon sandersonii*		√
JUNCACEAE	*Juncus exsertus*	√	
JUNCACEAE	*Juncus punctorius*	√	
JUNCACEAE	*Juncus rigidus*	√	
LAMIACEAE	*Leucas capensis*	√	√
LAMIACEAE	*Mentha aquatica*	√	
LAMIACEAE	*Salvia disermas*	√	
LAMIACEAE	*Salvia verbenaca*	√	
LAMIACEAE	*Stachys burchelliana*	√	
LENTIBULARIACEAE	*Utricularia gibba*	√	
LOBELIACEAE	*Lobelia erinus*	√	
LOBELIACEAE	*Lobelia thermalis*	√	
LOPHIOCARPACEAE	*Lophiocarpus polystachyus*	√	
LORANTHACEAE	*Tapinanthus oleifolius*	√	
MALPIGHIACEAE	*Sphedamnocarpus pruriens* subsp*. pruriens*	√	

MALPIGHIACEAE	*Triaspis hypericoides* subsp*. hypericoides*	√	√
MALVACEAE	*Abutilon betschuanicum*	√	
MALVACEAE	*Abutilon dinteri*	√	
MALVACEAE	*Abutilon rehmannii*	√	
MALVACEAE	*Corchorus pinnatipartitus*	√	
MALVACEAE	*Hermannia bicolor*	√	
MALVACEAE	*Hermannia burchellii*	√	
MALVACEAE	*Hermannia comosa*	√	
MALVACEAE	*Hermannia linearifolia*	√	
MALVACEAE	*Hermannia linnaeoides*	√	
MALVACEAE	*Hermannia marginata*	√	
MALVACEAE	*Hermannia resedifolia*	√	
MALVACEAE	*Hermannia stellulata*	√	
MALVACEAE	*Hermannia tomentosa*	√	
MALVACEAE	*Hibiscus marlothianus*	√	
MALVACEAE	*Melhania burchellii*	√	
MALVACEAE	*Melhania prostrata*	√	
MALVACEAE	*Melhania virescens*	√	
MALVACEAE	*Pavonia burchellii*	√	
MALVACEAE	*Sida chrysantha*	√	√
MALVACEAE	*Sida cordifolia* subsp*. cordifolia*	√	
MALVACEAE	*Waltheria indica*	√	
MARSILEACEAE	*Marsilea burchellii*	√	

MENISPERMACEAE	*Antizoma angustifolia*	√	
MESEMBRYANTHEMACEAE	*Antimima lawsonii*	√	
MESEMBRYANTHEMACEAE	*Ebracteola wilmaniae*	√	
MESEMBRYANTHEMACEAE	*Hereoa wilmaniae*		√
MESEMBRYANTHEMACEAE	*Nananthus aloides*	√	
MESEMBRYANTHEMACEAE	*Prepodesma orpenii*	√	
MESEMBRYANTHEMACEAE	*Ruschia griquensis*	√	
MOLLUGINACEAE	*Hypertelis salsoloides* var. *salsoloides*	√	
MOLLUGINACEAE	*Limeum aethiopicum* var. *aethiopicum*	√	
MOLLUGINACEAE	*Limeum aethiopicum* var. *intermedium*	√	
MOLLUGINACEAE	*Limeum arenicolum*	√	
MOLLUGINACEAE	*Limeum fenestratum* var. *fenestratum*	√	
MOLLUGINACEAE	*Limeum sulcatum* var. *robustum*	√	
MOLLUGINACEAE	*Limeum sulcatum* var. *sulcatum*	√	
MOLLUGINACEAE	*Limeum viscosum* subsp. *transvaalense*	√	
MOLLUGINACEAE	*Mollugo cerviana* var. *cerviana*	√	
MOLLUGINACEAE	*Suessenguthiella scleranthoides*	√	
NYMPHAEACEAE	*Nymphaea nouchali* var. *caerulea*	√	
OLEACEAE	*Menodora africana*	√	√
OLEACEAE	*Olea europaea* subsp. *africana*	√	
OROBANCHACEAE	*Alectra pumila*	√	
OROBANCHACEAE	*Striga bilabiata* subsp. *bilabiata*	√	
OROBANCHACEAE	*Striga elegans*	√	√

OROBANCHACEAE	*Striga gesnerioides*	√	
OXALIDACEAE	*Oxalis depressa*	√	
OXALIDACEAE	*Oxalis lawsonii*	√	
PASSIFLORACEAE	*Adenia repanda*	√	
PEDALIACEAE	*Ceratotheca triloba*	√	
PEDALIACEAE	*Harpagophytum procumbens* subsp. *procumbens*	√	
PEDALIACEAE	*Sesamum capense*	√	
PHYLLANTHACEAE	*Phyllanthus angolensis*	√	
PHYLLANTHACEAE	*Phyllanthus humilis*	√	
PHYLLANTHACEAE	*Phyllanthus parvulus* var. *garipensis*	√	
PHYLLANTHACEAE	*Phyllanthus parvulus* var. *parvulus*	√	√
PHYLLANTHACEAE	*Phyllanthus pentandrus*	√	
POACEAE	*Agrostis lachnantha* var. *lachnantha*	√	
POACEAE	*Andropogon chinensis*	√	
POACEAE	*Andropogon eucomus*	√	
POACEAE	*Andropogon schirensis*	√	√
POACEAE	*Anthephora argentea*	√	
POACEAE	*Anthephora pubescens*	√	√
POACEAE	*Aristida adscensionis*	√	
POACEAE	*Aristida congesta* subsp. *barbicollis*	√	√
POACEAE	*Aristida congesta* subsp. *congesta*	√	√
POACEAE	*Aristida diffusa*		√
POACEAE	*Aristida engleri* var. *ramosissima*	√	

POACEAE	*Aristida meridionalis*	√	
POACEAE	*Aristida stipitata* subsp. *graciliflora*	√	
POACEAE	*Aristida stipitata* subsp. *spicata*	√	
POACEAE	*Aristida stipitata* subsp. *stipitata*	√	
POACEAE	*Aristida vestita*	√	
POACEAE	*Brachiaria marlothii*	√	
POACEAE	*Brachiaria nigropedata*	√	√
POACEAE	*Brachiaria serrata*	√	√
POACEAE	*Bromus pectinatus*	√	
POACEAE	*Cenchrus ciliaris*	√	√
POACEAE	*Chrysopogon serrulatus*	√	
POACEAE	*Coelachyrum yemenicum*	√	
POACEAE	*Cymbopogon caesius*	√	√
POACEAE	*Cymbopogon pospischilii*	√	√
POACEAE	*Cynodon dactylon*	√	
POACEAE	*Cynodon incompletus*	√	
POACEAE	*Cynodon transvaalensis*	√	
POACEAE	*Digitaria eriantha*	√	
POACEAE	*Digitaria polyphylla*	√	
POACEAE	*Digitaria seriata*	√	
POACEAE	*Digitaria ternata*	√	
POACEAE	*Diheteropogon amplectens* var. *amplectens*	√	√
POACEAE	*Eleusine coracana* subsp. *africana*	√	

POACEAE	*Elionurus muticus*	√	√
POACEAE	*Enneapogon cenchroides*	√	
POACEAE	*Enneapogon desvauxii*	√	
POACEAE	*Enneapogon scaber*	√	
POACEAE	*Enneapogon scoparius*	√	√
POACEAE	*Eragrostis amabilis*	√	
POACEAE	*Eragrostis bicolor*	√	
POACEAE	*Eragrostis capensis*	√	
POACEAE	*Eragrostis chloromelas*	√	√
POACEAE	*Eragrostis cilianensis*	√	
POACEAE	*Eragrostis curvula*	√	√
POACEAE	*Eragrostis echinochloidea*	√	
POACEAE	*Eragrostis gummiflua*	√	
POACEAE	*Eragrostis homomalla*	√	
POACEAE	*Eragrostis lehmanniana* var. *lehmanniana*	√	√
POACEAE	*Eragrostis micrantha*	√	
POACEAE	*Eragrostis nindensis*	√	√
POACEAE	*Eragrostis obtusa*	√	
POACEAE	*Eragrostis pallens*	√	
POACEAE	*Eragrostis procumbens*	√	
POACEAE	*Eragrostis remotiflora*	√	
POACEAE	*Eragrostis rigidior*	√	
POACEAE	*Eragrostis stapfii*	√	

POACEAE	*Eragrostis trichophora*	√	
POACEAE	*Eragrostis truncata*	√	
POACEAE	*Eragrostis viscosa*	√	
POACEAE	*Eustachys paspaloides*	√	√
POACEAE	*Festuca littoralis*	√	
POACEAE	*Fingerhuthia africana*	√	√
POACEAE	*Helictotrichon turgidulum*	√	
POACEAE	*Heteropogon contortus*	√	√
POACEAE	*Hyparrhenia anamesa*	√	
POACEAE	*Hyparrhenia hirta*	√	
POACEAE	*Leptochloa fusca*	√	
POACEAE	*Megaloprotachne albescens*	√	
POACEAE	*Melinis nerviglumis*	√	√
POACEAE	*Melinis repens* subsp*. repens*	√	√
POACEAE	*Microchloa caffra*	√	
POACEAE	*Oropetium capense*	√	
POACEAE	*Panicum coloratum* var. *coloratum*	√	
POACEAE	*Panicum kalaharense*	√	
POACEAE	*Panicum schinzii*	√	
POACEAE	*Panicum stapfianum*	√	
POACEAE	*Pogonarthria squarrosa*	√	√
POACEAE	*Schizachyrium sanguineum*	√	
POACEAE	*Schmidtia pappophoroides*	√	

POACEAE	*Setaria sphacelata* var. *sphacelata*	√	
POACEAE	*Setaria sphacelata* var. *torta*	√	
POACEAE	*Sporobolus acinifolius*	√	
POACEAE	*Sporobolus discosporus*	√	
POACEAE	*Sporobolus fimbriatus*	√	
POACEAE	*Stipagrostis amabilis*	√	
POACEAE	*Stipagrostis hirtigluma* subsp*. patula*	√	
POACEAE	*Stipagrostis obtusa*	√	
POACEAE	*Stipagrostis uniplumis* var. *uniplumis*	√	√
POACEAE	*Themeda triandra*	√	√
POACEAE	*Tragus koelerioides*	√	√
POACEAE	*Tragus racemosus*	√	
POACEAE	*Trichoneura grandiglumis*	√	√
POACEAE	*Triraphis andropogonoides*	√	√
POACEAE	*Triraphis schinzii*	√	
POACEAE	*Urelytrum agropyroides*	√	√
POLYGALACEAE	*Polygala hottentotta*	√	√
POLYGALACEAE	*Polygala krumanina*	√	
POLYGALACEAE	*Polygala leptophylla*	√	
POLYGALACEAE	*Polygala leptophylla* var*. armata*	√	
POLYGALACEAE	*Polygala leptophylla* var*. leptophylla*	√	
POLYGONACEAE	*Oxygonum alatum* var*. alatum*	√	
POLYGONACEAE	*Oxygonum dregeanum* subsp*. canescens* var.	√	√

	canescens		
POLYGONACEAE	*Persicaria hystricula*	√	
PORTULACACEAE	*Anacampseros filamentosa* subsp. *filamentosa*	√	
PORTULACACEAE	*Portulaca kermisina*		√
PORTULACACEAE	*Portulaca quadrifida*	√	
POTAMOGETONACEAE	*Potamogeton schweinfurthii*	√	
PTERIDACEAE	*Actiniopteris radiata*	√	
RANUNCULACEAE	*Clematis brachiata*	√	
RESEDACEAE	*Oligomeris dipetala* var. *dipetala*	√	
RHAMNACEAE	*Helinus spartioides*	√	
RHAMNACEAE	*Ziziphus mucronata* subsp. *mucronata*	√	
RUBIACEAE	*Anthospermum rigidum* subsp. *pumilum*	√	√
RUBIACEAE	*Anthospermum rigidum* subsp. *rigidum*	√	
RUBIACEAE	*Kohautia caespitosa* subsp. *brachyloba*	√	√
RUBIACEAE	*Nenax microphylla*	√	
RUBIACEAE	*Vangueria infausta* subsp. *infausta*	√	
SANTALACEAE	*Thesium hystrix*	√	
SANTALACEAE	*Thesium lineatum*		√
SANTALACEAE	*Thesium utile*		√
SANTALACEAE	*Thesium zeyheri*	√	
SCROPHULARIACEAE	*Aptosimum albomarginatum*	√	
SCROPHULARIACEAE	*Aptosimum elongatum*	√	
SCROPHULARIACEAE	*Aptosimum marlothii*	√	

SCROPHULARIACEAE	*Chaenostoma halimifolium*	√	
SCROPHULARIACEAE	*Chaenostoma patrioticum*	√	
SCROPHULARIACEAE	*Diclis petiolaris*	√	
SCROPHULARIACEAE	*Jamesbrittenia atropurpurea* subsp. *atropurpurea*	√	√
SCROPHULARIACEAE	*Jamesbrittenia atropurpurea* subsp. *pubescens*	√	
SCROPHULARIACEAE	*Jamesbrittenia aurantiaca*	√	
SCROPHULARIACEAE	*Jamesbrittenia integerrima*	√	
SCROPHULARIACEAE	*Peliostomum leucorrhizum*	√	
SCROPHULARIACEAE	*Selago albomarginata*	√	
SCROPHULARIACEAE	*Selago densiflora*		√
SCROPHULARIACEAE	*Selago mixta*	√	
SCROPHULARIACEAE	*Selago paniculata*	√	
SCROPHULARIACEAE	*Selago saxatilis*	√	
SCROPHULARIACEAE	*Sutera griquensis*	√	
SCROPHULARIACEAE	*Sutera halimifolia*		√
SCROPHULARIACEAE	*Veronica anagallis-aquatica*	√	
SINOPTERIDACEAE	*Cheilanthes eckloniana*	√	
SINOPTERIDACEAE	*Cheilanthes hirta* forma *laxa*	√	
SINOPTERIDACEAE	*Cheilanthes hirta* var. *brevipilosa*	√	
SINOPTERIDACEAE	*Cheilanthes multifida* var. *multifida*	√	
SINOPTERIDACEAE	*Pellaea calomelanos* var. *calomelanos*	√	
SOLANACEAE	*Lycium cinereum*	√	
SOLANACEAE	*Lycium hirsutum*	√	

SOLANACEAE	*Lycium horridum*		√
SOLANACEAE	*Lycium pumilum*	√	
SOLANACEAE	*Lycium schizocalyx*	√	
SOLANACEAE	*Solanum catombelense*	√	
SOLANACEAE	*Solanum lichtensteinii*	√	
SOLANACEAE	*Solanum panduriforme*	√	
SOLANACEAE	*Solanum retroflexum*	√	
SOLANACEAE	*Solanum sisymbrifolium*		√
SOLANACEAE	*Solanum supinum* var. *supinum*	√	
SOLANACEAE	*Solanum tomentosum* var. *tomentosum*	√	
SOLANACEAE	*Withania somnifera*	√	
STERCULIACEAE	*Hermannia quartiniana*	√	√
STERCULIACEAE	*Melhania rehmannii*	√	√
THEOPHRASTACEAE	*Samolus valerandi*	√	
THYMELAEACEAE	*Gnidia polycephala*	√	
TILIACEAE	*Corchorus asplenifolius*	√	√
TILIACEAE	*Grewia flava*	√	√
VAHLIACEAE	*Vahlia capensis* subsp. *vulgaris* var. *linearis*	√	
VERBENACEAE	*Chascanum adenostachyum*	√	√
VERBENACEAE	*Chascanum hederaceum* var. *hederaceum*	√	
VERBENACEAE	*Chascanum pinnatifidum* var. *pinnatifidum*	√	√
VERBENACEAE	*Lantana rugosa*	√	√
VISCACEAE	*Viscum rotundifolium*	√	

ZYGOPHYLLACEAE	*Tribulus zeyheri* subsp. *zeyheri*	√	
ZYGOPHYLLACEAE	*Zygophyllum pubescens*	√	
Asbestos Hills			
ACANTHACEAE	*Barleria bechuanensis*	√	
ACANTHACEAE	*Barleria lichtensteiniana*	√	
ACANTHACEAE	*Blepharis integrifolia* var. *integrifolia*	√	
ACANTHACEAE	*Blepharis marginata*	√	√
ACANTHACEAE	*Dyschoriste pseuderecta*	√	
ACANTHACEAE	*Glossochilus burchellii*	√	√
ACANTHACEAE	*Justicia puberula*	√	
ACANTHACEAE	*Justicia thymifolia*	√	
ACANTHACEAE	*Monechma divaricatum*	√	√
ACANTHACEAE	*Monechma genistifolium* subsp. *australe*	√	
ACANTHACEAE	*Monechma incanum*	√	
AIZOACEAE	*Aizoon asbestinum*	√	
AIZOACEAE	*Plinthus cryptocarpus*	√	
AIZOACEAE	*Tetragonia arbuscula*	√	
AMARANTHACEAE	*Aerva leucura*	√	
AMARANTHACEAE	*Hermbstaedtia fleckii*	√	√
AMARANTHACEAE	*Hermbstaedtia odorata* var. *albi-rosea*	√	
AMARANTHACEAE	*Hermbstaedtia odorata* var. *aurantiaca*	√	
AMARANTHACEAE	*Hermbstaedtia odorata* var. *odorata*	√	
AMARANTHACEAE	*Kyphocarpa angustifolia*	√	√

AMARANTHACEAE	*Sericorema sericea*	√	
AMARYLLIDACEAE	*Haemanthus humilis* subsp. *humilis*	√	
ANACARDIACEAE	*Searsia burchellii*	√	
ANACARDIACEAE	*Searsia ciliata*	√	√
ANACARDIACEAE	*Searsia lancea*	√	
ANACARDIACEAE	*Searsia pendulina*	√	
ANACARDIACEAE	*Searsia pyroides* var. *pyroides*	√	
ANACARDIACEAE	*Searsia tridactyla*	√	
APIACEAE	*Deverra burchellii*	√	
APOCYNACEAE	*Brachystelma circinatum*	√	
APOCYNACEAE	*Cynanchum orangeanum*	√	
APOCYNACEAE	*Fockea angustifolia*	√	
APOCYNACEAE	*Gomphocarpus fruticosus* subsp. *fruticosus*	√	
APOCYNACEAE	*Gomphocarpus tomentosus* subsp. *tomentosus*	√	
APOCYNACEAE	*Hoodia gordonii*	√	
APOCYNACEAE	*Huernia barbata* subsp. *barbata*	√	
APOCYNACEAE	*Huernia clavigera*	√	
APOCYNACEAE	*Pachypodium succulentum*	√	
APOCYNACEAE	*Pentarrhinum insipidum*	√	
APOCYNACEAE	*Piaranthus decipiens*	√	
ASPARAGACEAE	*Asparagus bechuanicus*	√	
ASPARAGACEAE	*Asparagus exuvialis* forma *exuvialis*	√	
ASPARAGACEAE	*Asparagus laricinus*		√

ASPARAGACEAE	*Asparagus nelsii*	√	
ASPARAGACEAE	*Asparagus suaveolens*	√	
ASPHODELACEAE	*Aloe dichotoma*	√	
ASPHODELACEAE	*Aloe grandidentata*	√	√
ASPHODELACEAE	*Aloe hereroensis* var. *hereroensis*	√	
ASPHODELACEAE	*Bulbine abyssinica*	√	
ASPHODELACEAE	*Trachyandra saltii* var. *saltii*	√	
ASPLENIACEAE	*Asplenium cordatum*	√	
ASTERACEAE	*Arctotis acaulis*	√	
ASTERACEAE	*Arctotis venusta*	√	
ASTERACEAE	*Berkheya pinnatifida* subsp. *pinnatifida*	√	
ASTERACEAE	*Chrysocoma ciliata*	√	√
ASTERACEAE	*Chrysocoma obtusata*	√	
ASTERACEAE	*Cineraria vallis-pacis*	√	
ASTERACEAE	*Dicoma capensis*	√	
ASTERACEAE	*Dicoma macrocephala*	√	√
ASTERACEAE	*Dimorphotheca cuneata*	√	
ASTERACEAE	*Dimorphotheca polyptera*	√	
ASTERACEAE	*Eriocephalus ericoides* subsp. *griquensis*	√	
ASTERACEAE	*Eriocephalus glandulosus*	√	
ASTERACEAE	*Eriocephalus karooicus*	√	
ASTERACEAE	*Euryops subcarnosus* subsp. *vulgaris*	√	√
ASTERACEAE	*Felicia filifolia* subsp. *filifolia*	√	

ASTERACEAE	*Felicia muricata* subsp. *cinerascens*	√	
ASTERACEAE	*Felicia muricata* subsp*. muricata*	√	√
ASTERACEAE	*Felicia namaquana*	√	
ASTERACEAE	*Felicia ovata*	√	
ASTERACEAE	*Garuleum schinzii* subsp. *schinzii*	√	
ASTERACEAE	*Gazania krebsiana* subsp*. arctotoides*	√	
ASTERACEAE	*Gazania krebsiana* subsp*. serrulata*	√	√
ASTERACEAE	*Geigeria filifolia*	√	√
ASTERACEAE	*Geigeria ornativa* subsp. *ornativa*	√	
ASTERACEAE	*Helichrysum arenicola*	√	
ASTERACEAE	*Helichrysum cerastioides* var. *cerastioides*	√	
ASTERACEAE	*Helichrysum lineare*	√	
ASTERACEAE	*Helichrysum lucilioides*	√	
ASTERACEAE	*Helichrysum nudifolium* var. *nudifolium*	√	
ASTERACEAE	*Helichrysum spiciforme*	√	
ASTERACEAE	*Helichrysum zeyheri*	√	√
ASTERACEAE	*Hertia ciliata*	√	
ASTERACEAE	*Hertia pallens*		√
ASTERACEAE	*Ifloga glomerata*	√	
ASTERACEAE	*Lactuca inermis*	√	
ASTERACEAE	*Laggera decurrens*	√	
ASTERACEAE	*Leysera tenella*	√	
ASTERACEAE	*Lopholaena cneorifolia*	√	

ASTERACEAE	*Nidorella resedifolia* subsp. *resedifolia*	√	
ASTERACEAE	*Osteospermum leptolobum*	√	
ASTERACEAE	*Osteospermum microphyllum*	√	
ASTERACEAE	*Osteospermum spinescens*	√	
ASTERACEAE	*Othonna auriculifolia*	√	
ASTERACEAE	*Pegolettia retrofracta*	√	√
ASTERACEAE	*Pentzia calcarea*	√	
ASTERACEAE	*Pentzia incana*	√	
ASTERACEAE	*Pentzia quinquefida*	√	
ASTERACEAE	*Pentzia sphaerocephala*		√
ASTERACEAE	*Phymaspermum aciculare*	√	
ASTERACEAE	*Phymaspermum parvifolium*	√	
ASTERACEAE	*Platycarphella parvifolia*	√	
ASTERACEAE	*Psiadia punctulata*	√	
ASTERACEAE	*Pteronia cylindracea*	√	
ASTERACEAE	*Pteronia mucronata*	√	
ASTERACEAE	*Pteronia unguiculata*	√	
ASTERACEAE	*Rosenia humilis*	√	
ASTERACEAE	*Senecio carnosus*	√	
ASTERACEAE	*Senecio consanguineus*	√	
ASTERACEAE	*Senecio inaequidens*	√	
ASTERACEAE	*Senecio reptans*	√	
ASTERACEAE	*Senecio sisymbriifolius*	√	

ASTERACEAE	*Tarchonanthus camphoratus*	√	√
ASTERACEAE	*Tarchonanthus obovatus*	√	√
ASTERACEAE	*Tripteris crassifolia*	√	
ASTERACEAE	*Tripteris dentata*	√	
ASTERACEAE	*Troglophyton capillaceum* subsp. *capillaceum*	√	
ASTERACEAE	*Ursinia nana* subsp*. nana*	√	
BEGONIACEAE	*Rhigozum obovatum*		√
BORAGINACEAE	*Anchusa riparia*	√	
BORAGINACEAE	*Ehretia alba*	√	
BORAGINACEAE	*Ehretia rigida*		√
BORAGINACEAE	*Heliotropium ciliatum*	√	
BORAGINACEAE	*Heliotropium lineare*	√	
BORAGINACEAE	*Heliotropium strigosum*	√	
BRASSICACEAE	*Erucastrum austroafricanum*	√	
BRASSICACEAE	*Erucastrum strigosum*	√	
BRASSICACEAE	*Heliophila minima*	√	
BRASSICACEAE	*Heliophila suavissima*	√	√
BRASSICACEAE	*Heliophila trifurca*	√	
BRASSICACEAE	*Lepidium africanum* subsp*. divaricatum*	√	
CAMPANULACEAE	*Wahlenbergia androsacea*	√	
CAMPANULACEAE	*Wahlenbergia denticulata* var. *denticulata*	√	
CAMPANULACEAE	*Wahlenbergia nodosa*	√	√
CAMPANULACEAE	*Wahlenbergia undulata*	√	

CAPPARACEAE	*Boscia albitrunca*	√	√
CAPPARACEAE	*Cadaba aphylla*	√	√
CAPPARACEAE	*Cleome angustifolia* subsp*. diandra*	√	
CAPPARACEAE	*Cleome rubella*	√	√
CARYOPHYLLACEAE	*Dianthus micropetalus*	√	√
CARYOPHYLLACEAE	*Dianthus namaensis* var. *dinteri*	√	
CARYOPHYLLACEAE	*Pollichia campestris*	√	
CELASTRACEAE	*Gymnosporia buxifolia*	√	√
CELASTRACEAE	*Maytenus ilicina*	√	
CELASTRACEAE	*Maytenus undata*	√	
CELASTRACEAE	*Putterlickia pyracantha*	√	
CELASTRACEAE	*Putterlickia saxatilis*	√	
CHENOPODIACEAE	*Atriplex semibaccata* var. *appendiculata*	√	
CHENOPODIACEAE	*Atriplex suberecta*	√	
CHENOPODIACEAE	*Chenopodium hederiforme* var*. dentatum*	√	
COLCHICACEAE	*Colchicum melanthoides* subsp*. melanthoides*	√	
COLCHICACEAE	*Ornithoglossum dinteri*	√	√
COMMELINACEAE	*Commelina africana* var. *krebsiana*	√	√
COMMELINACEAE	*Commelina livingstonii*	√	
CONVOLVULACEAE	*Convolvulus boedeckerianus*	√	
CONVOLVULACEAE	*Convolvulus ocellatus* var. *ocellatus*	√	
CONVOLVULACEAE	*Convolvulus sagittatus*	√	
CONVOLVULACEAE	*Evolvulus alsinoides*	√	

CONVOLVULACEAE	*Ipomoea bolusiana*	√	
CONVOLVULACEAE	*Ipomoea obscura* var. *obscura*	√	
CONVOLVULACEAE	*Ipomoea oenotheroides*	√	
CONVOLVULACEAE	*Ipomoea suffruticosa*	√	
CONVOLVULACEAE	*Seddera suffruticosa*	√	√
CRASSULACEAE	*Adromischus trigynus*	√	
CRASSULACEAE	*Cotyledon orbiculata* var. *dactylopsis*	√	
CRASSULACEAE	*Cotyledon orbiculata* var. *orbiculata*	√	
CRASSULACEAE	*Crassula corallina* subsp. *corallina*	√	
CRASSULACEAE	*Crassula muscosa* var. *muscosa*	√	
CRASSULACEAE	*Kalanchoe rotundifolia*	√	
CUCURBITACEAE	*Acanthosicyos naudinianus*	√	
CUCURBITACEAE	*Coccinia sessilifolia*	√	
CUCURBITACEAE	*Cucumis heptadactylus*	√	√
CUCURBITACEAE	*Cucumis kalahariensis*	√	
CUCURBITACEAE	*Cucumis myriocarpus* subsp. *myriocarpus*	√	
CUCURBITACEAE	*Cucumis zeyheri*	√	
CUCURBITACEAE	*Kedrostis foetidissima*	√	
CUCURBITACEAE	*Kedrostis hirtella*	√	
CYPERACEAE	*Bulbostylis burchellii*	√	
CYPERACEAE	*Bulbostylis hispidula*		√
CYPERACEAE	*Bulbostylis humilis*		√
CYPERACEAE	*Cyperus margaritaceus* var. *margaritaceus*	√	√

CYPERACEAE	*Cyperus marginatus*	√	
CYPERACEAE	*Eleocharis dregeana*	√	
CYPERACEAE	*Fuirena pubescens* var. *pubescens*	√	
CYPERACEAE	*Scirpoides burkei*	√	
DRACAENACEAE	*Sansevieria aethiopica*	√	
EBENACEAE	*Diospyros austro-africana* var. *microphylla*	√	√
EBENACEAE	*Euclea crispa* subsp. *ovata*	√	
EBENACEAE	*Euclea undulata*	√	√
ERIOSPERMACEAE	*Eriospermum porphyrium*	√	
EUPHORBIACEAE	*Croton gratissimus* var. *gratissimus*	√	
EUPHORBIACEAE	*Euphorbia aequoris*	√	
EUPHORBIACEAE	*Euphorbia bergii*	√	
EUPHORBIACEAE	*Euphorbia duseimata*	√	
EUPHORBIACEAE	*Euphorbia fusca*	√	
EUPHORBIACEAE	*Euphorbia gariepina* subsp. *gariepina*	√	
EUPHORBIACEAE	*Euphorbia inaequilatera*		√
EUPHORBIACEAE	*Euphorbia mauritanica* var. *mauritanica*	√	√
EUPHORBIACEAE	*Euphorbia rhombifolia*	√	√
EUPHORBIACEAE	*Euphorbia wilmaniae*	√	
EUPHORBIACEAE	*Phyllanthus parvulus* var. *parvulus*		√
FABACEAE	*Argyrolobium argenteum*	√	
FABACEAE	*Argyrolobium pauciflorum* var. *semiglabrum*	√	
FABACEAE	*Calobota cuspidosa*	√	√

FABACEAE	*Chamaecrista biensis*	√	
FABACEAE	*Crotalaria griquensis*	√	
FABACEAE	*Crotalaria virgultalis*	√	
FABACEAE	*Cyamopsis serrata*	√	
FABACEAE	*Elephantorrhiza elephantina*	√	
FABACEAE	*Indigofera sessifolia*		√
FABACEAE	*Indigofera alternans* var. *alternans*	√	
FABACEAE	*Indigofera charlieriana* var. *charlieriana*	√	
FABACEAE	*Indigofera daleoides* var. *daleoides*	√	
FABACEAE	*Indigofera denudata*	√	
FABACEAE	*Indigofera filipes*	√	
FABACEAE	*Indigofera heterotricha*	√	
FABACEAE	*Indigofera sessilifolia*	√	
FABACEAE	*Indigofera vicioides* var. *vicioides*	√	
FABACEAE	*Lessertia affinis*	√	
FABACEAE	*Lessertia macrostachya* var. *macrostachya*	√	
FABACEAE	*Lotononis burchellii*	√	
FABACEAE	*Lotononis laxa*	√	
FABACEAE	*Melolobium burchelli*	√	
FABACEAE	*Melolobium candicans*	√	
FABACEAE	*Melolobium macrocalyx* var. *macrocalyx*	√	
FABACEAE	*Melolobium microphyllum*	√	
FABACEAE	*Parkinsonia africana*	√	

FABACEAE	*Ptycholobium biflorum* subsp*. angolensis*	√	
FABACEAE	*Rhynchosia confusa*	√	
FABACEAE	*Rhynchosia totta* var. *totta*	√	√
FABACEAE	*Senegalia mellifera* subsp. *detinens*		√
FABACEAE	*Senna italica* subsp*. arachoides*	√	
FABACEAE	*Sutherlandia frutescens*	√	
FABACEAE	*Sutherlandia microphylla*	√	
FABACEAE	*Tephrosia burchellii*	√	
FABACEAE	*Tephrosia pupurea*		√
FABACEAE	*Vachellia erioloba*	√	
FABACEAE	*Vachellia haematoxylon*	√	
FABACEAE	*Vachellia hebeclada* subsp. *hebeclada*	√	
FABACEAE	*Vachellia tortilis* subsp. *heteracantha*	√	
GERANIACEAE	*Monsonia angustifolia*	√	
GERANIACEAE	*Pelargonium multicaule* subsp. *multicaule*	√	
GISEKIACEAE	*Gisekia pharnacioides*		√
HYACINTHACEAE	*Albuca collina*	√	
HYACINTHACEAE	*Albuca glandulosa*	√	
HYACINTHACEAE	*Albuca namaquensis*	√	
HYACINTHACEAE	*Albuca tortuosa*	√	
HYACINTHACEAE	*Drimia intricata*	√	
HYACINTHACEAE	*Drimia macrantha*	√	
HYACINTHACEAE	*Drimia physodes*	√	

HYACINTHACEAE	*Drimia sanguinea*	√	
HYACINTHACEAE	*Eucomis autumnalis* subsp. *amaryllidifolia*	√	
HYACINTHACEAE	*Schizocarphus nervosus*	√	
ICACINACEAE	*Pyrenacantha scandens*	√	
IRIDACEAE	*Babiana bainesii*	√	√
IRIDACEAE	*Babiana hypogaea*	√	
IRIDACEAE	*Duthieastrum linifolium*	√	
IRIDACEAE	*Freesia andersoniae*	√	
IRIDACEAE	*Gladiolus orchidiflorus*	√	
IRIDACEAE	*Gladiolus permeabilis* subsp*. edulis*	√	
IRIDACEAE	*Lapeirousia plicata* subsp. *longifolia*	√	
IRIDACEAE	*Lapeirousia plicata* subsp. *plicata*	√	
IRIDACEAE	*Moraea pallida*	√	
IRIDACEAE	*Moraea polystachya*	√	√
JUNCACEAE	*Juncus punctorius*	√	
JUNCACEAE	*Juncus rigidus*	√	
LAMIACEAE	*Leucas capensis*	√	√
LAMIACEAE	*Salvia disermas*	√	
LAMIACEAE	*Salvia namaensis*	√	
LAMIACEAE	*Salvia verbenaca*	√	
LAMIACEAE	*Stachys burchelliana*	√	√
LAMIACEAE	*Stachys spathulata*	√	
LOBELIACEAE	*Lobelia thermalis*	√	

MALPIGHIACEAE	*Triapsis hypericoides* subsp. *hypericoides*	√	
MALVACEAE	*Abutilon austro-africanum*	√	
MALVACEAE	*Corchorus asplenifolius*	√	√
MALVACEAE	*Grewia flava*	√	√
MALVACEAE	*Hermannia abrotanoides*	√	
MALVACEAE	*Hermannia bryoniifolia*	√	
MALVACEAE	*Hermannia burkei*	√	
MALVACEAE	*Hermannia comosa*	√	√
MALVACEAE	*Hermannia eenii*	√	
MALVACEAE	*Hermannia erodioides*	√	
MALVACEAE	*Hermannia jacobeifolia*	√	
MALVACEAE	*Hermannia linearifolia*	√	
MALVACEAE	*Hermannia linnaeoides*	√	
MALVACEAE	*Hermannia stellulata*	√	
MALVACEAE	*Hermannia tomentosa*	√	
MALVACEAE	*Hibiscus fleckii*	√	
MALVACEAE	*Hibiscus marlothianus*	√	
MALVACEAE	*Hibiscus micranthus* var. *micranthus*	√	
MALVACEAE	*Hibiscus pusillus*		√
MALVACEAE	*Melhania prostrata*	√	√
MALVACEAE	*Melhania rehmannii*	√	√
MALVACEAE	*Melhania virescens*	√	
MALVACEAE	*Pavonia burchellii*	√	

MALVACEAE	*Sida chrysantha*	√	√
MALVACEAE	*Sida cordifolia* subsp. *cordifolia*	√	
MARSILEACEAE	*Marsilea burchellii*	√	
MELIACEAE	*Nymania capensis*	√	
MELIANTHACEAE	*Melianthus comosus*	√	
MENISPERMACEAE	*Antizoma angustifolia*	√	
MESEMBRYANTHEMACEAE	*Chasmatophyllum musculinum*	√	
MESEMBRYANTHEMACEAE	*Ebracteola wilmaniae*	√	
MESEMBRYANTHEMACEAE	*Hereroa wilmaniae*	√	
MESEMBRYANTHEMACEAE	*Nananthus aloides*	√	
MESEMBRYANTHEMACEAE	*Prepodesma orpenii*	√	
MESEMBRYANTHEMACEAE	*Ruschia griquensis*	√	
MESEMBRYANTHEMACEAE	*Titanopsis calcarea*	√	
MOLLUGINACEAE	*Hypertelis salsoloides* var. *salsoloides*	√	
MOLLUGINACEAE	*Limeum aethiopicum* var. *aethiopicum*	√	
MOLLUGINACEAE	*Limeum aethiopicum* var. *intermedium*	√	
MOLLUGINACEAE	*Limeum arenicolum*	√	
MOLLUGINACEAE	*Limeum argute-carinatum* var. *argute-carinatum*	√	√
MOLLUGINACEAE	*Limeum argute-carinatum* var. *kwebense*	√	
MOLLUGINACEAE	*Limeum fenestratum* var. *fenestratum*	√	
MOLLUGINACEAE	*Limeum sulcatum* var. *sulcatum*	√	√
MOLLUGINACEAE	*Pharnaceum brevicaule*	√	
MORACEAE	*Ficus cordata subsp. cordata*	√	

NEURADACEAE	*Grielum humifusum* var*. humifusum*	√	
NEURADACEAE	*Grielum sinuatum*	√	
NYCTAGINACEAE	*Commicarpus pentandrus*	√	
NYCTAGINACEAE	*Phaeoptilum spinosum*	√	
OLEACEAE	*Menodora africana*	√	
OLEACEAE	*Olea europaea* subsp*. africana*	√	
OPHIOGLOSSACEAE	*Ophioglossum polyphyllum* var. *polyphyllum*	√	
ORCHIDACEAE	*Eulophia ovalis* var. *ovalis*	√	
OXALIDACEAE	*Oxalis depressa*	√	
OXALIDACEAE	*Oxalis lawsonii*	√	
PAPAVERACEAE	*Papaver aculeatum*	√	
PASSIFLORACEAE	*Adenia repanda*	√	
PEDALIACEAE	*Harpagophytum procumbens* subsp. *procumbens*	√	
PEDALIACEAE	*Sesamum triphyllum* var. *triphyllum*	√	
PHYLLANTHACEAE	*Phyllanthus incurvus*	√	√
PHYLLANTHACEAE	*Phyllanthus maderaspatensis*	√	√
PHYLLANTHACEAE	*Phyllanthus parvulus var.garipensis*	√	
PHYTOLACCACEAE	*Lophiocarpus polystachyus*		√
PLANTAGINACEAE	*Plantago lanceolata*	√	
POACEAE	*Agrostis lachnantha* var. *lachnantha*	√	
POACEAE	*Andropogon eucomus*	√	
POACEAE	*Anthephora pubescens*	√	√
POACEAE	*Aristida adscensionis*	√	

POACEAE	*Aristida congesta* subsp*. barbicollis*	√	√
POACEAE	*Aristida congesta* subsp*. congesta*	√	√
POACEAE	*Aristida diffusa*	√	
POACEAE	*Aristida meridionalis*	√	
POACEAE	*Aristida stipitata* subsp. *graciliflora*	√	
POACEAE	*Aristida stipitata* subsp. *spicata*	√	
POACEAE	*Aristida stipitata* subsp. *stipitata*	√	
POACEAE	*Aristida vestita*	√	
POACEAE	*Brachiaria brizantha*	√	
POACEAE	*Brachiaria marlothii*	√	
POACEAE	*Brachiaria nigropedata*	√	
POACEAE	*Brachiaria serrata*	√	√
POACEAE	*Bromus pectinatus*	√	
POACEAE	*Calamagrostis epigejos* var. *capensis*	√	
POACEAE	*Cenchrus ciliaris*	√	
POACEAE	*Centropodia glauca*	√	
POACEAE	*Chloris virgata*	√	
POACEAE	*Chrysopogon serrulatus*	√	√
POACEAE	*Cymbopogon caesius*	√	
POACEAE	*Cymbopogon pospischilii*	√	√
POACEAE	*Cynodon dactylon*	√	
POACEAE	*Cynodon incompletus*	√	
POACEAE	*Digitaria eriantha*	√	√

POACEAE	*Digitaria polyphylla*	√	√
POACEAE	*Elionurus muticus*		√
POACEAE	*Enneapogon cenchroides*		√
POACEAE	*Enneapogon desvauxii*	√	
POACEAE	*Enneapogon scaber*	√	
POACEAE	*Enneapogon scoparius*	√	√
POACEAE	*Eragrostis bicolor*	√	
POACEAE	*Eragrostis chloromelas*	√	√
POACEAE	*Eragrostis cilianensis*	√	
POACEAE	*Eragrostis curvula*	√	
POACEAE	*Eragrostis echinochloidea*	√	
POACEAE	*Eragrostis gummiflua*	√	
POACEAE	*Eragrostis homomalla*	√	
POACEAE	*Eragrostis lehmanniana* var. *lehmanniana*	√	√
POACEAE	*Eragrostis macrochlamys* var. *wilmaniae*	√	
POACEAE	*Eragrostis nindensis*	√	√
POACEAE	*Eragrostis obtusa*	√	
POACEAE	*Eragrostis pallens*	√	
POACEAE	*Eragrostis pilgeriana*	√	
POACEAE	*Eragrostis porosa*	√	
POACEAE	*Eragrostis procumbens*	√	
POACEAE	*Eragrostis rotifer*	√	
POACEAE	*Eragrostis trichophora*	√	√

POACEAE	*Eragrostis truncata*	√	
POACEAE	*Eustachys paspaloides*	√	
POACEAE	*Fingerhuthia africana*	√	√
POACEAE	*Heteropogon contortus*	√	√
POACEAE	*Hyparrhenia hirta*	√	
POACEAE	*Leptochloa appletonii*	√	
POACEAE	*Melinis nerviglumis*	√	
POACEAE	*Melinis repens* subsp. *grandiflora*	√	
POACEAE	*Melinis repens* subsp. *repens*	√	√
POACEAE	*Microchloa caffra*	√	√
POACEAE	*Oropetium capense*	√	
POACEAE	*Panicum coloratum* var. *coloratum*	√	
POACEAE	*Panicum maximum*	√	
POACEAE	*Panicum stapfianum*	√	
POACEAE	*Pogonarthria squarrosa*	√	√
POACEAE	*Polypogon griquensis*	√	
POACEAE	*Schismus barbatus*	√	
POACEAE	*Schmidtia kalahariensis*	√	
POACEAE	*Schmidtia pappophoroides*	√	
POACEAE	*Setaria sphacelata* var. *sphacelata*	√	
POACEAE	*Setaria sphacelata* var. *torta*	√	
POACEAE	*Sporobolus acinifolius*	√	
POACEAE	*Sporobolus discosporus*	√	

POACEAE	*Sporobolus fimbriatus*	√	√
POACEAE	*Sporobolus ludwigii*	√	
POACEAE	*Stipagrostis ciliata* var*. capensis*	√	
POACEAE	*Stipagrostis namaquensis*	√	
POACEAE	*Stipagrostis obtusa*	√	
POACEAE	*Stipagrostis uniplumis* var. *neesii*	√	
POACEAE	*Stipagrostis uniplumis* var*. uniplumis*	√	√
POACEAE	*Themeda triandra*	√	√
POACEAE	*Tragus berteronianus*	√	
POACEAE	*Tragus koelerioides*	√	√
POACEAE	*Tragus racemosus*	√	
POACEAE	*Trichoneura grandiglumis*	√	√
POACEAE	*Triraphis andropogonoides*	√	√
POACEAE	*Triraphis purpurea*	√	
POLYGALACEAE	*Polygala hottentotta*	√	√
POLYGALACEAE	*Polygala krumanina*	√	√
POLYGALACEAE	*Polygala leptophylla*	√	
POLYGALACEAE	*Polygala leptophylla* var. *leptophylla*	√	
POLYGALACEAE	*Polygala seminuda*	√	
POLYGONACEAE	*Oxygonum alatum* var. *alatum*	√	
POLYGONACEAE	*Oxygonum dregeanum* subsp*. canescens* var. *canescens*	√	
POLYGONACEAE	*Persicaria hystricula*	√	

POLYGONACEAE	*Polygonum bellardii*	√	
PORTULACACEAE	*Avonia albissima*	√	
PORTULACACEAE	*Portulaca kermisina*		√
PORTULACACEAE	*Portulaca quadrifida*	√	
RESEDACEAE	*Oligomeris dipetala* var. *dipetala*	√	
RHAMNACEAE	*Ziziphus mucronata* subsp*. mucronata*	√	
RICCIACEAE	*Riccia albolimbata*	√	
RICCIACEAE	*Riccia crinita*	√	
RICCIACEAE	*Riccia okahandjana*	√	
RUBIACEAE	*Anthospermum rigidum* subsp. *pumilum*	√	√
RUBIACEAE	*Kohautia caespitosa* subsp. *brachyloba*	√	√
RUBIACEAE	*Kohautia cynanchica*	√	
RUBIACEAE	*Vangueria infausta* subsp. *infausta*	√	
SANTALACEAE	*Thesium hystrix*	√	
SANTALACEAE	*Thesium lacinulatum*	√	
SANTALACEAE	*Thesium lineatum*		√
SCROPHULARIACEAE	*Aptosimum indivisum*	√	
SCROPHULARIACEAE	*Aptosimum marlothii*	√	
SCROPHULARIACEAE	*Chaenostoma halimifolium*	√	
SCROPHULARIACEAE	*Chaenostoma patrioticum*	√	
SCROPHULARIACEAE	*Chaenostoma rotundifolium*	√	
SCROPHULARIACEAE	*Jamesbrittenia atropurpurea* subsp*. atropurpurea*	√	
SCROPHULARIACEAE	*Jamesbrittenia aurantiaca*	√	

SCROPHULARIACEAE	*Jamesbrittenia integerrima*	√	
SCROPHULARIACEAE	*Jamesbrittenia tysonii*	√	
SCROPHULARIACEAE	*Manulea burchellii*	√	
SCROPHULARIACEAE	*Nemesia lilacina*	√	
SCROPHULARIACEAE	*Peliostomum leucorrhizum*	√	√
SCROPHULARIACEAE	*Peliostomum origanoides*		√
SCROPHULARIACEAE	*Selago acocksii*	√	
SCROPHULARIACEAE	*Selago albida*	√	√
SCROPHULARIACEAE	*Selago albomarginata*	√	
SCROPHULARIACEAE	*Selago mixta*	√	
SCROPHULARIACEAE	*Selago saxatilis*	√	
SCROPHULARIACEAE	*Sutera griquensis*	√	
SCROPHULARIACEAE	*Sutera halimifolia*		√
SINOPTERIDACEAE	*Cheilanthes dolomiticola*	√	
SINOPTERIDACEAE	*Cheilanthes eckloniana*	√	
SINOPTERIDACEAE	*Cheilanthes hirta* var. *brevipilosa*	√	
SINOPTERIDACEAE	*Cheilanthes hirta* var. *hirta*	√	
SINOPTERIDACEAE	*Pellaea calomelanos* var. *calomelanos*	√	
SOLANACEAE	*Lycium horridum*	√	
SOLANACEAE	*Lycium pilifolium*	√	
SOLANACEAE	*Solanum burchellii*	√	
SOLANACEAE	*Solanum lichtensteinii*		√
SOLANACEAE	*Solanum namaquense*	√	

SOLANACEAE	*Solanum retroflexum*	√	
SOLANACEAE	*Solanum sisymbrifolium*		√
SOLANACEAE	*Solanum supinum* var. *supinum*	√	
SOLANACEAE	*Withania somnifera*	√	
THYMELAEACEAE	*Gnidia burchellii*	√	
THYMELAEACEAE	*Gnidia polycephala*	√	√
TYPHACEAE	*Typha capensis*	√	
VAHLIACEAE	*Vahlia capensis* subsp. *vulgaris* var. *linearis*	√	
VERBENACEAE	*Chascanum pinnatifidum* var. *pinnatifidum*	√	√
VERBENACEAE	*Lantana rugosa*	√	√
VISCACEAE	*Viscum rotundifolium*	√	
ZYGOPHYLLACEAE	*Tribulus zeyheri* subsp. *zeyheri*	√	
ZYGOPHYLLACEAE	*Zygophyllum gilfillanii*	√	
ZYGOPHYLLACEAE	*Zygophyllum lichtensteinianum*	√	
ZYGOPHYLLACEAE	*Zygophyllum microcarpum*	√	
ZYGOPHYLLACEAE	*Zygophyllum pubescens*	√	
Ghaap Plateau			
ACANTHACEAE	*Barleria bechuanensis*	√	
ACANTHACEAE	*Barleria macrostegia*	√	
ACANTHACEAE	*Barleria rigida*	√	
ACANTHACEAE	*Blepharis integrifolia* var. *integrifolia*	√	
ACANTHACEAE	*Blepharis marginata*	√	√
ACANTHACEAE	*Glossochilus burchellii*	√	

ACANTHACEAE	*Justicia thymifolia*	√	
ACANTHACEAE	*Monechma divaricatum*	√	√
AIZOACEAE	*Galenia affinis*	√	
AMARANTHACEAE	*Achyranthes aspera*		√
AMARANTHACEAE	*Aerva leucura*	√	
AMARANTHACEAE	*Hermbstaedtia odorata* var. *odorata*	√	
AMARANTHACEAE	*Kyphocarpa angustifolia*	√	√
AMARANTHACEAE	*Pupalia lappacea* var*. lappacea*	√	√
AMARANTHACEAE	*Pupalia lappacea* var. *velutina*	√	
AMARANTHACEAE	*Sericorema sericea*	√	√
AMARYLLIDACEAE	*Brunsvigia radulosa*	√	
ANACARDIACEAE	*Searsia ciliata*	√	√
ANACARDIACEAE	*Searsia lancea*		√
ANACARDIACEAE	*Searsia tenuinervis*	√	
ANACARDIACEAE	*Searsia tridactyla*	√	√
ANTHERICACEAE	*Chlorophytum angulicaule*	√	
ANTHERICACEAE	*Chlorophytum fasciculatum*	√	
ANTHERICACEAE	*Chlorophytum krauseanum*	√	
APIACEAE	*Centella asiatica*	√	
APIACEAE	*Deverra burchellii*	√	
APOCYNACEAE	*Fockea angustifolia*	√	
APOCYNACEAE	*Gomphocarpus fruticosus* subsp. *fruticosus*	√	
APOCYNACEAE	*Gomphocarpus tomentosus* subsp. *tomentosus*	√	

APOCYNACEAE	*Orbea lutea* subsp. *lutea*	√	
APOCYNACEAE	*Pentarrhinum insipidum*	√	√
APOCYNACEAE	*Stapelia grandiflora* var. *grandiflora*	√	
ASPARAGACEAE	*Asparagus cooperi*	√	
ASPARAGACEAE	*Asparagus laricinus*	√	√
ASPARAGACEAE	*Asparagus suaveolens*	√	√
ASPHODELACEAE	*Aloe grandidentata*		√
ASPHODELACEAE	*Trachyandra saltii* var. *saltii*	√	
ASTERACEAE	*Amphiglossa triflora*	√	
ASTERACEAE	*Arctotheca calendula*	√	
ASTERACEAE	*Arctotis venusta*	√	
ASTERACEAE	*Berkheya pinnatifida* subsp. *pinnatifida*	√	
ASTERACEAE	*Chrysocoma ciliata*	√	√
ASTERACEAE	*Chrysocoma obtusata*	√	
ASTERACEAE	*Cineraria exilis*	√	
ASTERACEAE	*Cineraria vallis-pacis*	√	
ASTERACEAE	*Denekia capensis*	√	
ASTERACEAE	*Dicoma anomala* subsp. *gerrardii*	√	
ASTERACEAE	*Dicoma macrocephala*	√	
ASTERACEAE	*Dicoma schinzii*	√	
ASTERACEAE	*Eriocephalus ericoides* subsp*. griquensis*	√	√
ASTERACEAE	*Felicia fascicularis*		√
ASTERACEAE	*Felicia filifolia* subsp*. filifolia*	√	

ASTERACEAE	*Felicia hirsuta*	√	
ASTERACEAE	*Felicia muricata* subsp. *cinerascens*	√	
ASTERACEAE	*Felicia muricata* subsp. *muricata*	√	√
ASTERACEAE	*Gazania krebsiana* subsp. *arctotoides*	√	
ASTERACEAE	*Gazania krebsiana* subsp. *serrulata*	√	√
ASTERACEAE	*Geigeria brevifolia*	√	
ASTERACEAE	*Geigeria burkei* subsp. *burkei* var. *burkei*	√	
ASTERACEAE	*Geigeria filifolia*	√	√
ASTERACEAE	*Geigeria ornativa* subsp. *ornativa*	√	
ASTERACEAE	*Gnaphalium englerianum*	√	
ASTERACEAE	*Gnaphalium filagopsis*	√	
ASTERACEAE	*Helichrysum argyrosphaerum*	√	
ASTERACEAE	*Helichrysum caespititium*	√	
ASTERACEAE	*Helichrysum dregeanum*	√	
ASTERACEAE	*Helichrysum lucilioides*	√	
ASTERACEAE	*Helichrysum nudifolium* var. *nudifolium*	√	
ASTERACEAE	*Helichrysum paronychioides*	√	
ASTERACEAE	*Helichrysum tomentosulum* subsp. *aromaticum*	√	
ASTERACEAE	*Helichrysum zeyheri*	√	√
ASTERACEAE	*Hirpicium echinus*	√	
ASTERACEAE	*Ifloga glomerata*	√	
ASTERACEAE	*Mikaniopsis cissampelina*	√	
ASTERACEAE	*Nidorella hottentotica*	√	

ASTERACEAE	*Nidorella resedifolia* subsp. *resedifolia*	√	
ASTERACEAE	*Nolletia ciliaris*	√	
ASTERACEAE	*Osteospermum muricatum* subsp. *muricatum*	√	
ASTERACEAE	*Pegolettia retrofracta*	√	
ASTERACEAE	*Pentzia calcarea*	√	√
ASTERACEAE	*Pentzia globosa*	√	√
ASTERACEAE	*Pentzia oppositifolia*	√	
ASTERACEAE	*Pentzia quinquefida*	√	
ASTERACEAE	*Pentzia sphaerocephala*		√
ASTERACEAE	*Rennera stellata*	√	
ASTERACEAE	*Schkuhria pinnata*		√
ASTERACEAE	*Senecio inaequidens*	√	
ASTERACEAE	*Senecio reptans*	√	
ASTERACEAE	*Tarchonanthus camphoratus*	√	√
ASTERACEAE	*Tarchonanthus obovatus*	√	√
ASTERACEAE	*Ursinia nana* subsp*. leptophylla*	√	
ASTERACEAE	*Vernonia galpinii*	√	
BORAGINACEAE	*Anchusa riparia*	√	
BORAGINACEAE	*Ehretia rigida*		√
BORAGINACEAE	*Heliotropium ciliatum*	√	
BORAGINACEAE	*Heliotropium nelsonii*	√	
BORAGINACEAE	*Lithospermum cinereum*	√	
BORAGINACEAE	*Lithospermum scabrum*	√	

BRASSICACEAE	*Erucastrum griquense*	√	
BRASSICACEAE	*Erucastrum strigosum*	√	
BRASSICACEAE	*Erucrastrum griquense*	√	
BRASSICACEAE	*Lepidium trifurcum*	√	
BRASSICACEAE	*Rorippa fluviatilis* var. *caledonica*	√	
BRASSICACEAE	*Rorippa fluviatilis* var. *fluviatilis*	√	
BRASSICACEAE	*Sisymbrium turczaninowii*	√	
BUDDLEJACEAE	*Buddleja saligna*	√	
CAMPANULACEAE	*Wahlenbergia androsacea*	√	
CAMPANULACEAE	*Wahlenbergia denticulata* var. *denticulata*	√	
CAMPANULACEAE	*Wahlenbergia denticulata* var. *transvaalensis*	√	
CAMPANULACEAE	*Wahlenbergia nodosa*	√	
CAMPANULACEAE	*Wahlenbergia paniculata*	√	
CAMPANULACEAE	*Wahlenbergia undulata*	√	
CAPPARACEAE	*Cadaba aphylla*	√	√
CAPPARACEAE	*Cleome angustifolia* subsp. *diandra*	√	
CAPPARACEAE	*Cleome maculata*	√	
CAPPARACEAE	*Cleome rubella*	√	√
CARYOPHYLLACEAE	*Dianthus micropetalus*	√	√
CARYOPHYLLACEAE	*Herniaria erckertii* subsp. *erckertii* var. *dewetii*	√	
CARYOPHYLLACEAE	*Pollichia campestris*	√	
CARYOPHYLLACEAE	*Silene undulata* subsp. *undulata*	√	
CELASTRACEAE	*Gymnosporia buxifolia*	√	√

CELASTRACEAE	*Gymnosporia lowiczii* subsp. *namibiensis*	√	
CHENOPODIACEAE	*Chenopodium phillipsianum*	√	
COLCHICACEAE	*Ornithoglossum dinteri*	√	√
COLCHICACEAE	*Ornithoglossum vulgare*	√	
COMMELINACEAE	*Commelina africana* var. *barberae*	√	
COMMELINACEAE	*Commelina africana* var. *krebsiana*	√	
COMMELINACEAE	*Commelina africana* var. *lancispatha*	√	√
COMMELINACEAE	*Commelina livingstonii*	√	
COMMELINACEAE	*Cyanotis speciosa*	√	
CONVOLVULACEAE	*Convolvulus ocellatus* var. *ocellatus*	√	
CONVOLVULACEAE	*Convolvulus sagittatus*	√	
CONVOLVULACEAE	*Evolvulus alsinoides*	√	
CONVOLVULACEAE	*Ipomoea bolusiana*	√	
CONVOLVULACEAE	*Ipomoea obscura* var. *obscura*	√	
CONVOLVULACEAE	*Ipomoea suffruticosa*	√	
CONVOLVULACEAE	*Xenostegia tridentata* subsp. *angustifolia*	√	
CRASSULACEAE	*Crassula campestris*	√	
CRASSULACEAE	*Crassula nodulosa* var. *nodulosa* forma *nodulosa*	√	
CUCURBITACEAE	*Citrullus lanatus*	√	
CUCURBITACEAE	*Coccinia sessilifolia*	√	
CUCURBITACEAE	*Cucumis africanus*	√	
CUCURBITACEAE	*Cucumis heptadactylus*	√	√
CUCURBITACEAE	*Cucumis myriocarpus* subsp. *leptodermis*	√	

CUCURBITACEAE	*Cucumis myriocarpus* subsp*. myriocarpus*	√	
CUCURBITACEAE	*Momordica balsamina*	√	
CYPERACEAE	*Bulbostylis burchellii*	√	
CYPERACEAE	*Bulbostylis hispidula*		√
CYPERACEAE	*Bulbostylis humilis*		√
CYPERACEAE	*Carex burchelliana*	√	
CYPERACEAE	*Cladium mariscus* subsp. *jamaicense*	√	
CYPERACEAE	*Cyperus bellus*	√	√
CYPERACEAE	*Cyperus longus* var. *tenuiflorus*	√	
CYPERACEAE	*Cyperus margaritaceus* var. *margaritaceus*	√	
CYPERACEAE	*Cyperus marginatus*	√	
CYPERACEAE	*Cyperus marlothii*	√	
CYPERACEAE	*Cyperus sphaerospermus*	√	
CYPERACEAE	*Cyperus usitatus*	√	
CYPERACEAE	*Kyllinga alba*	√	√
CYPERACEAE	*Scirpoides dioeca*	√	
DIPSACACEAE	*Scabiosa columbaria*	√	
EBENACEAE	*Diospyros austro-africana* var. *microphylla*	√	√
EBENACEAE	*Diospyros lycioides*		√
EBENACEAE	*Euclea crispa* subsp*. ovata*	√	
EBENACEAE	*Euclea undulata*		√
ELATINACEAE	*Bergia anagalloides*	√	
ELATINACEAE	*Bergia pentheriana*	√	

ERIOSPERMACEAE	*Eriospermum porphyrium*	√	
ERIOSPERMACEAE	*Eriospermum schinzii*		√
EUPHORBIACEAE	*Acalypha segetalis*	√	
EUPHORBIACEAE	*Euphorbia bergii*	√	√
EUPHORBIACEAE	*Euphorbia duseimata*	√	
EUPHORBIACEAE	*Euphorbia inaequilatera* var. *inaequilatera*	√	√
EUPHORBIACEAE	*Euphorbia rectirama*	√	
EUPHORBIACEAE	*Phyllanthus parvulus*		√
EUPHORBIACEAE	*Seidelia triandra*	√	
FABACEAE	*Calobota cuspidosa*	√	
FABACEAE	*Chamaecrista biensis*	√	
FABACEAE	*Crotalaria distans* subsp. *distans*	√	
FABACEAE	*Crotalaria griquensis*		√
FABACEAE	*Crotalaria spartioides*	√	
FABACEAE	*Dichilus lebeckioides*	√	
FABACEAE	*Elephantorrhiza elephantina*	√	√
FABACEAE	*Indigastrum argyraeum*	√	√
FABACEAE	*Indigofera sessifolia*		√
FABACEAE	*Indigofera alternans* var. *alternans*	√	
FABACEAE	*Indigofera charlieriana*		√
FABACEAE	*Indigofera comosa*	√	
FABACEAE	*Indigofera cryptantha* var. *cryptantha*	√	
FABACEAE	*Indigofera daleoides* var. *daleoides*	√	

FABACEAE	*Indigofera filipes*	√	
FABACEAE	*Indigofera heterotricha*	√	
FABACEAE	*Indigofera melanadenia*	√	
FABACEAE	*Indigofera rhytidocarpa* subsp. *rhytidocarpa*	√	
FABACEAE	*Indigofera sessiliflora*	√	
FABACEAE	*Indigofera vicioides*		√
FABACEAE	*Listia bainesii*	√	
FABACEAE	*Lotononis burchellii*	√	
FABACEAE	*Lotononis crumanina*	√	
FABACEAE	*Lotononis hirsuta*		√
FABACEAE	*Lotononis listii*	√	
FABACEAE	*Melolobium calycinum*	√	√
FABACEAE	*Melolobium candicans*	√	
FABACEAE	*Melolobium canescens*	√	
FABACEAE	*Melolobium macrocalyx* var. *macrocalyx*	√	
FABACEAE	*Neorautanenia ficifolia*	√	
FABACEAE	*Pomaria burchellii* subsp. *burchellii*	√	
FABACEAE	*Pteronia glauca*		√
FABACEAE	*Rhynchosia confusa*	√	
FABACEAE	*Rhynchosia totta* var. *totta*	√	
FABACEAE	*Senegalia mellifera* subsp. *detinens*	√	√
FABACEAE	*Senna italica* subsp. *arachoides*	√	
FABACEAE	*Tephrosia burchellii*	√	√

FABACEAE	*Tephrosia longipes*		√
FABACEAE	*Tephrosia lupinifolia*	√	
FABACEAE	*Vachellia erioloba*	√	
FABACEAE	*Vachellia tortilis*		√
FABACEAE	*Vahellia robusta* subsp*. robusta*	√	
FABACEAE	*Zornia milneana*	√	
GENTIANACEAE	*Sebaea exigua*	√	
GENTIANACEAE	*Sebaea grandis*	√	
GENTIANACEAE	*Sebaea pentandra* var. *pentandra*	√	
GERANIACEAE	*Monsonia angustifolia*	√	√
GERANIACEAE	*Pelargonium nanum*	√	
GISEKIACEAE	*Gisekia pharnacioides* var. *pharnacioides*	√	√
HYACINTHACEAE	*Dipcadi viride*	√	
HYACINTHACEAE	*Ledebouria revoluta*	√	
HYACINTHACEAE	*Ledebouria undulata*	√	
HYACINTHACEAE	*Schizocarphus nervosus*	√	
HYPOXIDACEAE	*Hypoxis iridifolia*	√	
IRIDACEAE	*Babiana bainesii*	√	√
IRIDACEAE	*Babiana hypogaea*	√	
IRIDACEAE	*Duthieastrum linifolium*	√	
IRIDACEAE	*Gladiolus permeabilis* subsp*. edulis*	√	
IRIDACEAE	*Lapeirousia erythrantha*	√	
IRIDACEAE	*Lapeirousia plicata* subsp. *plicata*	√	

IRIDACEAE	*Moraea polystachya*	√	√
IRIDACEAE	*Moraea simulans*	√	
JUNCACEAE	*Juncus oxycarpus*	√	
JUNCACEAE	*Juncus rigidus*	√	
KEWACEAE	*Kewa salsoloides*		√
LAMIACEAE	*Acrotome inflata*	√	
LAMIACEAE	*Leucas capensis*	√	
LAMIACEAE	*Ocimum americanum* var. *americanum*	√	
LAMIACEAE	*Salvia disermas*	√	
LAMIACEAE	*Salvia verbenaca*	√	
LAMIACEAE	*Stachys spathulata*	√	
LAMIACEAE	*Syncolostemon canescens*	√	
LAMIACEAE	*Syncolostemon linearis*	√	
LAMIACEAE	*Syncolostemon persimilis*	√	
LOBELIACEAE	*Lobelia angolensis*	√	
LOBELIACEAE	*Lobelia erinus*	√	
LOBELIACEAE	*Lobelia thermalis*	√	
LOPHIOCARPACEAE	*Lophiocarpus polystachyus*	√	
LYTHRACEAE	*Ammannia prieuriana*	√	
LYTHRACEAE	*Nesaea drummondii*	√	
MALVACEAE	*Corchorus asplenifolius*	√	
MALVACEAE	*Corchorus pinnatipartitus*	√	√
MALVACEAE	*Grewia flava*	√	√

MALVACEAE	*Hermannia bicolor*	√	
MALVACEAE	*Hermannia burkei*	√	
MALVACEAE	*Hermannia coccocarpa*	√	
MALVACEAE	*Hermannia comosa*	√	
MALVACEAE	*Hermannia eenii*	√	
MALVACEAE	*Hermannia glanduligera*	√	
MALVACEAE	*Hermannia jacobeifolia*	√	
MALVACEAE	*Hermannia linnaeoides*	√	√
MALVACEAE	*Hermannia quartiniana*	√	
MALVACEAE	*Hermannia stellulata*	√	
MALVACEAE	*Hermannia tomentosa*	√	
MALVACEAE	*Hibiscus marlothianus*	√	√
MALVACEAE	*Melhania didyma*	√	
MALVACEAE	*Melhania integra*	√	
MALVACEAE	*Melhania prostrata*	√	
MALVACEAE	*Pavonia burchellii*	√	
MALVACEAE	*Sida chrysantha*	√	
MALVACEAE	*Sida ovata*	√	
MARSILEACEAE	*Marsilea capensis*	√	
MELIACEAE	*Nymania capensis*	√	
MENISPERMACEAE	*Antizoma angustifolia*	√	
MESEMBRYANTHEMACEAE	*Ebracteola wilmaniae*	√	
MESEMBRYANTHEMACEAE	*Prepodesma orpenii*	√	

MESEMBRYANTHEMACEAE	*Ruschia calcarea*		√
MOLLUGINACEAE	*Hypertelis salsoloides* var*. salsoloides*	√	
MOLLUGINACEAE	*Limeum aethiopicum* var. *intermedium*	√	
MOLLUGINACEAE	*Limeum argute-carinatum*		√
MOLLUGINACEAE	*Limeum fenestratum* var. *fenestratum*	√	√
MOLLUGINACEAE	*Limeum pterocarpum* var. *pterocarpum*	√	
MOLLUGINACEAE	*Limeum sulcatum* var. *robustum*	√	
MOLLUGINACEAE	*Limeum sulcatum* var*. sulcatum*	√	√
MOLLUGINACEAE	*Limeum viscosum* subsp. *transvaalense*	√	
NYCTAGINACEAE	*Commicarpus pentandrus*	√	
OLEACEAE	*Menodora africana*	√	
OLEACEAE	*Olea europaea*		√
OLINIACEAE	*Olinia emarginata*	√	
OPHIOGLOSSACEAE	*Ophioglossum polyphyllum* var. *polyphyllum*	√	√
OROBANCHACEAE	*Alectra orobanchoides*	√	
OROBANCHACEAE	*Cycnium adonense*	√	
OROBANCHACEAE	*Striga gesnerioides*	√	
OXALIDACEAE	*Oxalis depressa*	√	√
PEDALIACEAE	*Sesamum triphyllum* var. *triphyllum*	√	√
PHYLLANTHACEAE	*Phyllanthus angolensis*	√	
POACEAE	*Anthephora pubescens*	√	
POACEAE	*Arisrida scabrivalvis*		√
POACEAE	*Aristida adscensionis*	√	√

POACEAE	*Aristida congesta* subsp. *congesta*	√	√
POACEAE	*Aristida diffusa*		√
POACEAE	*Aristida meridionalis*	√	√
POACEAE	*Aristida mollissima* subsp. *mollissima*	√	
POACEAE	*Aristida pilgeri*	√	
POACEAE	*Aristida stipitata* subsp. *graciliflora*	√	
POACEAE	*Aristida stipitata* subsp. *spicata*	√	
POACEAE	*Aristida vestita*	√	
POACEAE	*Brachiaria marlothii*	√	
POACEAE	*Brachiaria nigropedata*	√	
POACEAE	*Chrysopogon serrulatus*	√	√
POACEAE	*Cymbopogon caesius*	√	
POACEAE	*Cymbopogon pospischilii*	√	√
POACEAE	*Cynodon dactylon*	√	
POACEAE	*Cynodon incompletus*	√	
POACEAE	*Digitaria eriantha*	√	√
POACEAE	*Digitaria polyphylla*	√	
POACEAE	*Digitaria seriata*	√	
POACEAE	*Diheteropogon amplectens* var. *amplectens*	√	
POACEAE	*Enneapogon desvauxii*	√	√
POACEAE	*Ennepogon scoparius*		√
POACEAE	*Eragrostis bicolor*	√	
POACEAE	*Eragrostis chloromelas*	√	√

POACEAE	*Eragrostis curvula*	√	
POACEAE	*Eragrostis echinochloidea*	√	√
POACEAE	*Eragrostis gummiflua*	√	
POACEAE	*Eragrostis lehmanniana* var. *lehmanniana*	√	√
POACEAE	*Eragrostis micrantha*	√	
POACEAE	*Eragrostis nindensis*	√	√
POACEAE	*Eragrostis obtusa*	√	√
POACEAE	*Eragrostis pallens*	√	
POACEAE	*Eragrostis rigidior*	√	
POACEAE	*Eragrostis rotifer*	√	
POACEAE	*Eragrostis superba*		√
POACEAE	*Eragrostis trichophora*	√	√
POACEAE	*Eragrostis truncata*	√	
POACEAE	*Eustachys paspaloides*	√	√
POACEAE	*Fingerhuthia africana*	√	√
POACEAE	*Hemarthria altissima*	√	
POACEAE	*Heteropogon contortus*	√	√
POACEAE	*Melinis nerviglumis*	√	
POACEAE	*Melinis repens* subsp. *grandiflora*	√	
POACEAE	*Melinis repens* subsp. *repens*	√	
POACEAE	*Oropetium capense*	√	√
POACEAE	*Panicum coloratum* var. *coloratum*	√	
POACEAE	*Panicum kalaharense*	√	

POACEAE	*Panicum maximum*	√	
POACEAE	*Panicum schinzii*	√	
POACEAE	*Panicum stapfianum*	√	√
POACEAE	*Perotis patens*	√	
POACEAE	*Pogonarthria squarrosa*	√	√
POACEAE	*Polypogon griquensis*	√	
POACEAE	*Schmidtia pappophoroides*	√	
POACEAE	*Setaria sphacelata* var. *sphacelata*	√	
POACEAE	*Setaria sphacelata* var. *torta*	√	
POACEAE	*Setaria verticillata*	√	
POACEAE	*Sporobolus acinifolius*	√	
POACEAE	*Sporobolus discosporus*	√	
POACEAE	*Sporobolus fimbriatus*	√	√
POACEAE	*Stipagrostis uniplumis* var. *neesii*	√	
POACEAE	*Stipagrostis uniplumis* var*. uniplumis*	√	
POACEAE	*Themeda triandra*	√	√
POACEAE	*Tragus koelerioides*	√	√
POACEAE	*Tragus racemosus*	√	√
POACEAE	*Trichoneura grandiglumis*	√	
POACEAE	*Triraphis andropogonoides*	√	
POACEAE	*Urelytrum agropyroides*	√	
POLYGALACEAE	*Polygala asbestina*		√
POLYGALACEAE	*Polygala hottentotta*	√	

POLYGALACEAE	*Polygala krumanina*	√	
POLYGALACEAE	*Polygala uncinata*	√	
POLYGONACEAE	*Oxygonum alatum* var. *alatum*	√	√
POLYGONACEAE	*Oxygonum dregeanum* subsp*. canescens* var. *canescens*	√	
POLYGONACEAE	*Oxygonum dregeanum* subsp*. canescens var.linearifolium*	√	
POLYGONACEAE	*Persicaria hystricula*	√	
POLYGONACEAE	*Rumex rhodesius*	√	
PORTULACACEAE	*Portulaca kermesina*	√	√
PORTULACACEAE	*Portulaca quadrifida*	√	
PORTULACACEAE	*Talinum tenuissimum*	√	
RANUNCULACEAE	*Clematis brachiata*	√	
RANUNCULACEAE	*Clematis oweniae*	√	
RESEDACEAE	*Oligomeris dipetala* var*. dipetala*	√	
RHAMNACEAE	*Ziziphus mucronata*		√
RUBIACEAE	*Anthospermum rigidum* subsp. *pumilum*	√	
RUBIACEAE	*Anthospermum rigidum* subsp. *rigidum*	√	
RUBIACEAE	*Kohautia caespitosa* subsp. *brachyloba*	√	√
RUBIACEAE	*Kohautia cynanchica*	√	
RUBIACEAE	*Nenax microphylla*	√	
RUBIACEAE	*Rubia horrida*	√	
RUBIACEAE	*Spermacoce senensis*	√	

RUBIACEAE	*Vangueria infausta* subsp. *infausta*	√	
SANTALACEAE	*Thesium albomontanum*	√	
SANTALACEAE	*Thesium burkei*	√	
SANTALACEAE	*Thesium hystricoides*	√	
SANTALACEAE	*Thesium hystrix*	√	
SANTALACEAE	*Thesium lineatum*		√
SCROPHULARIACEAE	*Aptosimum elongatum*	√	
SCROPHULARIACEAE	*Aptosimum indivisum*	√	
SCROPHULARIACEAE	*Chaenostoma patrioticum*	√	
SCROPHULARIACEAE	*Diclis petiolaris*	√	
SCROPHULARIACEAE	*Jamesbrittenia atropurpurea* subsp. *atropurpurea*	√	
SCROPHULARIACEAE	*Jamesbrittenia aurantiaca*	√	
SCROPHULARIACEAE	*Melanospermum foliosum*	√	
SCROPHULARIACEAE	*Mimulus gracilis*	√	
SCROPHULARIACEAE	*Nemesia lilacina*	√	
SCROPHULARIACEAE	*Peliostomum leucorrhizum*		√
SCROPHULARIACEAE	*Selago albida*		√
SCROPHULARIACEAE	*Selago mixta*	√	
SCROPHULARIACEAE	*Selago welwitschii* var. *australis*	√	
SOLANACEAE	*Lycium cinereum*	√	√
SOLANACEAE	*Lycium hirsutum*	√	
SOLANACEAE	*Lycium schizocalyx*	√	
SOLANACEAE	*Solanum coccineum*	√	

SOLANACEAE	*Solanum leucophaeum*	√	
SOLANACEAE	*Solanum panduriforme*	√	
SOLANACEAE	*Solanum retroflexum*	√	
SOLANACEAE	*Solanum sisymbrifolium*		√
SOLANACEAE	*Solanum supinum* var. *supinum*	√	
SOLANACEAE	*Withania somnifera*	√	
STERCULIACEAE	*Hermannia modesta*		√
STERCULIACEAE	*Melhania rehmannii*		√
TECOPHILAEACEAE	*Walleria nutans*	√	
THYMELAEACEAE	*Gnidia burchellii*	√	
THYMELAEACEAE	*Gnidia polycephala*	√	
VAHLIACEAE	*Vahlia capensis* subsp*. capensis*	√	
VAHLIACEAE	*Vahlia capensis* subsp*. vulgaris* var. *linearis*	√	
VERBENACEAE	*Chascanum pinnatifidum* var*. pinnatifidum*	√	√
VERBENACEAE	*Lantana mearnsii* var. *latibracteolata*	√	
VERBENACEAE	*Lippia scaberrima*	√	
VISCACEAE	*Viscum rotundifolium*	√	
ZYGOPHYLLACEAE	*Roepera pubescens*		√
ZYGOPHYLLACEAE	*Tribulus terrestris*		√

Table B4. List of the highest ranked plant families with corresponding species numbers per family in each mountain.

Langberg		Asbestos Hills		Kuruman Hills		Ghaap Plateau	
Poaceae	93	Poaceae	93	Poaceae	104	Poaceae	73
Asteraceae	58	Asteraceae	72	Asteraceae	74	Asteraceae	59
Fabaceae	39	Fabaceae	41	Fabaceae	65	Fabaceae	47
Malvaceae	20	Malvaceae	24	Malvaceae	25	Malvaceae	21
Scrophulariaceae	17	Scrophulariaceae	21	Cyperaceae	21	Cyperaceae	17
Cyperaceae	14	Euphorbiaceae	17	Scrophulariaceae	20	Scrophulariaceae	13
Acanthaceae	12	Acanthaceae	12	Euphorbiaceae	16	Molluginaceae	10
Euphorbiaceae	12	Hyacinthaceae	12	Acanthaceae	13	Solanaceae	10
Hyacinthaceae	11	Apocynaceae	11	Solanaceae	13	Acanthaceae	9
Convolvulaceae	9	Molluginaceae	11	Iridaceae	12	Iridaceae	9
Apocynaceae	8	Cyperaceae	10	Amaranthaceae	11	Lamiaceae	9
Santalaceae	8	Iridaceae	10	Molluginaceae	10	Rubiaceae	9

Cucurbitaceae	7	Convolvulaceae	9	Apocynaceae	9	Euphorbiaceae	9
Asparagaceae	6	Solanaceae	9	Convolvulaceae	9	Amaranthaceae	8
Iridaceae	6	Cucurbitaceae	8	Mesembryanthemaceae	9	Convolvulaceae	7
Mesembryanthemaceae	6	Mesembryanthemaceae	8	Anacardiaceae	8	Cucurbitaceae	7
Capparaceae	5	Amaranthaceae	7	Rubiaceae	8	Hyacinthaceae	7
Celastraceae	5	Anacardiaceae	6	Asphodelaceae	7	Apocynaceae	6
Molluginaceae	5	Boraginaceae	6	Boraginaceae	7	Boraginaceae	6
Amaranthaceae	4	Brassicaceae	6	Cucurbitaceae	7	Brassicaceae	6

Table B5. Summary of PERMANOVA statistical results indicating the significance of observed herbaceous compositional differences across the mountains.

	Pseudo-F	**p-value**	**t-value**
Main test	9.138	0.001	
Variation among all mountains			
Pair-wise tests			
Kuruman Hills *vs.* Langberg		0.001	2.482
Kuruman Hills *vs.* Ghaap Plateau		0.001	3.765
Kuruman Hills *vs.* Asbestos Hills		0.001	3.008
Langberg *vs.* Ghaap Plateau		0.001	2.957
Langberg *vs.* Asbestos Hills		0.001	2.641
Ghaap Plateau *vs.* Asbestos Hills		0.001	3.212

Table B6. Top 20 ranked taxa according to number of individuals with corresponding number of subplots of the Modified Whittaker plots within which they were recorded. Dominant species that contributed more than 50% of total number of individuals are indicated in bold.

Species	**Family**	**No. sub-plots**	**No. individuals**
a) Langberg			
Eragrostis nindensis	**Poaceae**	**8**	**125**
Brachiaria nigropedata	**Poaceae**	**10**	**80**
Eragrostis chloromelas	**Poaceae**	**4**	**54**
Aristida congesta	**Poaceae**	**8**	**45**
Evolvulus alsinoides	**Convolvulaceae**	**7**	**41**
Melinis repens	**Poaceae**	**11**	**38**

Bulbostylis humilis	Cyperaceae	4	29
Digitaria eriantha	Poaceae	5	22
Portulaca kermesina	Portulacaceae	4	17
Aristida diffusa	Poaceae	6	15
Cymbopogon pospischilii	Poaceae	3	14
Eragrostis lehmanniana	Poaceae	8	13
Pogonarthria squarrosa	Poaceae	4	13
Heteropogon contortus	Poaceae	5	11
Phyllanthus parvulus	Euphorbiaceae	7	11
Schmidtia pappophoroides	Poaceae	3	11
Elionurus muticus	Poaceae	1	10
Cleome rubella	Capparaceae	3	9
Bulbostylis hispidula	Cyperaceae	2	8
Themeda triandra	Poaceae	2	8
b) Asbestos Hills			
Tragus koelerioides	**Poaceae**	**14**	**169**
Cymbopogon pospischilii	**Poaceae**	**14**	**168**
Aristida diffusa	**Poaceae**	**16**	**102**
Phyllanthus parvulus	**Euphorbiaceae**	**12**	**88**
Aristida congesta	**Poaceae**	**9**	**82**
Glossochilus burchellii	**Acanthaceae**	**11**	**56**
Anthephora pubescens	Poaceae	8	50
Heteropogon contortus	Poaceae	9	43
Eragrostis nindensis	Poaceae	3	39

Melinis repens	Poaceae	7	34
Bulbostylis humilis	Cyperaceae	7	30
Fingerhuthia africana	Poaceae	5	29
Sida chrysantha	Malvaceae	7	25
Brachiaria serrata	Poaceae	4	21
Eragrostis lehmanniana	Poaceae	4	19
Kyphocarpa angustifolia	Amaranthaceae	5	18
Bulbostylis hispidula	Cyperaceae	1	14
Corchorus asplenifolius	Tiliaceae	7	14
Chascanum pinnatifidum	Verbenaceae	9	13
Geigeria filifolia	Asteraceae	1	13
c) Kuruman Hills			
Diheteropogon amplectens	**Poaceae**	**13**	**264**
Bulbostylis hispidula	**Cyperaceae**	**12**	**188**
Phyllanthus parvulus	**Euphorbiaceae**	**14**	**110**
Brachiaria serrata	**Poaceae**	**9**	**89**
Anthephora pubescens	**Poaceae**	**8**	**88**
Elionurus muticus	**Poaceae**	**8**	**86**
Aristida diffusa	Poaceae	8	59
Themeda triandra	Poaceae	5	39
Chascanum adenostachyum	Verbenaceae	5	33
Melinis repens	Poaceae	9	32
Cymbopogon ceasius	Poaceae	8	29
Eragrostis nindensis	Poaceae	2	26

Aristida congesta	Poaceae	6	25
Brachiaria nigropedata	Poaceae	3	25
Heteropogon contortus	Poaceae	6	23
Andropogon schirensis	Poaceae	3	19
Euclea undulata	Ebenaceae	3	18
Dicoma anomala	Asteraceae	1	14
Eragrostis chloromelas	Poaceae	1	14
Melinis nerviglumis	Poaceae	2	12
d) Ghaap Plateau			
Bulbostylis humilis	**Cyperaceae**	**14**	**997**
Enneapogon desvauxii	**Poaceae**	**11**	**618**
Aristida congesta	**Poaceae**	**5**	**242**
Oxalis depressa	Oxalidaceae	7	207
Fingerhuthia africana	Poaceae	11	101
Cymbopogon pospischilii	Poaceae	11	88
Tragus racemosa	Poaceae	7	83
Tragus koelerioides	Poaceae	6	77
Arisrida scabrivalvis	Poaceae	2	62
Themeda triandra	Poaceae	7	57
Eragrostis lehmanniana	Poaceae	9	48
Limeum fenestratum	Molluginaceae	6	45
Digitaria eriantha	Poaceae	2	38
Chrysopogon serrulatus	Poaceae	3	28
Aristida adscensionis	Poaceae	2	27

Moraea polystachya	Iridaceae	3	27
Euphorbia inaequilatera	Euphorbiaceae	9	23
Oropetium capense	Poaceae	4	23
Eragrostis trichophora	Poaceae	6	20
Limeum argute-carinatum	Molluginaceae	6	18

Table B7. Number of GWC endemics according to total numbers, range restriction as well as growth forms. Adapted from Frisby *et al.* (2019).

REGION	NO. GWC ENDEMICS	RESTRICTED GWC ENDEMICS	GRASSES	HERBACEOUS FORBS (7)	SUCCULENTS (6)	LIGNIFIED FORBS (5)	SHRUBS (7)
GHAAP PLATEAU	23	3 forbs		7	4	5	7
IRONSTONE HILLS COMBINED	21						
KURUMAN HILLS	17	0		4	3	4	7
ASBESTOS HILLS	15	1 succulent		1	5	3	7
LANGBERG	14	1 succulent 1 grass	1	1	3	4	6

Table B8. Species description of *Nerine hesseoides*, a recently added GWC endemic.

Nerine hesseoides L.Bolus in Fl. Pl. South Africa 18 t. 683 (1938). Type: South Africa, Barkly West. Rocklands, March 1931, Turner, KMG 2704 (KMG, holotypes; BOL, K, isotypes). Perennial geophyte, reach plant height of approximately 200 mm (Germishuizen & Meyer, 2003). Considered to occur in Free State, North West and Northern Cape, however it is suspected that identifications of specimens were incorrect. Listed under the Least concern category of the Red List (Snijman & Victor, 2004). Habitat preference for limestone and dolomite (JSTOR, 2019) and thus found on the Ghaap Plateau in the Northern Cape.

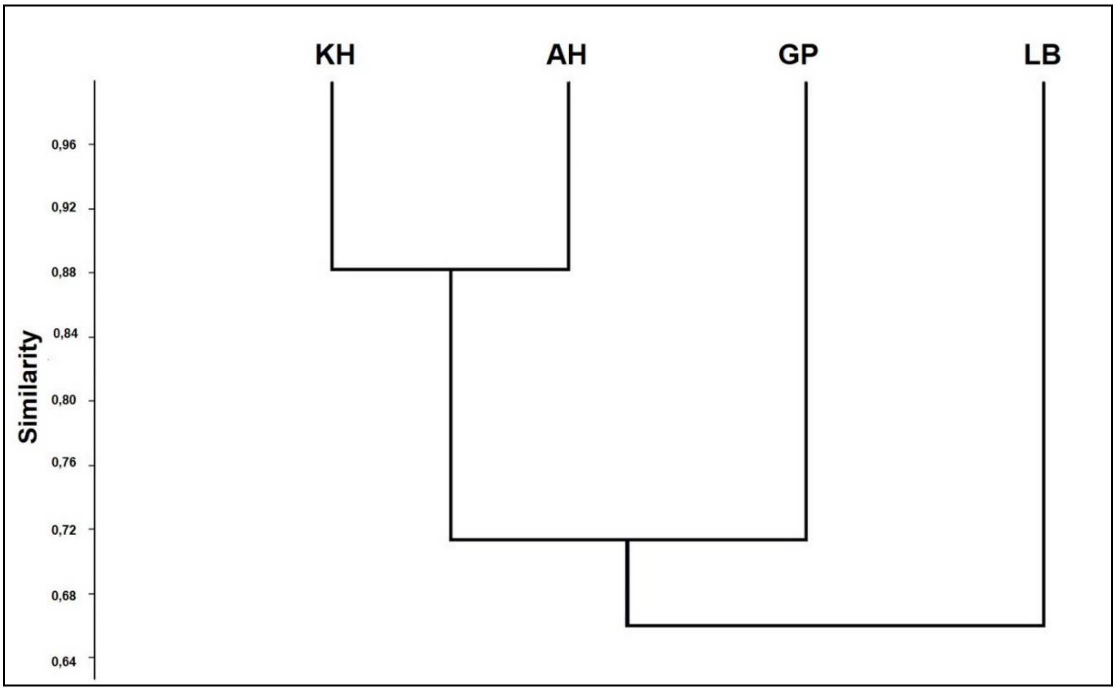

Figure B1. Dendrogram of Spearman correlation on family level.

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Appendix C

Supplementary tables and figures relating to Chapter 5

Table C1. Summary of PERMANOVA and PERMDISP results evaluating soil characteristics within mountain plant communities based on Bray-Curtis distances.

				PERMDISP **F=4.481, p=0.007**	
	Pseudo-F	**t**	**p**	**t**	**p**
Main test					
Variation among all mountain ecosystems	23.847		0.001		
Pair-wise tests					
Kuruman Hills *vs.* Langberg		6.233	0.001	1.218	0.233^{NS}
Kuruman Hills *vs.* Ghaap Plateau		3.494	0.001	1.202	0.239^{NS}
Kuruman Hills *vs.* Asbestos Hills		2.676	0.001	2.687	0.012
Langberg *vs.* Ghaap Plateau		5.84	0.001	2.073	0.047
Langberg *vs.* Asbestos Hills		6.966	0.001	1.296	0.205^{NS}
Ghaap Plateau *vs.* Asbestos Hills		3.04	0.001	3.133	0.004

Table C2. Summary of PERMANOVA and PERMDISP results evaluating herbaceous species composition within mountain plant communities based on Bray-Curtis distances.

				PERMDISP F=6.738, p<0.001	
	Pseudo-F	t	p	t	p
Main test					
Variation among all mountain ecosystems	8.998		0.001		
Pair-wise tests					
Kuruman Hills *vs.* Langberg		2.486	0.001	2.253	0.05
Kuruman Hills *vs.* Ghaap Plateau		3.741	0.001	0.253	0.81^{NS}
Kuruman Hills *vs.* Asbestos Hills		3.011	0.001	1.854	0.101^{NS}
Langberg *vs.* Ghaap Plateau		2.893	0.001	2.41	0.034
Langberg *vs.* Asbestos Hills		2.63	0.001	4.226	<0.001
Ghaap Plateau *vs.* Asbestos Hills		3.195	0.001	2.565	0.02

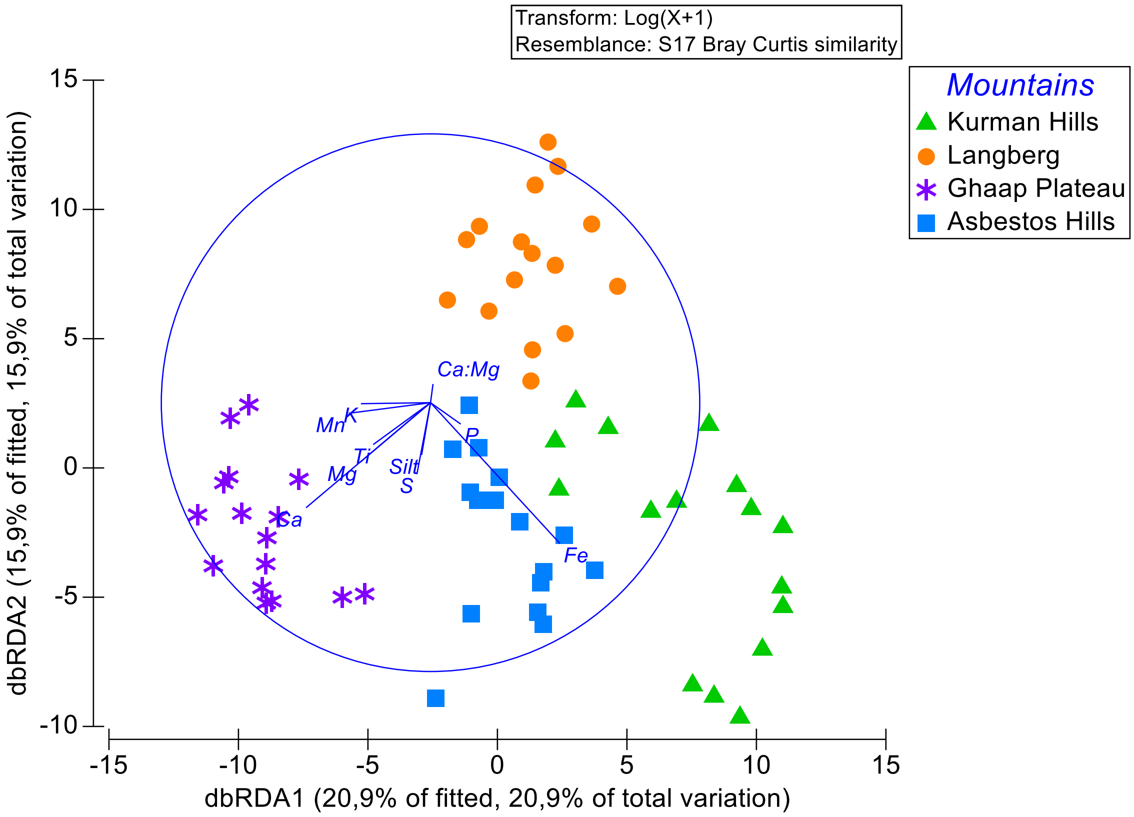

Figure C1. Distance based redundancy analysis (dbRDA) of ten soil parameters associated with compositional differences between mountain plant communities.

Table C3. Multiple regression models for each diversity- and structure measure with identified significant variables. ***MAP*** **– mean annual precipitation,** ***CEC*** **– Cation exchange capacity.**

	b*	SE of b*	b	SE of b	t-value	p-value
Diversity measures						
Species richness ($F_{7.56}$=7.191, p<0.001, R^2=0.473)						
Intercept			28.142	9.0	3.127	0.003
pH	0.552	0.224	0.161	0.065	2.468	0.017
Mg	-0.998	0.218	-0.842	0.184	-4.585	<0.001
Ca:Mg	-1.419	0.429	-0.968	0.293	-3.308	0.002
Ca	1.417	0.553	0.477	0.186	2.562	0.013
%sand	-0.495	0.201	-4.331	1.754	-2.469	0.017
Pielou's evenness ($F_{8.55}$=6.425, p<0.001, R^2=0.483)						
Intercept			3.615	2.527	1.405	0.166
Fe	0.493	0.131	0.054	0.014	3.775	<0.001
CEC	0.464	0.171	0.207	0.076	2.72	0.009
%silt	-0.503	0.249	-0.072	0.036	-2.02	0.048
Shannon Diversity ($F_{7.56}$=3.943, p=0.002, R^2=0.33)						

Intercept			1.684	2.098	0.803	0.425
Al	0.539	0.157	0.427	0.125	3.425	0.001
CEC	0.532	0.215	0.523	0.211	2.473	0.017
Ti	-0.348	0.15	-0.344	0.148	-2.315	0.024
Simpson Diversity ($F_{7.56}$=5.17, $p<0.001$, R^2=0.393)						
Intercept			0.417	1.248	0.334	0.74
Fe	0.346	0.128	0.04	0.015	2.696	0.009
Al	0.543	0.141	0.208	0.054	3.856	<0.001
Ti	-0.316	0.157	-0.151	0.075	-2.016	0.049
CEC	0.489	0.159	0.232	0.075	3.082	0.003
P	-0.267	0.129	-0.123	0.059	-2.073	0.043
Structure						
Density ($F_{9.54}$=12.816, $p<0.001$, R^2=0.681)						
Intercept			8.779	21.68	0.405	0.687
pH	0.593	0.172	0.373	0.108	3.44	0.001
MAP	0.361	0.135	2.628	0.983	2.673	0.001
Mg	-0.363	0.14	-0.66	0.255	-2.59	0.012

S	-0.514	0.146	-0.56	0.159	-3.517	<0.001
Mn	0.241	0.118	0.2	0.1	2.044	0.046
P	0.38	0.129	1.534	0.519	2.956	0.005
Al	-0.302	0.147	-1.013	0.492	-2.057	0.045
Herbaceous plant height ($F_{4.59}=12.302$, $p<0.001$, $R^2=0.455$)						
Intercept			-2.086	2.183	-0.956	0.343
pH	-0.596	0.151	-0.145	0.037	-3.949	<0.001
%silt	-0.411	0.156	-0.212	0.08	-2.642	0.011
MAP	0.44	0.144	1.234	0.405	3.045	0.004
Percentage grass cover ($F_{6.57}=4.841$, $p<0.001$, $R^2=0.338$)						
Intercept			22.905	17.081	1.341	0.185
MAP	0.502	0.165	2.275	0.748	3.043	0.004
pH	-0.291	0.137	-0.114	0.054	-2.123	0.038
%sand	-0.577	0.243	-6.777	2.85	-2.378	0.021
P	0.332	0.165	0.834	0.416	2.008	0.049
Percentage herbaceous forb cover ($F_{7.56}=7.575$, $p<0.001$, $R^2=0.486$)						
Intercept			32.031	20.146	1.59	0.118
MAP	0.417	0.149	2.889	1.029	2.808	0.007

Mg	-0.413	0.139	-0.715	0.24	-2.976	0.004
Fe	-0.641	0.171	-0.621	0.166	-3.748	<0.001
Mn	0.362	0.175	0.282	0.136	2.073	0.043
Percentage lignified forb cover ($F_{10.53}$=3.117, p=0.003, R^2=0.37)						
Intercept			66.76	32.625	2.046	0.046
Fe	1.109	0.277	1.369	0.342	3.999	<0.001
K	0.672	0.218	2.705	0.879	3.079	0.003
Mn	-0.825	0.248	-0.817	0.246	-3.319	0.002
%silt	-0.856	0.288	-1.386	0.467	-2.97	0.005
%sand	-0.801	0.266	-18.287	6.071	-3.012	0.004
pH	0.694	0.301	0.528	0.229	2.307	0.025
Mg	-0.5	0.24	-1.103	0.53	-2.082	0.042
Percentage debris ($F_{5.58}$=3.85, p=0.004, R^2=0.25)						
Intercept			-7.731	7.244	-1.067	0.29
pH	-0.419	0.144	-0.185	0.063	-2.917	0.005
CEC	-0.376	0.158	-1.097	0.462	-2.376	0.021
Percentage bare soil ($F_{8.55}$=13.104, p<0.000, R^2=0.656)						

Intercept			1.418	27.948	0.051	0.96
Fe	-0.485	0.12	-0.735	0.183	-4.025	<0.001
CEC	-0.287	0.12	-1.779	0.744	-2.393	0.02
MAP	0.408	0.131	4.418	1.414	3.124	0.003
S	-0.407	0.157	-0.66	0.255	-2.586	0.012
Percentage rock ($F_{6.57}$=9.471, p<0.001, R^2=0.499)						
Intercept			21.132	22.378	0.944	0.349
Fe	0.441	0.139	0.615	0.194	3.168	0.003
MAP	-0.724	0.148	-7.208	1.479	-4.875	<0.001
S	0.538	0.132	0.803	0.196	4.091	<0.001
Mg	0.303	0.132	0.754	0.33	2.287	0.026
Frequency grass ($F_{4.27}$=3.375, p=0.023, R^2=0.333)						
Intercept			-3.719	6.094	-0.61	0.547
Mn	-0.724	0.26	-0.201	0.072	-2.784	0.01
CEC	0.558	0.244	0.767	0.336	2.286	0.03
Frequency herbaceous forbs ($F_{5.26}$=3.936, p=0.009, R^2=0.431)						
Intercept			8.427	2.832	2.975	0.006

Mn	0.727	0.257	0.226	0.08	2.831	0.009
Frequency lignified forbs ($F_{5.26}$=3.256, p=0.024, R^2=0.377)						
Intercept			2.826	0.643	4.397	<0.001
Mn	-1.06	0.295	-0.066	0.018	-3.596	0.001
Frequency shrubs ($F_{11.2}$=12.15, p<0.001, R^2=0.87)						
Intercept			-55.018	40.91	-1.345	0.194
MAP	-0.417	0.173	-4.595	1.907	-2.409	0.026
Ca	2.017	0.473	2.213	0.519	4.263	<0.001
Ca: Mg	-1.31	0.281	-2.916	0.625	-4.665	<0.001
Al	-0.363	0.17	-1.931	0.902	-2.14	0.045
%sand	0.697	0.216	20.524	6.364	3.225	0.004
P	-0.339	0.15	-2.088	0.923	-2.261	0.035
Frequency trees ($F_{3.28}$=4.103, p=0.016, R^2=0.305)						
Intercept			-63.375	21.268	-2.98	0.006
Ti	0.458	0.199	1.818	0.79	2.3	0.029
%sand	0.761	0.237	13.785	4.29	3.213	0.003
P	-0.477	0.207	-1.807	0.784	-2.305	0.029

.						
Intercept			0.963	0.324	2.973	0.006
Ca	-0.532	0.147	-0.029	0.008	-3.625	0.001
Shrub plant height ($F_{3.28}$=2.685, p=0.066, R^2=0.223)						
Intercept			-3.101	2.078	-1.493	0.147
%silt	-0.644	0.228	-0.257	0.091	-2.826	0.009
Tree plant height ($F_{12.19}$=2.474, p=0.038, R^2=0.61)						
Intercept			-133.235	46.792	-2.847	0.01
%sand	1.641	0.493	28.734	8.627	3.331	0.004
P	-0.86	0.283	-3.147	1.037	-3.034	0.007
K	-0.85	0.353	-2.542	1.055	-2.41	0.026
Fe	-1.273	0.418	-1.192	0.391	-3.047	0.007
Mn	0.782	0.356	0.591	0.269	2.194	0.041
Al	0.851	0.369	2.693	1.166	2.31	0.032
Lignified forb canopy area ($F_{3.28}$=4.633, p=0.01, R^2=0.332)						
Intercept			5.021	1.894	2.651	0.013
Ti	-0.495	0.171	-0.423	0.146	-2.9	0.007

Ca: Mg	-0.399	0.167	-0.118	0.049	-2.9	0.024
Shrub canopy area ($F_{3.28}$=3.518, p=0.028, R^2=0.274)						
Intercept			-8.303	6.157	1.349	0.188
%silt	-0.708	0.22	-0.866	0.269	-3.213	0.003
Tree canopy area ($F_{8.23}$=2.328, p=0.054, R^2=0.447)						
Intercept			-158.994	61.893	-2.569	0.017
%sand	0.727	0.269	33.911	12.547	2.703	0.013
Ti	0.781	0.262	7.977	2.678	2.979	0.007
pH	0.835	0.388	1.259	0.585	2.152	0.042

Appendix D

Supplementary tables and figures relating to Chapter 6

Table D1. Output of multiple linear regression models of biomass and environmental parameters.

Biomass	b*	SE of b*	b	SE of b	t-value	p-value
Total ($F_{4.59}$=6.0, p<0.001, R^2=0.29)						
Intercept			1.4	0.8	1.7	0.1
pH	-0.5	0.1	-0.02	0.004	-3.9	<0.001
Debris ($F_{4.59}$=9.4, p<0.001, R^2=0.39)						
Intercept			0.7	2.0	0.5	0.728
pH	-0.6	0.1	-0.2	0.04	-5.5	<0.001
Live ($F_{4.59}$=6.2, p<0.001, R^2=0.295)						
Intercept			15	14.4	1.0	0.302^{NS}
MAP	0.4	0.2	2.1	1.0	2.1	0.045
pH	-0.6	0.1	-0.3	0.1	-3.6	<0.001
%Sand	-0.3	0.2	-4.5	2.4	-2	0.061^{NS}
S	0.3	0.2	0.2	0.1	1.7	0.095^{NS}
Grass ($F_{2.61}$=6.4, p=0.003, R^2=0.174)						
Intercept			-9.4	4.4	-2.0	0.061^{NS}
MAP	0.5	0.1	2.9	0.9	1.5	0.001
pH	-0.4	0.1	-0.2	0.1	-3.0	0.004
Herbaceous forb ($F_{2.61}$=6.2, p=0.0004, R^2=0.168)						
Intercept			-0.1	0.3	-0.3	0.784^{NS}
MAP	0.5	0.1	0.1	0.1	3.3	0.002
pH	-0.4	0.1	-0.01	0.004	-2.8	0.007
Lignified forb ($F_{4.59}$=3.5, p=0.012, R^2=0.193)						

Intercept			7	11.8	0.6	0.553^{NS}
CEC	0.4	0.1	3.8	1.4	2.6	0.012
pH	-0.3	0.1	-0.5	0.2	-2.3	0.025
P	-0.2	0.1	-1.7	1.4	-1.2	0.22^{NS}
%Clay	0.1	0.1	0.8	0.8	1.1	0.296^{NS}

Table D2. Summary of linear- and quadratic regression analysis between diversity measures and biomass (i.e. total and live biomass) at regional scale. Red bold text is an indication of diversity measures and biomass that tested significantly linear.

Linear regression				**Quadratic regression (BIOM^2)**		
	Coefficient (b)	**t-value**	**p-value**		**t-value**	**p-value**
Total herbaceous biomass						
Total species						
Species richness	-182.815	-1.558	0.124	Species richness	1.182	0.241
F $_{(1.62)}$ =2.428, R^2=0.377				F $_{(1.62)}$ =1.397, R^2=0.022		
Evenness	6527.488	1.712	0.092	Evenness	1.077	0.286
F $_{(1.62)}$ =2.931, R^2=0.045				F $_{(1.62)}$ =1.159, R^2=0.183		
Shannon	15.838	0.014	0.989	Shannon	-0.557	0.56
F $_{(1.62)}$ <0.001, $R^{2<}$0.001				F $_{(1.62)}$ =0.31, R^2=0.005		
Simpson	1625.985	0.443	0.659	Simpson	-0.216	0.83
F $_{(1.62)}$ =0.196, R^2=0.003				F $_{(1.62)}$ =0.047, R^2=0.001		

Grasses						
Species richness	-255.797	-1.085	0.282	Species richness	-1.232	0.223
$F_{(1.62)}=1.178$, $R^2=0.186$				$F_{(1.62)}=1.517$, $R^2=0.024$		
Evenness	2276.559	0.69	0.493	Evenness	0.19	0.85
$F_{(1.62)}=0.477$, $R^2=0.008$				$F_{(1.62)}=0.036$, $R^2=0.001$		
Shannon	-220.048	-0.171	0.865	Shannon	-0.609	0.545
$F_{(1.62)}=0.029$, $R^2=0.001$				$F_{(1.62)}=0.371$, $R^2=0.006$		
Simpson	-234.938	-0.074	0.941	Simpson	-0.565	0.574
$F_{(1.62)}=0.006$, $R^2<0.001$				$F_{(1.62)}=0.319$, $R^2=0.005$		
Herbaceous forbs						
Species richness	-668.864	-2.034	0.046*			
$F_{(1.62)}=4.135$, $R^2=0.063$						
Evenness	-1569.18	-1.262	0.212	Evenness	-1.257	0.214
$F_{(1.62)}=1.592$, $R^2=0.025$				$F_{(1.62)}=1.58$, $R^2=0.025$		
Shannon	-1768.59	-1.428	0.158	Shannon	-1.389	0.17
$F_{(1.62)}=2.039$, $R^2=0.032$				$F_{(1.62)}=1.929$, $R^2=0.03$		
Simpson	-1362.59	-0.82	0.415	Simpson	-0.901	0.371

F $_{(1.62)}$ =0.673, R^2=0.011				F $_{(1.62)}$ =0.811, R^2=0.013		
Lignified forbs						
Species richness	-99.649	-0.497	0.621	Species richness	-0.673	0.503
F $_{(1.62)}$ =0.247, R^2=0.004				F $_{(1.62)}$ =0.453, R^2=0.007		
Evenness	-2322.74	-1.379	0.173	Evenness	-1.938	0.057
F $_{(1.62)}$ =1.901, R^2=0.03				F $_{(1.62)}$ =3.754, R^2=0.057		
Shannon	-814.225	-0.933	0.354	Shannon	-1.28	0.206
F $_{(1.62)}$ =0.871, R^2=0.014				F $_{(1.62)}$ =1.637, R^2=0.026		
Simpson	-1601.5	-0.942	0.35	Simpson	-1.415	0.162
F $_{(1.62)}$ =0.886, R^2=0.014				F $_{(1.62)}$ =2.0, R^2=0.031		

Live herbaceous biomass						
Total species						
Species richness	18.087	1.055	0.295	Species richness	1.182	0.242
F $_{(1.62)}$ =1.114, R^2=0.018				F $_{(1.62)}$ =1.397, R^2=0.007		
Evenness	1028.951	1.875	0.066	Evenness	1.799	0.077
F $_{(1.62)}$ =3.515, R^2=0.054				F $_{(1.62)}$ =3.235, R^2=0.05		
Shannon	312.632	2.019	0.048*			
F $_{(1.62)}$ =4.075, R^2=0.062						
Simpson	1103.835	2.153	0.035*			
F $_{(1.62)}$ =4.636, R^2=0.07						
Grasses						
Species richness	16.39	0.477	0.635	Species richness	0.584	0.562
F $_{(1.62)}$ =0.228, R^2=0.004				F $_{(1.62)}$ =0.341, R^2=0.006		
Evenness	617.693	1.308	0.196	Evenness	1.182	0.242
F $_{(1.62)}$ =1.712, R^2=0.027				F $_{(1.62)}$ =1.4, R^2=0.022		
Shannon	271.742	1.482	0.143	Shannon	1.413	0.163
F $_{(1.62)}$ =2.196, R^2=0.034				F $_{(1.62)}$ =2.0, R^2=0.031		

Simpson	615.303	1.364	0.178	Simpson	1.28	0.205
F $_{(1.62)}$ =1.86, R^2=0.029				F $_{(1.62)}$ =1.64, R^2=0.026		
Herbaceous forbs						
Species richness	-54.094	-1.112	0.27	Species richness	-1.144	0.257
F $_{(1.62)}$ =1.237, R^2=0.196				F $_{(1.62)}$ =1.309, R^2=0.021		
Evenness	-155.485	-0.859	0.394	Evenness	-0.89	0.377
F $_{(1.62)}$ =0.738, R^2=0.012				F $_{(1.62)}$ =0.792, R^2=0.126		
Shannon	-94.104	-0.518	0.606	Shannon	-0.63	0.531
F $_{(1.62)}$ =0.269, R^2=0.004				F $_{(1.62)}$ =0.396, R^2=0.006		
Simpson	-161.6130	-0.672	0.504	Simpson	-0.741	0.462
F $_{(1.62)}$ =0.452, R^2=0.007				F $_{(1.62)}$ =0.549, R^2=0.009		
Lignified forbs						
Species richness	58.281	2.075	0.042*			
F $_{(1.62)}$ =4.304, R^2=0.065						
Evenness	153.894	0.624	0.535	Evenness	0.685	0.496
F $_{(1.62)}$ =0.39, R^2=0.006				F $_{(1.62)}$ =0.47, R^2=0.008		
Shannon	194.738	1.563	0.123	Shannon	1.656	0.103

F $_{(1.62)}$ =2.443, R^2=0.038				F $_{(1.62)}$ =2.741, R^2=0.042		
Simpson	225.844	0.918	0.362	Simpson	0.966	0.338
F $_{(1.62)}$ =0.843, R^2=0.013				F $_{(1.62)}$ =0.934, R^2=0.015		

Table D3. Summary of linear- and quadratic regression analysis between diversity measures and live biomass for each mountain rangeland at local scale. Red bold text is an indication of diversity measures and biomass that tested significantly linear.

Linear regression				**Quadratic regression (BIOM^2)**		
	Coefficient (b)	**t-value**	**p-value**		**t-value**	**p-value**
Langberg						
Total species						
Species richness	-3.616	-0.097	0.924	Species richness	0.216	0.832
$F_{(1.14)}=0.009$, $R^2=0.001$				$F_{(1.14)}=0.047$, $R^2=0.003$		
Evenness	102.964	0.096	0.925	Evenness	0.285	0.78
$F_{(1.14)}=0.009$, $R^2=0.001$				$F_{(1.14)}=0.081$, $R^2=0.006$		
Shannon	25.752	0.09	0.929	Shannon	0.398	0.697
$F_{(1.14)}=0.008$, $R^2=0.001$				$F_{(1.14)}=0.158$, $R^2=0.011$		
Simpson	22.309	0.026	00.98	Simpson	0.263	0.796
$F_{(1.14)}=0.001$, $R^2<0.001$				$F_{(1.14)}=0.069$, $R^2=0.005$		

Grasses						
Species richness	-21.603	-0.33	0.746	Species richness	-0.289	0.777
$F_{(1.14)}$ =0.109, R^{2}=0.008				$F_{(1.14)}$ =0.084, R^{2}=0.006		
Evenness	-180.491	-0.175	0.864	Evenness	-0.031	0.976
$F_{(1.14)}$ =0.031, R^{2}=0.002				$F_{(1.14)}$ =0.001, R^{2}<0.001		
Shannon	-18.11	-0.049	0.962	Shannon	0.016	0.988
$F_{(1.14)}$ =0.002, R^{2}<0.001				$F_{(1.14)}$ <0.001, R^{2}<0.001		
Simpson	-215.738	-0.245	0.81	Simpson	-0.115	0.91
$F_{(1.14)}$ =0.06, R^{2}=0.004				$F_{(1.14)}$ =0013, R^{2}<0.001		
Herbaceous forbs						
Species richness	140.166	-1.433	0.174	Species richness	-1.39	0.186
$F_{(1.14)}$ =2.054, R^{2}=0.128				$F_{(1.14)}$ =1.931, R^{2}=0.121		
Evenness	-356.105	-1.052	0.311	Evenness	-1.229	0.239
$F_{(1.14)}$ =1.106, R^{2}=0.073				$F_{(1.14)}$ =1.51, R^{2}=0.097		
Shannon	-507.179	-1.14	0.273	Shannon	-1.279	0.222
$F_{(1.14)}$ =1.3, R^{2}=0.085				$F_{(1.14)}$ =1.635, R^{2}=0.105		
Simpson	-333.417	-0.749	0.466	Simpson	-0.968	0.35

F $_{(1.14)}$ =0.561, R^2=0.039				F $_{(1.14)}$ =0.937, R^2=0.063		
Lignified forbs						
Species richness	30.834	0.599	0.559	Species richness	1.017	0.326
F $_{(1.14)}$ =0.359, R^2=0.025				F $_{(1.14)}$ =1.035, R^2=0.069		
Evenness	55.469	0.169	0.868	Evenness	0.632	0.538
F $_{(1.14)}$ =0.029, R^2=0.002				F $_{(1.14)}$ =0.399, R^2=0.028		
Shannon	122.04	0.627	0.541	Shannon	1.173	0.261
F $_{(1.14)}$ =0.393, R^2=0.027				F $_{(1.14)}$ =1.375, R^2=0.089		
Simpson	131.349	0.371	0.716	Simpson	0.845	0.412
F $_{(1.14)}$ =0138, R^2=0.01				F $_{(1.14)}$ =0.714, R^2=0.049		
Asbestos Hills						
Total species						
Species richness	-58.742	-1.346	0.2	Species richness	-1.199	0.251
F $_{(1.14)}$ =1.811, R^2=0.115				F $_{(1.14)}$ =1.437, R^2=0.093		
Evenness	-1962.41	-0.585	0.568	Evenness	-0.338	0.741
F $_{(1.14)}$ =0.342, R^2=0.024				F $_{(1.14)}$ =0.114, R^2=0.008		

Shannon	-747.248	-1.276	0.223	Shannon	-1.06	0.307
F $_{(1.14)}$ =1.628, R^2=0.104				F $_{(1.14)}$ =1.123, R^2=0.074		
Simpson	-2919.66	-0.817	0.427	Simpson	-0.638	0.534
F $_{(1.14)}$ =0.668, R^2=0.046				F $_{(1.14)}$ =0.406, R^2=0.028		

Grasses						
Species richness	-97.246	-1.04	0.316	Species richness	-0.842	0.414
F $_{(1.14)}$ =1.081, R^2=0.072				F $_{(1.14)}$ =0.708, R^2=0.048		
Evenness	2068.445	0.784	0.446	Evenness	0.864	0.402
F $_{(1.14)}$ =0.615, R^2=0.042				F $_{(1.14)}$ =0.747, R^2=0.051		
Shannon	-324.623	-0.507	0.62	Shannon	-0.337	0.741
F $_{(1.14)}$ =0.257, R^2=0.018				F $_{(1.14)}$ =0.114, R^2=0.008		
Simpson	-178.398	-0.075	0.941	Simpson	0.02	0.984
F $_{(1.14)}$ =0.01, R^2<0.001				F $_{(1.14)}$ <0.001, R^2<0.001		
Herbaceous forbs						
Species richness	-216.625	-1.294	0.217	Species richness	-1.26	0.228
F $_{(1.14)}$ =1.675, R^2=0.107				F $_{(1.14)}$ =1.589, R^2=0.102		
Evenness	-457.521	-1.248	0.233	Evenness	-1.152	0.269

F $_{(1.14)}$ =1.557, R^2=0.1				F $_{(1.14)}$ =1.327, R^2=0.087		
Shannon	-486.121	-1.126	0.279	Shannon	-1.096	0.291
F $_{(1.14)}$ =1.269, R^2=0.083				F $_{(1.14)}$ =1.202, R^2=0.079		
Simpson	-593.903	-1.208	0.247	Simpson	-1.104	0.288
F $_{(1.14)}$ =1.459, R^2=0.094				F $_{(1.14)}$ =1.22, R^2=0.08		

Lignified forbs						
Species richness	-63.975	-0.822	0.425	Species richness	-0.765	0.457
F $_{(1.14)}$ =0.676, R^2=0.046				F $_{(1.14)}$ =0.586, R^2=0.04		
Evenness	337.686	0.252	0.805	Evenness	0.341	0.739
F $_{(1.14)}$ =0.063, R^2=0.005				F $_{(1.14)}$ =0.116, R^2=0.008		
Shannon	-180.282	-0.371	0.716	Shannon	-0.248	0.808
F $_{(1.14)}$ =0.138, R^2=0.01				F $_{(1.14)}$ =0.061, R^2=0.004		
Simpson	131.966	0.1	0.922	Simpson	0.234	0.819
F $_{(1.14)}$ =0.01, R^2=0.001				F $_{(1.14)}$ =0.055, R^2=0.004		

Kuruman Hills						
Total species						
Species richness	65.81	2.863	0.013*			
$F_{(1.14)}$ =8.197, R^2=0.369						
Evenness	-1204.16	-0.596	0.561	Evenness	-0.728	0.479
$F_{(1.14)}$ =0.355, R^2=0.025				$F_{(1.14)}$ =0.53, R^2=0.037		
Shannon	475.909	1.433	0.174	Shannon	1.343	0.201
$F_{(1.14)}$ =2.055, R^2=0.128				$F_{(1.14)}$ =1.803, R^2=0.114		
Simpson	1282.688	0.727	0.479	Simpson	0.657	0.522
$F_{(1.14)}$ =0.529, R^2=0.036				$F_{(1.14)}$ =0.431, R^2=0.03		

Grasses						
Species richness	104.86	2.415	0.03*			
$F_{(1.14)}$ =5.831, R^2=0.294						
Evenness	-2263.06	-1.629	0.126	Evenness	-1.854	0.085
$F_{(1.14)}$ =2.654, R^2=0.159				$F_{(1.14)}$ =3.436, R^2=0.197		
Shannon	507.55	1.486	0.16	Shannon	1.192	0.253
$F_{(1.14)}$ =2.209, R^2=0.136				$F_{(1.14)}$ =1.421, R^2=0.092		
Simpson	669.285	0.508	0.619	Simpson	0.224	0.826
$F_{(1.14)}$ =0.259, R^2=0.018				$F_{(1.14)}$ =0.05, R^2=0.004		
Herbaceous forbs						
Species richness	200.972	2.067	0.058	Species richness	2.289	0.038*
$F_{(1.14)}$ =4.27, R^2=0.234				$F_{(1.14)}$ =5.241, R^2=0.272		
Evenness	387.196	1.268	0.226	Evenness	1.209	0.247
$F_{(1.14)}$ =1.607, R^2=0.103				$F_{(1.14)}$ =1.462, R^2=0.095		
Shannon	591.329	1.83	0.089	Shannon	1.836	0.088
$F_{(1.14)}$ =3.349, R^2=0.193				$F_{(1.14)}$ =3.369, R^2=0.194		
Simpson	753.347	1.546	0.145	Simpson	1.514	0.152

$F_{(1.14)}=2.387, R^2=0.146$				$F_{(1.14)}=2.292, R^2=0.141$		
Lignified forbs						
Species richness	115.272	1.809	0.092	Species richness	1.922	0.075
$F_{(1.14)}=3.274, R^2=0.19$				$F_{(1.14)}=3.7, R^2=0.209$		
Evenness	-1163.33	-1.86	0.084	Evenness	-2.022	0.063
$F_{(1.14)}=3.46, R^2=0.198$				$F_{(1.14)}=4.088, R^2=0.226$		
Shannon	-213.62	-0.576	0.574	Shannon	-0.629	0.54
$F_{(1.14)}=0.331, R^2=0.023$				$F_{(1.14)}=0.395, R^2=0.027$		
Simpson	-817.596	-1.442	0.171	Simpson	-1.548	0.144
$F_{(1.14)}=2.08, R^2=0.129$				$F_{(1.14)}=2.4, R^2=0.146$		
Ghaap Plateau						
Total species						
Species richness	56.281	1.972	0.069	Species richness	1.477	0.162
$F_{(1.14)}=3.89, R^2=0.217$				$F_{(1.14)}=2.183, R^2=0.135$		
Evenness	1242.319	2.257	0.041*			
$F_{(1.14)}=5.093, R^2=0.267$						

Shannon	464.515	2.708	0.017*			
$F_{(1.14)}=7.335$, $R^2=0.344$						
Simpson	1257.94	2.402	0.031*			
$F_{(1.14)}=5.771$, $R^2=0.292$						
Grasses						
Species richness	-1.759	-0.033	0.974	Species richness	-0.224	0.826
$F_{(1.14)}=0.001$, $R^2<0.001$				$F_{(1.14)}=0.05$, $R^2=0.004$		
Evenness	335.638	0.799	0.438	Evenness	0.767	0.456
$F_{(1.14)}=0.638$, $R^2=0.044$				$F_{(1.14)}=0.588$, $R^2=0.04$		
Shannon	141.632	0.7	0.496	Shannon	0.566	0.581
$F_{(1.14)}=0.488$, $R^2=0.0338$				$F_{(1.14)}=0.32$, $R^2=0.022$		
Simpson	265.79	0.602	0.557	Simpson	0.546	0.594
$F_{(1.14)}=0.362$, $R^2=0.025$				$F_{(1.14)}=0.298$, $R^2=0.021$		
Herbaceous forbs						
Species richness	127.331	1.958	0.071	Species richness	1.591	0.134
$F_{(1.14)}=3.833$, $R^2=0.215$				$F_{(1.14)}=2.53$, $R^2=0.153$		
Evenness	622.383	2.136	0.051	Evenness	2.077	0.057

$F_{(1.14)}$ =4.565, R^2=0.246				$F_{(1.14)}$ =4.314, R^2=0.236		
Shannon	594.887	3.297	0.005*			
$F_{(1.14)}$ =10.87, R^2=0.437						
Simpson	883.317	3.034	0.009*			
$F_{(1.14)}$ =9.207, R^2=0.397						

Lignified forbs						
Species richness	85.273	1.808	0.092	Species richness	1.519	0.151
$F_{(1.14)}$ =3.269, R^2=0.189				$F_{(1.14)}$ =2.306, R^2=0.141		
Evenness	249.814	0.715	0.487	Evenness	0.335	0.743
$F_{(1.14)}$ =0.511, R^2=0.035				$F_{(1.14)}$ =0.112, R^2=0.008		
Shannon	203.6	1.227	0.24	Shannon	0.861	0.404
$F_{(1.14)}$ =1.505, R^2=0.097				$F_{(1.14)}$ =0.741, R^2=0.05		
Simpson	220.715	0.707	0.49	Simpson	0.373	0.715
$F_{(1.14)}$ =0.502, R^2=0.035				$F_{(1.14)}$ =0.139, R^2=0.009		

Table D4. Summary of linear- and quadratic regression analysis between biomass (kg/ha), total species- and PFG diversity.

Linear regression				Quadratic regression (BIOM^2)		
Diversity	**Coefficient (b)**	**t-value**	**p-value**		**t-value**	**p-value**
Total species F $_{(1.62)}$ =4.075, R^2=0.062	312.6	2.0	0.048*			
Grass species F $_{(1.62)}$ =2.196, R^2=0.034	274.7	1.5	0.144	F $_{(1.62)}$ =2.0, R^2=0.031	1.4	0.163
Herbaceous forb species F $_{(1.62)}$ =0.269, R^2=0.004	-94.1	-0.5	0.606	F $_{(1.62)}$ =0.4, R^2=0.006	-0.6	0.531
Lignified forb species F $_{(1.62)}$ =2.443, R^2=0.038	194.7	1.6	0.123	F $_{(1.62)}$ =2.7, R^2=0.042	1.7	0.103

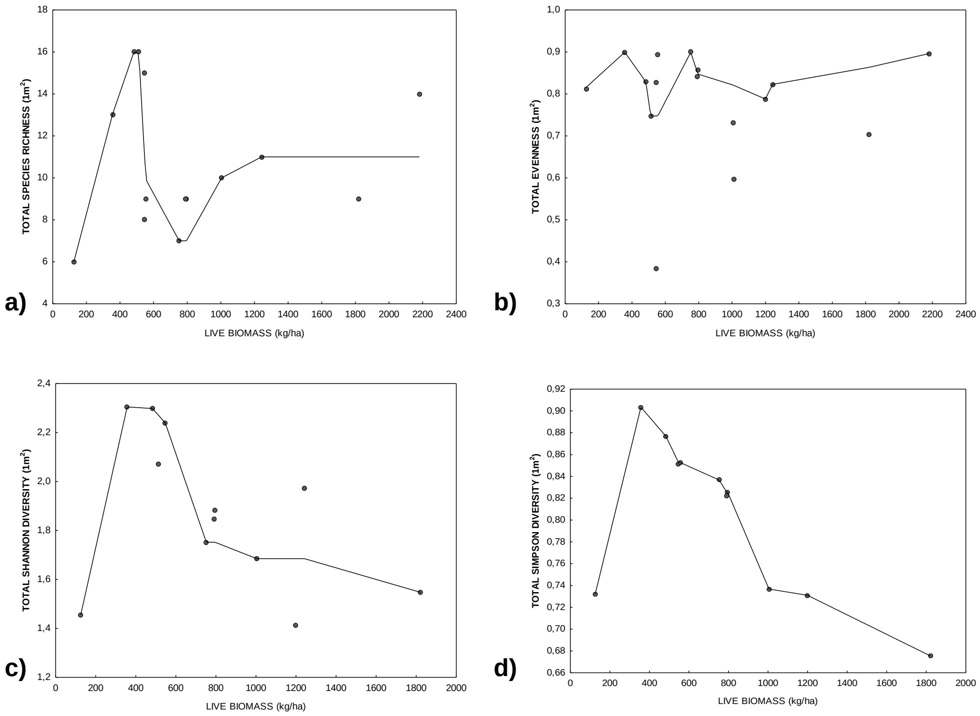

Figure D1. Local diversity-biomass relationships of total species diversity indices for the Langberg, a) species richness, b) evenness, c) Shannon- and d) Simpson diversity.

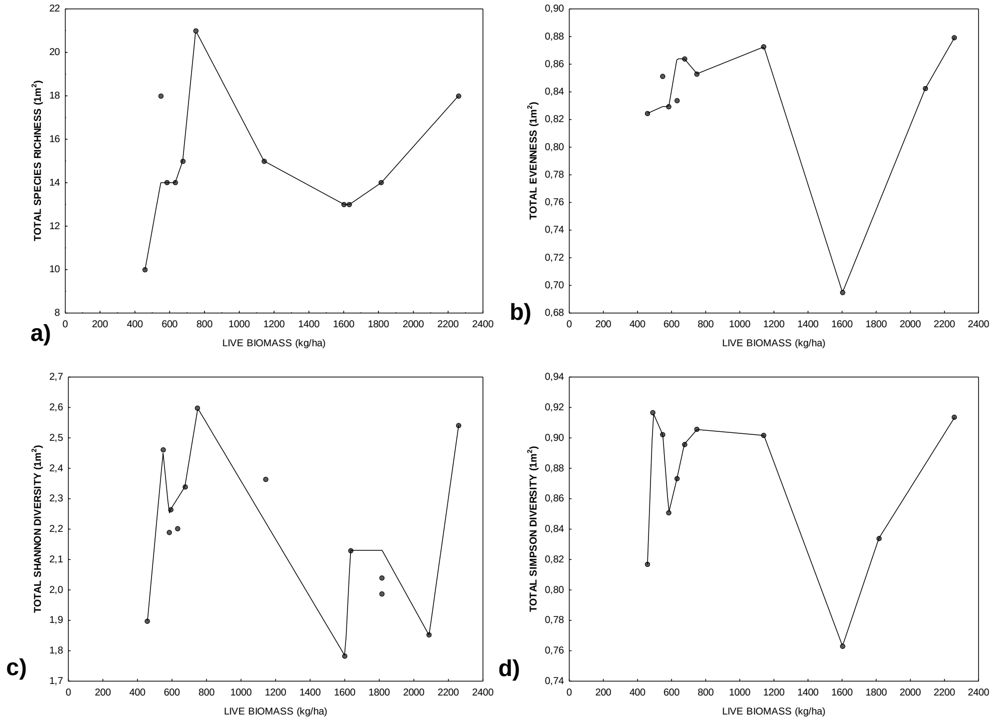

Figure D2. Local diversity-biomass relationships of total species diversity indices for the Asbestos Hills, a) species richness, b) evenness, c) Shannon- and d) Simpson diversity.

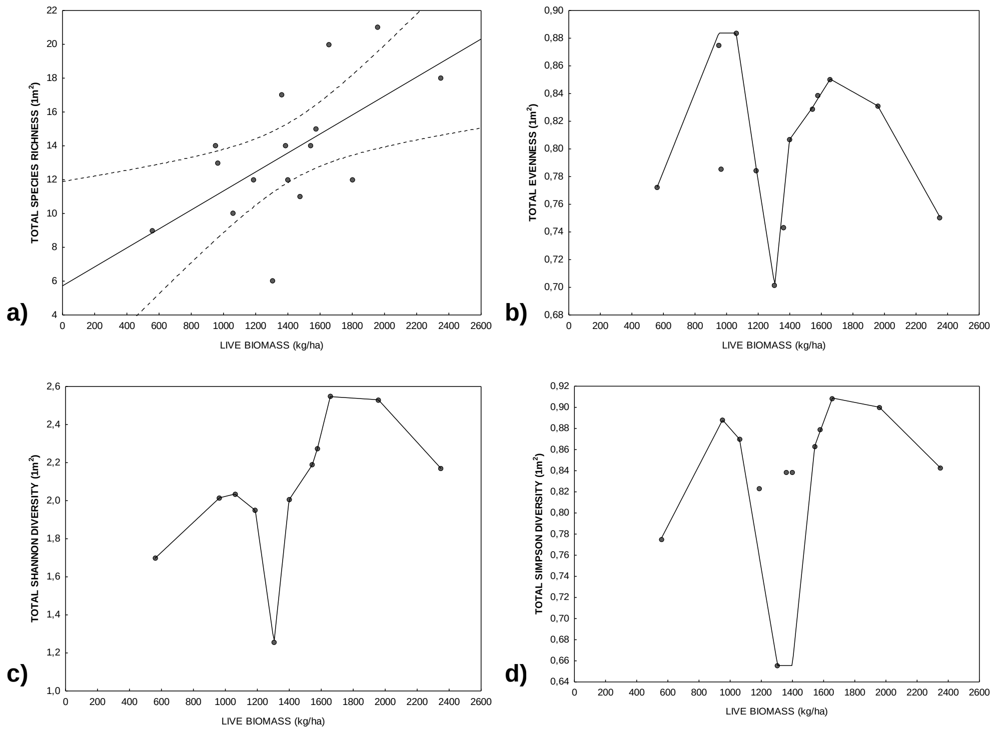

Figure D3. Local diversity-biomass relationships of total species diversity indices for the Kuruman Hills, a) species richness, b) evenness, c) Shannon- and d) Simpson diversity.

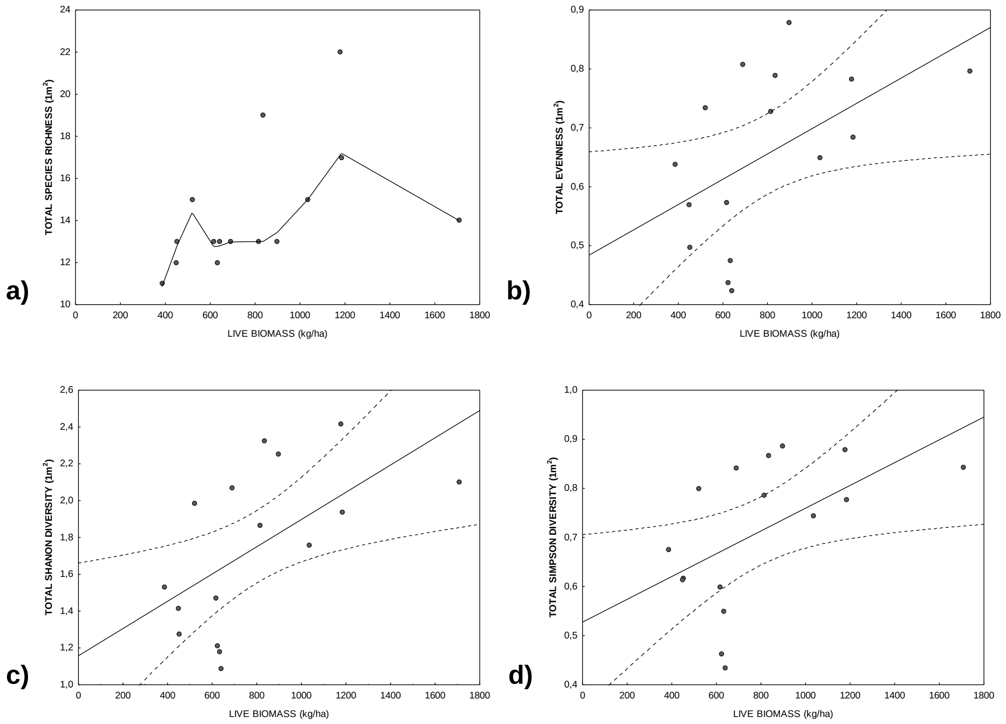

Figure D4. Local diversity-biomass relationships of total species diversity indices for the Ghaap Plateau, a) species richness, b) evenness, c) Shannon- and d) Simpson diversity.

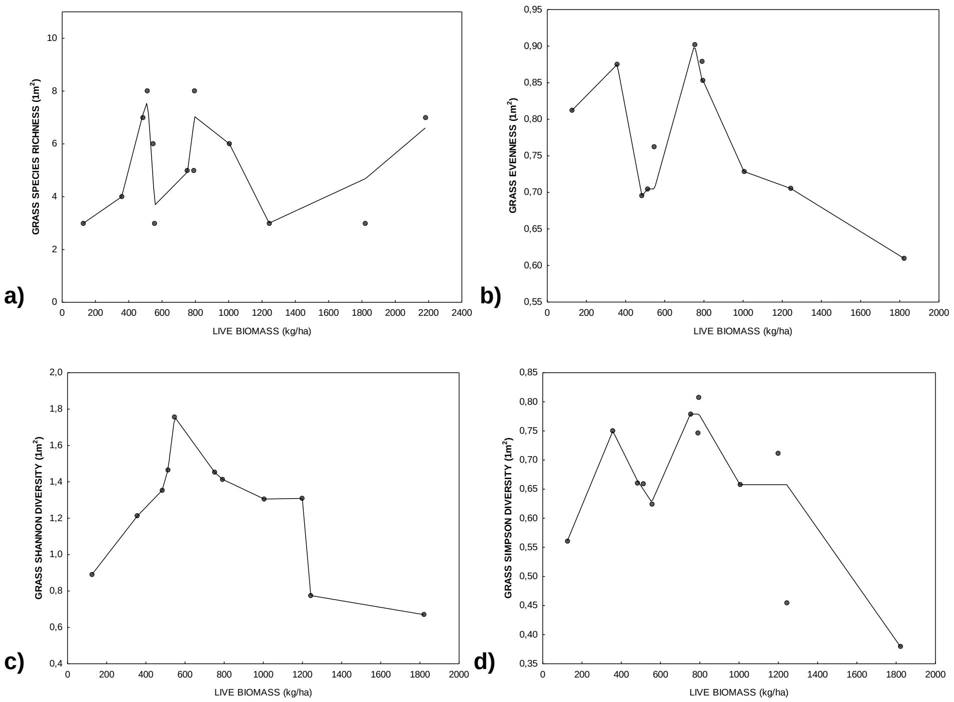

Figure D5. Local grass diversity-biomass relationships of grass species diversity indices for the Langberg, a) grass species richness, b) grass evenness, c) Shannon- and d) Simpson Diversity.

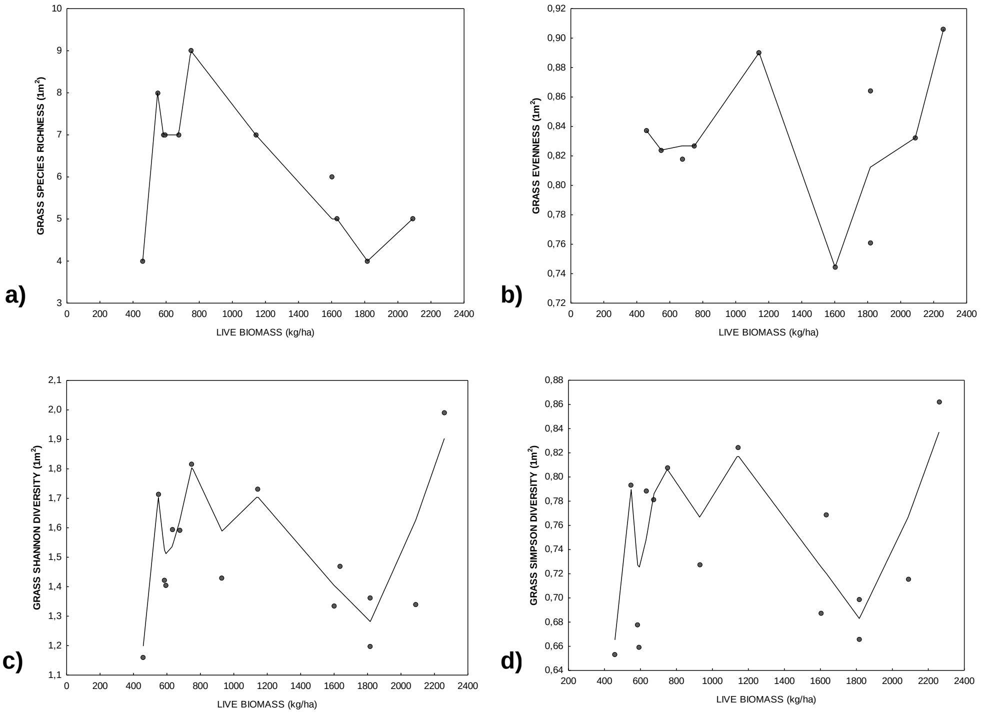

Figure D6. Local grass diversity-biomass relationships of grass species diversity indices for the Asbestos Hills, a) grass species richness, b) grass evenness, c) Shannon- and d) Simpson Diversity.

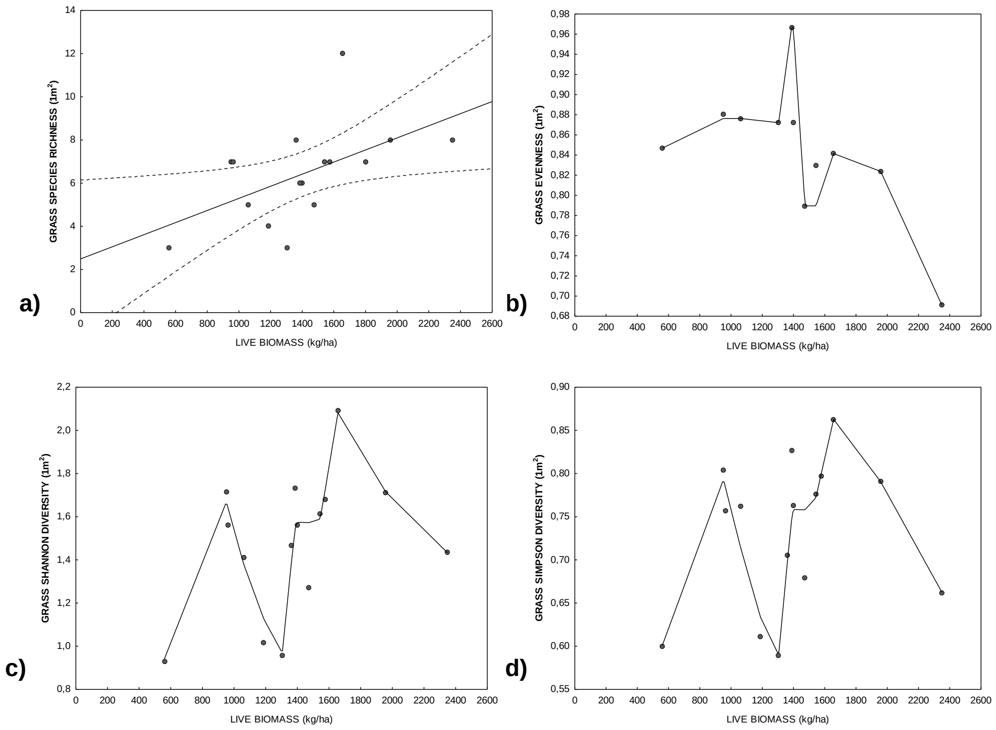

Figure D7. Local grass diversity-biomass relationships of grass species diversity indices for the Kuruman Hills, a) grass species richness, b) grass evenness, c) Shannon- and d) Simpson Diversity.

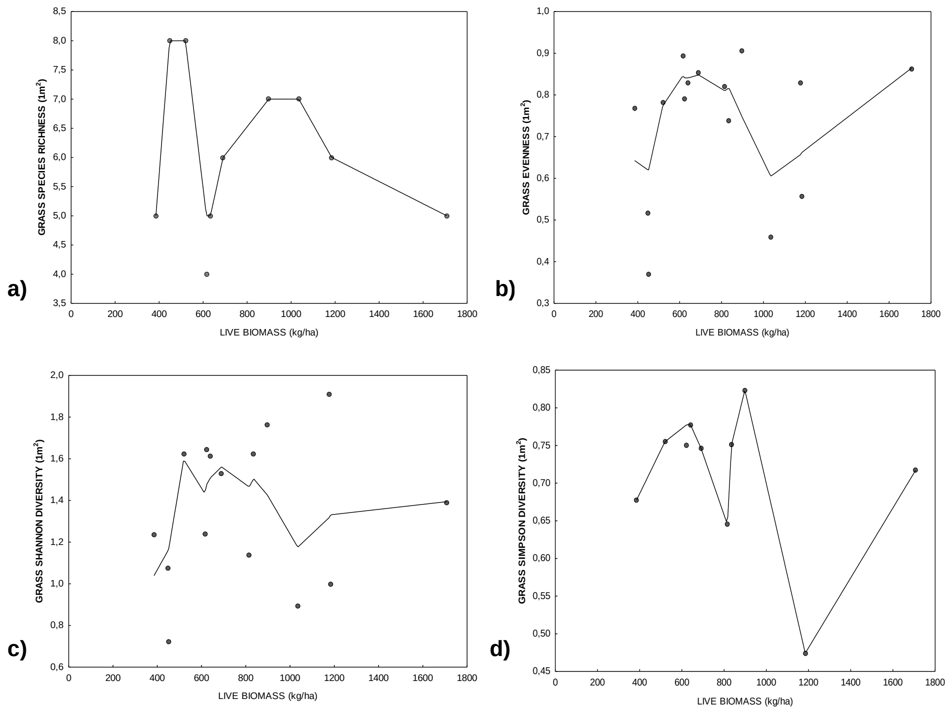

Figure D8. Local grass diversity-biomass relationships of grass species diversity indices for the Ghaap Plateau, a) grass species richness, b) grass evenness, c) Shannon- and d) Simpson Diversity.

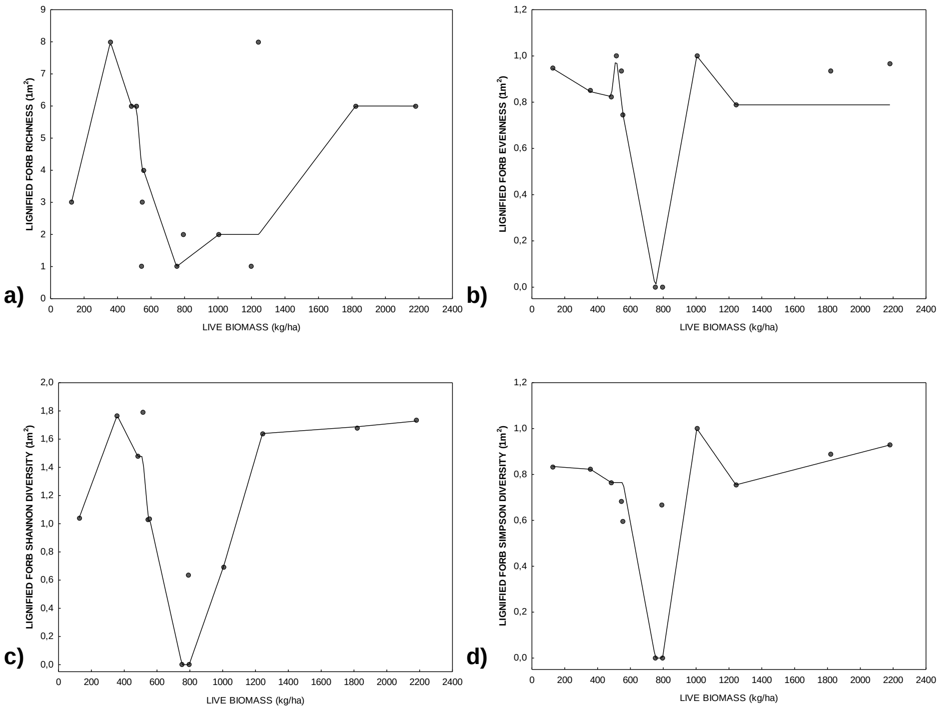

Figure D9. Local lignified forb diversity-biomass relationships of lignified forb species diversity indices for the Langberg, a) lignified forb species richness, b) lignified forb evenness, c) Shannon- and d) Simpson Diversity.

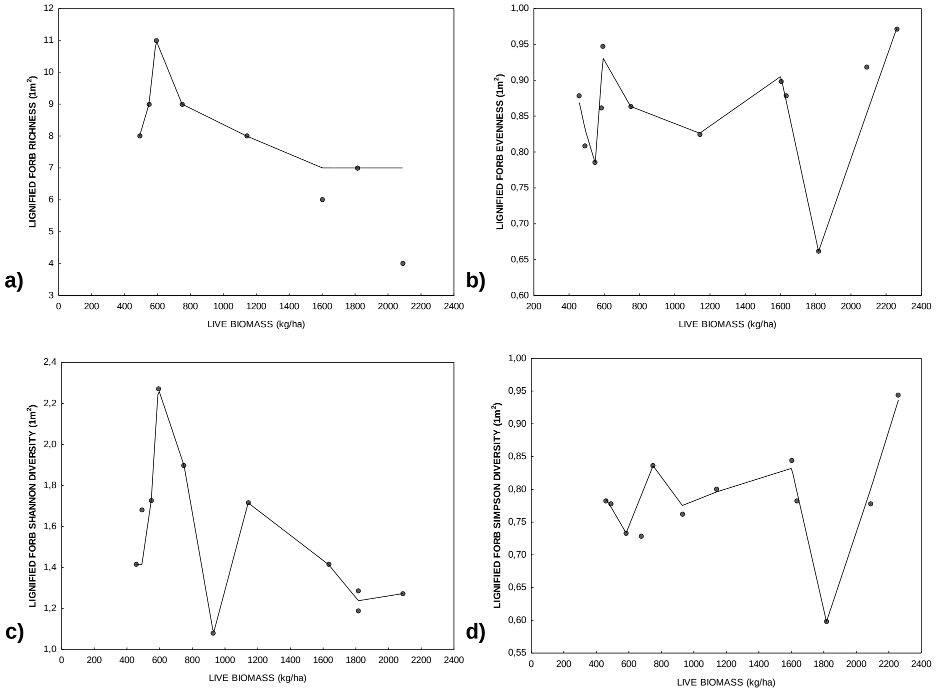

Figure D10. Local lignified forb diversity-biomass relationships of lignified forb species diversity indices for the Asbestos Hills, a) lignified forb species richness, b) lignified forb evenness, c) Shannon- and d) Simpson Diversity.

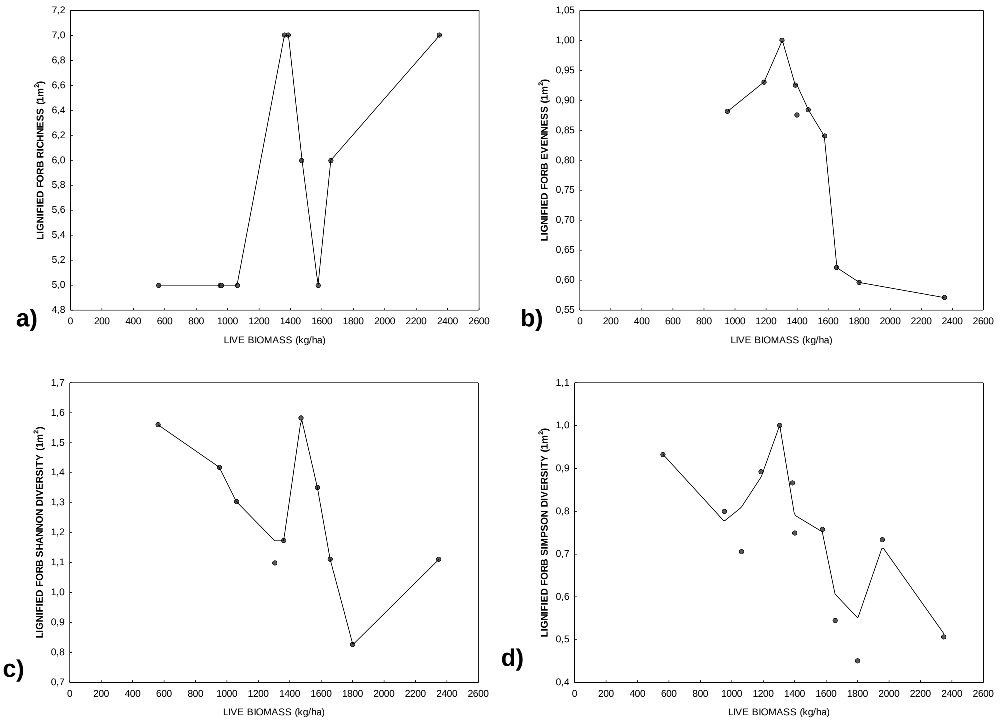

Figure D11. Local lignified forb diversity-biomass relationships of lignified forb species diversity indices for the Kuruman Hills, a) lignified forb species richness, b) lignified forb evenness, c) Shannon- and d) Simpson Diversity.

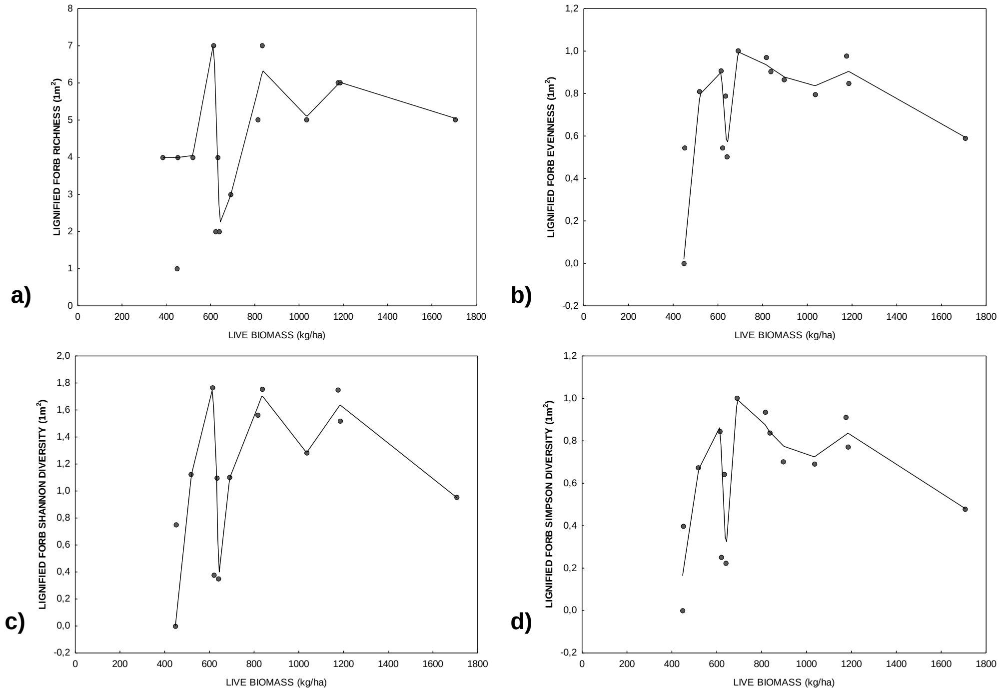

Figure D12. Local lignified forb diversity-biomass relationships of lignified forb species diversity indices for the Ghaap Plateau, a) lignified forb species richness, b) lignified forb evenness, c) Shannon- and d) Simpson Diversity.

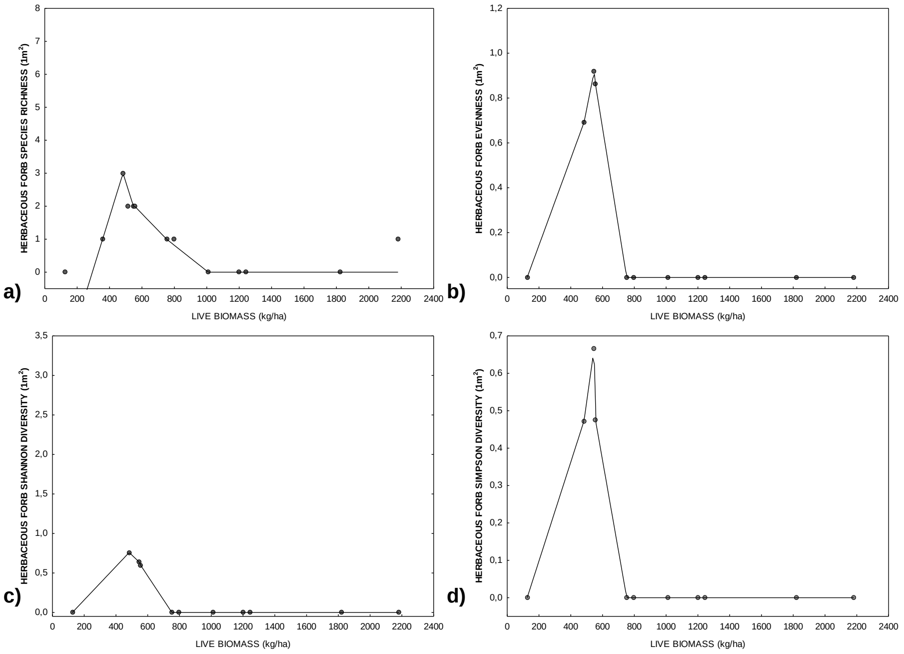

Figure D13. Local herbaceous forb diversity-biomass relationships of herbaceous forb species diversity indices for the Langberg, a) herbaceous forb species richness, b) herbaceous forb evenness, c) Shannon- and d) Simpson Diversity.

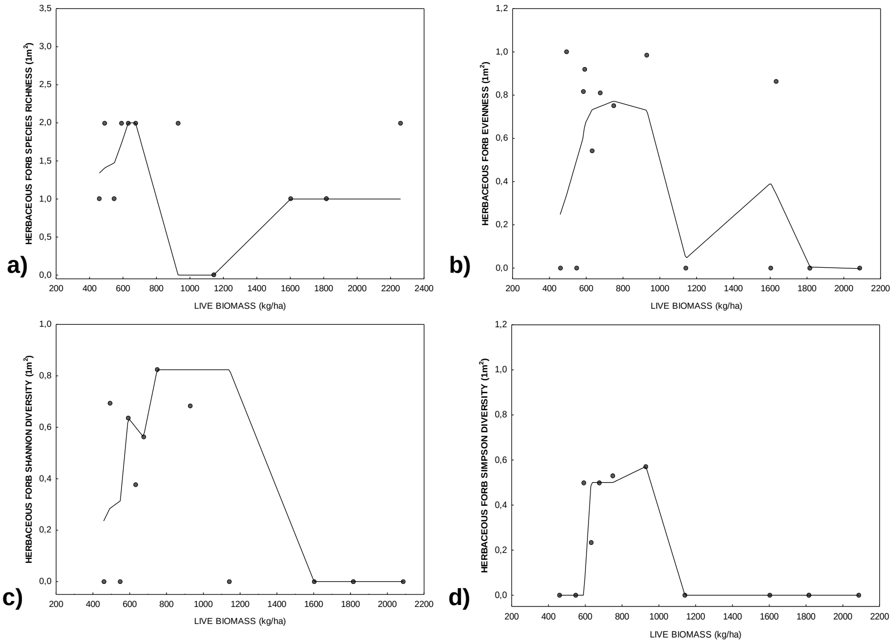

Figure D14. Local herbaceous forb diversity-biomass relationships of herbaceous forb species diversity indices for the Asbestos Hills, a) herbaceous forb species richness, b) herbaceous forb evenness, c) Shannon- and d) Simpson Diversity.

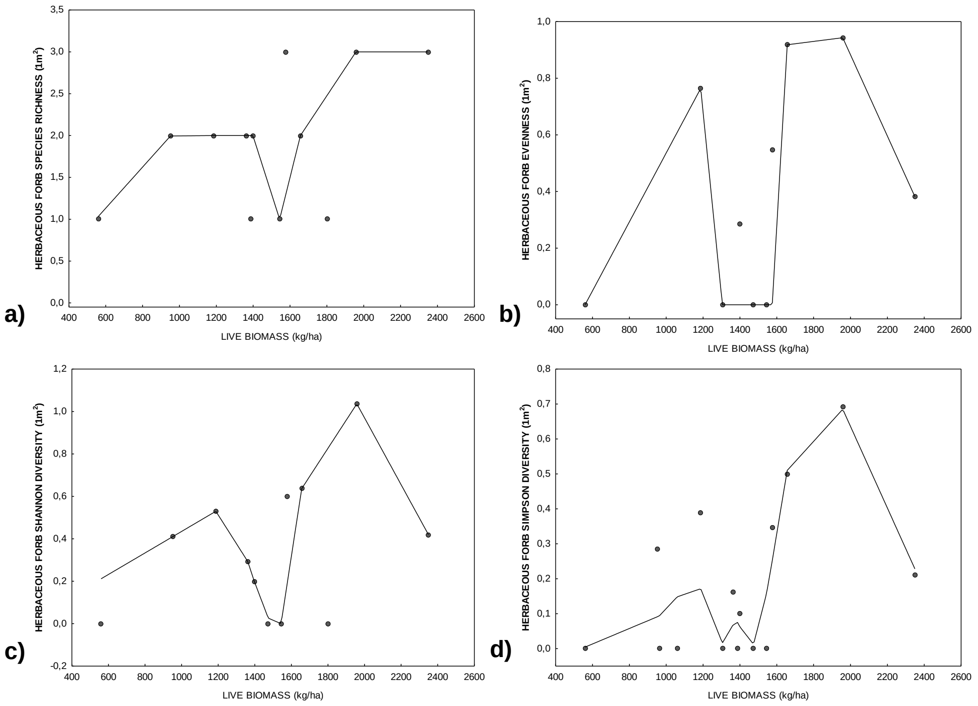

Figure D15. Local herbaceous forb diversity-biomass relationships of herbaceous forb species diversity indices for the Kuruman Hills, a) herbaceous forb species richness, b) herbaceous forb evenness, c) Shannon- and d) Simpson Diversity.

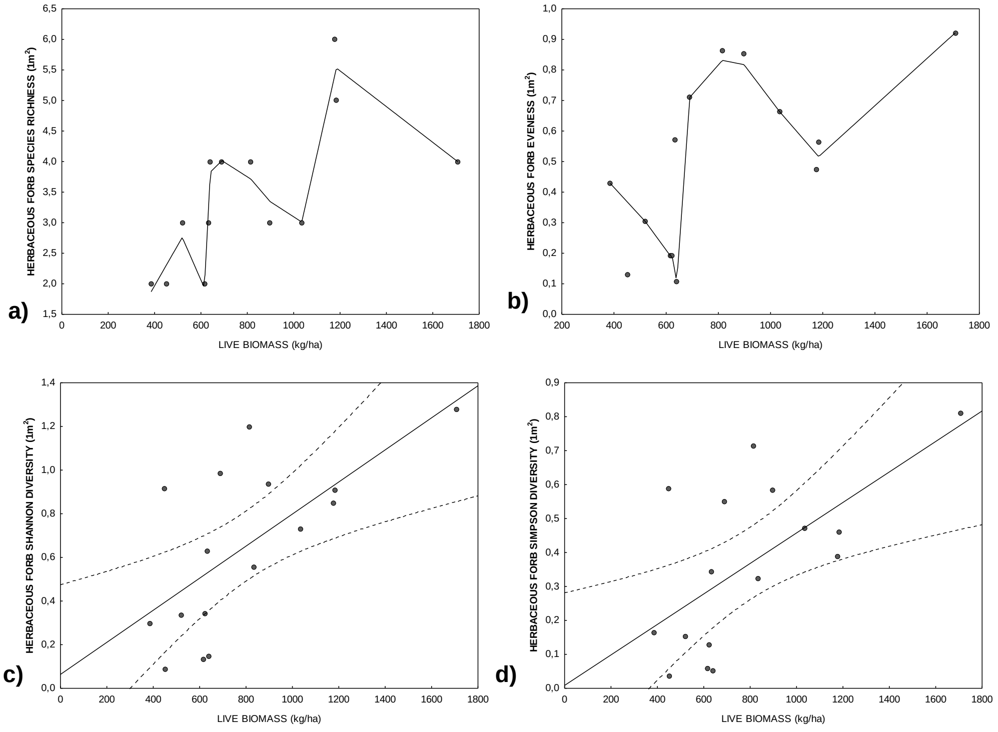

Figure D16. Local herbaceous forb diversity-biomass relationships of herbaceous forb species diversity indices for the Ghaap Plateau, a) herbaceous forb species richness, b) herbaceous forb evenness, c) Shannon- and d) Simpson Diversity.

Appendix E

Letter from editor

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UNIT FOR ENVIRONMENTAL SCIENCES AND MANAGEMENT

2020/11/30

To whom it may concern,

I wish to draw your attention to the following facts pertaining to the thesis: A GEOBOTANICAL INVESTIGATION OF MOUNTAIN ECOSYSTEMS IN GRIQUALAND WEST, SOUTH AFRICA, submitted in fulfilment of the requirements for the degree Doctor of Philosophy in Environmental Sciences at the Potchefstroom Campus of the North-West University submitted by Ms. N. van Staden.

This thesis was thoroughly reviewed and proof-read, and the contents were edited where necessary. Both grammatical and scientific amendments were made to the text.

Sincerely,

HVan Coller

Dr. Helga van Coller, PhD–Environmental Sciences

APPENDIX F

Published article

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Floristic analysis of semi-arid mountain ecosystems of the Griqualand West centre of plant endemism, Northern Cape, South Africa

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Abstract. *Van Staden N, Siebert SJ, Cilliers DP, Wilsenach D, Frisby AW. 2020. Floristic analysis of semi-arid mountain ecosystems of the Griqualand West centre of plant endemism, Northern Cape, South Africa. Biodiversitas 21: 1989-2002.* The Griqualand West Centre (GWC) is one of 13 centres of plant endemism in South Africa. Despite its unique flora, it remains poorly conserved and studied. A recent study identified an extensive geographical core area for the GWC, but endemic plant species were found to be absent from certain parts within these borders. To address this, we refined the current GWC borders based on an ecological niche model, which predicted that endemic species are restricted to four mountain ranges within GWC. Mountain floras within these refined borders were then floristically compared to assess whether they are hotspots of endemicity. Floristically, the Asteraceae, Fabaceae, Malvaceae, and Poaceae were the dominant plant families. Mountain ecosystems differed from one another at species level, with indicator species explaining the compositional differences. Distribution patterns of indicator species were determined by mean annual precipitation, Ca: Mg ratios, soil pH, cation exchange capacity, iron, and sand content. These environmental factors are possible drivers of niche partitioning, environmental filtering and habitat specialization in each mountain ecosystem. Limestone and banded ironstone habitats were identified as conservation priority areas, since they contained the highest numbers of rare and threatened GWC restricted-range species, of which six were narrow endemics.

Keywords: Asbestos, banded iron formation, Ghaap Plateau, Kuruman, limestone, quartzite

Abbreviations: ANOVA: Analysis of Variance; AUC: Area Under Curve; CCA: Canonical Correspondence Analysis; CEC: Cation Exchange Capacity; EC: Electrical Conductivity; GWC: Griqualand West Centre of Endemism; GW: Griqualand West; MAP: Mean Annual Precipitation; MAT: Mean Annual Temperature; MaxEnt: Maximum entropy; NMDS: Non-metric Multi-Dimensional Scaling; PERMANOVA: Permutational Multivariate Analysis of Variance; QDG: Quarter-Degree Grid; SAWS: South African Weather Service; XRF: X-ray fluorescence

INTRODUCTION

Mountain ecosystems are characterized by distinct floras (Harrison et al. 2009) due to habitat heterogeneity (Noroozi et al. 2018; Chakraborty 2019). Mountains are therefore considered to function like edaphic islands (Rajakaruna 2004), with specific microclimates and -habitats to which plant species are adapted by developing special traits (Rajakaruna 2004; Rajakaruna 2018), resulting in speciation and species-rich floras (Kruckeberg 1969). Many unique edaphic floras of mountain ecosystems have been found to be associated with centres of endemism (Van Wyk and Smith 2001; Williamson and Balkwill 2015; Noroozi et al. 2018). Edaphic floras are therefore rich in endemic, edaphic specialists (Schmiedel and Jürgens 1999; Siebert et al. 2002). This phenomenon is typical for banded ironstone (Jacobi et al. 2007; Markey and Dillon 2010), quartzite (Schmiedel and Jürgens 1999; Curtis et al. 2013), and carbonate soils (Peñas et al. 2005; Siebert and Siebert 2005; Mota et al. 2008). Mountain floras of GWC are characterized by these rock types (Frisby et al. 2019), and has a heterogeneous undulating landscape with diverse climate and unique vegetation types (Mucina and Rutherford 2006). Despite GWC's distinct vegetation, and known endemic flora of 24 endemics and two near-endemic plant species (Frisby et al. 2019), our understanding regarding its plant diversity patterns is limited. Botanical studies in GWC are few (Wilman 1946; Mostert 1967; Frisby et al. 2019; Van Munster et al. 2019) and, hence, a descriptive assessment of the endemic edaphic flora across different mountain geologies of GWC is required to encourage conservation initiatives (Table 1).

Globally, centres of endemism are inadequately conserved with some regions not being included within borders of protected areas (Millar et al. 2017). Hence, centres of endemism should garner more conservation attention and it is, therefore, essential to understand the patterns and drivers of endemism (Noroozi et al. 2018; Taylor-Smith et al. 2020). Accurate identification of the floristic borders of centers of endemism is imperative to aid with designs for effective and strategic biodiversity conservation and management (Wang et al. 2020). Accurate demarcation of centres of endemism at a finer scale is necessary to ensure comprehensive conservation and management of species to be protected (Cañadas et al. 2014). Endemic species have the potential to serve as flagship species, and conservation action will become more effective by focusing on regions where endemics occur exclusively (Noroozi et al. 2018; Taylor-Smith et al. 2020). This seems logical especially when funding for conservation is limited (Margules and Pressey 2000).

This study was conducted to promote conservation strategies by providing conservation authorities with detailed information to ensure proper conservation of GWC, by focusing on priority areas where endemic species occur at a finer scale. This paper addresses two primary aims to develop a better understanding of the GWC and its flora. Firstly, the borders of GWC are refined to establish which main mountain ranges fall within the centre by using a MaxEnt spatial model based on geology, climate, and topography in combination with distribution data of GWC endemics. Refining the borders of GWC will (i) result in a smaller geographical region that will allow for focused botanical studies and, (ii) ensure targeted conservation of endemic plant species. Secondly, the flora associated with the main mountain ecosystems within these newly refined borders will be described. By doing so, knowledge regarding floristic characteristics of the ecosystems will depict the distinctness of the mountain floras. Mountain floras will be described based on (i) dominant plant families, (ii) common species, (iii) indicator plant species, (iv) threatened and endemic species, and (v) species composition.

MATERIALS AND METHODS

Study area

GWC was first proposed and mapped by Van Wyk and Smith (2001). Recently, borders were described and set by Frisby et al. (2019). This description was based on QDG's of the total distribution of GWC endemic species *per se*, which resulted in an extensive area (75 172 km²).

The GWC falls within the Savanna Biome. The landscape is heterogenous with mountain ranges and/or ridges trending north-south (Figure 1), with the intermontane valleys filled with Kalahari sands (Mucina and Rutherford 2006). In the east, GWC consists of the dolomitic Ghaap Plateau bordering on an undulating set of low banded ironstone hills called the Asbestos- and Kuruman Hills. The landscape becomes more rugged in the west of GWC due to the quartzitic Langberg. These mountain systems are each characterized by endemic vegetation units, i.e. Ghaap Plateau Vaal Bushveld, Kuruman Mountain Bushveld, and Koranna-Langberg Mountain Bushveld (Mucina and Rutherford 2006).

Climate

GWC falls within the summer rainfall region of South Africa. Rainfall is highly erratic, and a semi-arid climate prevails. From east to west, a gradient of increasing aridity is evident. In the east, the Ghaap Plateau receives higher rainfall, whereas the Langberg in the west is a region of lower, more arid rainfall (Table 1). The Kuruman Hills receive higher rainfall than the southern Asbestos Hills of the same geology (Mucina and Rutherford 2006). The mountains are slightly cooler than the lower-lying areas (Mucina and Rutherford 2006; Frisby et al. 2019).

Geology and soil

Three subgroups of the Ghaap Group (Griqualand West Basin) are found in GWC, namely Campbell Rand, Schmidtsdrif and Asbestos Hills (Van Wyk and Smith 2001; Eriksson et al. 2006). The former two subgroups dominate on the Ghaap Plateau. Soils are rich in lime due to the prevalence of dolomite, limestone, and chert (Keyser 1997). Therefore, the soil of the Ghaap Plateau is rich in both magnesium (Mg) and calcium (Ca) (McCarthy and Rubidge 2005). On dolomites, soils are sandy and dark brown to reddish, while shallow, black, turfy and alkaline soils are found on limestone. Furthermore, the soil is underlain by weathered rock and slightly leached (Mucina and Rutherford 2006; AGIS 2007).

The Asbestos Hills subgroup dominates on the Kuruman- and Asbestos Hills that consist mainly of banded ironstone. Additionally, jaspillite, chert and riebeckite asbestos are associated with these two mountain ecosystems (Keyser 1997; Mucina and Rutherford 2006). Soils are sandy and shallow with 60-80% of the soil surface covered with boulders or rocks (Mucina and Rutherford 2006; AGIS 2007).

The geology of the Langberg consists of clastic sediments such as quartzite (white, pink and green), greywacke, lavas, conglomerate, and hematite of the Olifantshoek Supergroup (Keyser 1997; Mucina and Rutherford 2006). Arenaceous rocks (derived from or containing sand) of the Volop Group are well exposed in the landscape with red-brown arenites of the Matsap Subgroup overlying the Hartley Formation, which is a layer of conglomerate (Moen 2006). Slopes are steep (mostly 10-50°) with limited soil cover. Soils are rocky with exposed boulders and/or rocks covering more than 80% of the landscape (AGIS 2007). Soil texture varies from sandy loam to sandy clay loam (AGIS 2007).

Table 1. Summary of environmental conditions associated with each GWC mountain landscape (Mucina and Rutherford 2006)

Mountain	Approx. area (km²)	Altitude (m.a.s.l.)	MAT (°C)	MAP (mm)	Geology
Ghaap Plateau	14 997	1 100-1 500	17.1	370-425	Dolomite, limestone
Kuruman Hills	1 236	1 100-1 800	16.8	355-375	Banded ironstone
Asbestos Hills	2 117	1 100-1 800	16.8	290-360	Banded ironstone
Langberg	1 204	1 000-1 850	16.8	225-295	Quartzite

Note: Abbreviations in the table are as follows: Meters above sea level (m.a.s.l.), Mean annual temperature (MAT) and Mean annual precipitation (MAP).

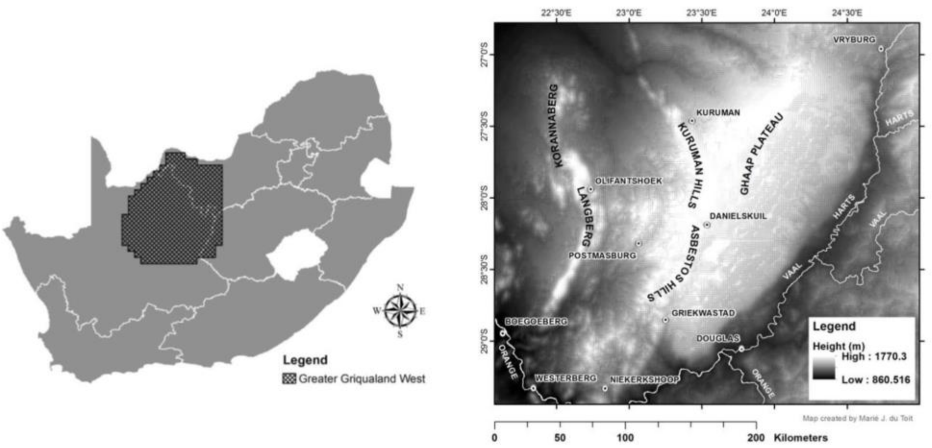

Figure 1. Main mountain ranges in GWC in the Greater Griqualand West area, Northern Cape, South Africa. The Langberg extends ultimately into the Korannaberg in the north. Since the Korannaberg falls outside the center and does not harbor any GWC endemics, this range was excluded from this study

Data collection and -analysis

Refining the borders

MaxEnt software (Elith et al. 2011; Phillips et al. 2019) was used to develop an ecological niche model for GWC based on bioclimatic variables. MaxEnt uses probability of occurrence to calculate the conditions in which species occur (Phillips et al. 2009). A total of 95 verified occurrence records for 24 endemics and two near-endemic species identified by Frisby et al. (2019) were used as presence records in the model. A total of 19 bioclimatic variables obtained from WorldClim version 2 (Fick and Hijmans 2017) represented environmental conditions (See supplementary, Table A1). An 80/20 split was applied to the occurrence records, with 80% of records (n=76) used to train the model and 20% (n=19) used to test the accuracy of the model prediction. Default settings were used, except for the replication number that was set to 100. The AUC score was used to determine the accuracy of the model (Bean et al. 2012), where an AUC of 1 would indicate a perfect prediction and 0.5 a random prediction (Phillips et al. 2006). An AUC of 0.979 was obtained suggesting a good model prediction. To convert the model output to a binary output usable for delineation purposes, a threshold was applied. The tenth percentile training presence logistic threshold (0.2772), that is suitable to (i) use when dealing with centres of endemism (Escalante et al. 2013) as well as (ii) studies relying on presence-only data (Callen and Miller 2015), was used. The binary output was finally intersected with the boundary delineated by Frisby et al. (2019) as well as the geology (See supplementary, Table A2) preferred by endemics in GWC.

Floristic analysis

Historical data

Species lists for GWC were obtained from BODATSA (Ranwashe 2019). This data was supplemented with specimen records obtained from herbaria with collections from the GW region, including PUC, KMG, PRU, KSAN, NMB, BLFU, and PRE. All distribution data were captured at species level at QDG resolution. Further distribution data were supplemented from literature sources (Van Wyk and Smith 2001; Mucina and Rutherford 2006).

Field sampling

The four mountain ecosystems within the refined border of the GWC were sampled in the wet season. Total rainfall, obtained from the SAWS for January to April 2018 (sampling year), ranged between 160.6 mm and 422.4 mm (west to east). A total of eight Modified-Whittaker plots (50 m x 20 m) were sampled per mountain system. The 50 m sides of transects were placed parallel to the slope of the mountain with the 20 m sides perpendicular to the 50 m sides. Two 1 m^2 sub-plots were sampled within two opposite corners of the plot. All rooted herbaceous individuals within sub-plots were identified up to species level and counted. Soil samples were collected for each Modified-Whittaker plot and five soil samples were randomly collected at a depth of 0-10 cm, depending on soil depth due to rockiness. From this, a composite sample was compiled and thoroughly mixed. Macro-and micro-nutrients of soil samples were analyzed using a portable XRF analyzer (Koch et al. 2017). Particle size distribution, soil pH, EC, CEC, percentage clay, and silt were analyzed according to procedures prescribed by the Non-Affiliated Soil Analysis Work Committee (1990).

Data analysis

Floristic analysis was conducted on the four mountain ranges within the refined borders of GWC. Plant lists were compiled for each mountain system based on historical distribution records that were obtained from herbarium specimens and combined with collected field data. A total of 44 field-collected plant specimens that could not be identified below genus level, were excluded from plant lists. Combined historical and field-collected data in the 1 m^2 sub-plots were used to identify the 20 largest plant families of each mountain which were furthermore ranked based on the number of species. Spearman's rank correlation coefficient tests were performed in Statistica version 13.3 (TIBCO 2017) to assess similarity of plant family rankings between mountains. This correlation analysis followed a pairwise comparison between mountain combinations and Spearman's rho (ρ), ranging from -1 and 1 (Schober et al. 2018), and was calculated for each pairwise rank. Significance was determined at $p<0.05$. Jaccard similarity coefficients were performed on presence or absence of collected species data within 1 m^2 sub-plots using PAST (Hammer et al. 2001). This analysis was conducted to establish the degree of similarity between sampled mountain systems based on presence/absence of herbaceous species. Plant species sampled in sub-plots of the Modified-Whittaker plots were ranked based on their overall abundances to reveal common plant species. NMDS scatter plot of 1 m^2 field collected data, using the Bray-Curtis dissimilarity distance measure, was constructed in Primer 6 (2012) to compare herbaceous species composition of mountain ecosystems. To assess whether clustering in the NMDS was significant, Non-parametric PERMANOVA analysis was conducted in Primer 6 (2012). Furthermore, indicator species analysis was performed in RStudio using the IndVal function under the labdsv package (Roberts 2016) and significance levels were set at $p<0.05$. To correlate abundance of collected indicator plant species within sub-plots with environmental variables, CCA was performed in Canoco 5 (Šmilauer and Lepš 2014).

RESULTS AND DISCUSSION

Refined borders of GWC

The niche model had an average AUC of 0.979 for the 100 replicate runs, suggesting high model performance and a very good prediction (Phillips et al. 2006). Bioclimatic variables that showed the highest model contribution included temperature seasonality (annual range in temperature), precipitation seasonality (annual range in precipitation) and precipitation of the driest quarter (Table 2). This model output was overlaid onto the geology that is known to harbor GWC endemics and the core area boundary proposed by Frisby et al. (2019). The refined area (Figure 2), where all three layers overlap, is strongly associated with mountainous habitats with their associated unique geology and cooler climate, implying that endemic plant species are absent from the warmer, sand-filled valleys. Thus, the mountains of GWC are identified as hotspots within the centre of endemism due to topographic heterogeneity, geology and climate (Cañadas et al. 2014; Noroozi et al. 2018; Tordoni et al. 2020). The newly refined boundaries of GWC covers 24 075 km^2, a surface area three times smaller than the core area of 75 172 km^2 as proposed by Frisby et al. (2019). The refined boundaries of GWC are thus identified as conservation priority and emphasize the need to focus on a finer scale when defining centres of plant endemism. Focusing conservation efforts on the endemic rich mountains will ensure that rare species are protected (Noroozi et al. 2018). However, a systematic conservation approach (Margules and Pressey 2000) and development of conservation plans are required (Tordoni et al. 2020), since identified hotspots of endemism within GWC lie outside the borders of established protected areas, i.e. Mokala National Park, Witsand Nature Reserve, and Tswalu Kalahari Reserve.

Table 2. Estimates of the relative contributions of bioclimatic variables (BIO) to the MaxEnt model for GWC endemics. Values shown are averages of 100 replicate runs.

Variable	Percent contribution (%)
BIO1 = Annual Mean Temperature	0.2
BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp))	1
BIO3 = Isothermality (BIO2/BIO7) (* 100)	0
BIO4 = Temperature Seasonality (standard deviation *100)	37.2
BIO5 = Max Temperature of Warmest Month	0.4
BIO6 = Min Temperature of Coldest Month	0.4
BIO7 = Temperature Annual Range (BIO5-BIO6)	2.4
BIO8 = Mean Temperature of Wettest Quarter	0.5
BIO9 = Mean Temperature of Driest Quarter	0.2
BIO10 = Mean Temperature of Warmest Quarter	0
BIO11 = Mean Temperature of Coldest Quarter	0.1
BIO12 = Annual Precipitation	5.5
BIO13 = Precipitation of Wettest Month	0.1
BIO14 = Precipitation of Driest Month	1.6
BIO15 = Precipitation Seasonality (Coefficient of Variation)	27.8
BIO16 = Precipitation of Wettest Quarter	0.1
BIO17 = Precipitation of Driest Quarter	21.4
BIO18 = Precipitation of Warmest Quarter	1.3
BIO19 = Precipitation of Coldest Quarter	0

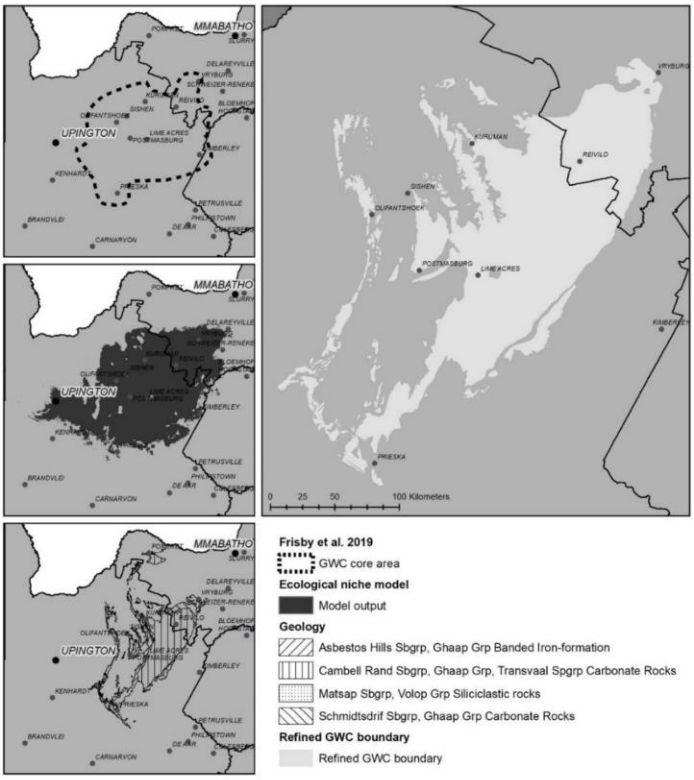

Figure 2. Refined GWC borders as predicted by overlays of the ecological niche model for endemic plant species with the core area defined by Frisby et al. (2019) and rock types known to harbor GWC endemics

Soil characteristics

Ca content exceeded 11 000 mg/kg on the Ghaap Plateau, whilst Mg reached levels above 5 000 mg/kg (Table 3). Consequently, the Ca: Mg ratio was above 2 and the soil pH>7. These soil chemical properties of dolomite and limestone soil are supported by Lee (1999). Iron (Fe) levels were high (>50 000 mg/kg) on banded ironstone Asbestos- and Kuruman Hills (Table 3) due to presence of hematite (Fe_2O_3) and magnetite (Fe_3O_4) (Trendall 2013). Ca: Mg ratios were high due to lower concentrations of Mg (<3000mg/kg) and higher Ca content (>3000 mg/kg). Furthermore, the two banded ironstone habitats were characterized by more acidic soils (pH<7) (Thompson and Sheehy 2011). This suggests that that banded ironstone differs from acidic serpentine soils that are usually associated with higher concentrations of Mg than Ca (Robinson et al. 1996; Alexander 2011). Aluminum (Al) levels exceeded 30 000 mg/kg on the Langberg and Asbestos Hills (Table 3). Despite Al being one of the most abundant metals in soils, the availability thereof to plants is dependent on low soil pH (Gupta et al. 2013; Bojórquez-Quintal et al. 2017). When soil acidity increases, Al can become available to plants and inhibit plant growth (Abedi et al. 2013; Bojórquez-Quintal et al. 2017). However, Al may be beneficial to certain taxa or contribute to the development of tolerance mechanisms in plants (Bojórquez-Quintal et al. 2017). In addition, Al levels act as an environmental filter (Abedi et al. 2013) that contribute to compositional and structural changes in plant communities (Mota et al. 2018). Acid and sandy soils, especially those associated with quartzite, are known to be rich in Al, low in clay content and all of potassium (K), sodium (Na), Mg and Ca, and, hence, considered nutrient-poor (Negreiros et al. 2014; Do Carmo and Jacobi 2016). EC, an indicator of soil fertility (Fourie 2019), for the dry Langberg and Asbestos Hills, was below 23 Ms/m and indicating lower fertility (Table 3). In contrast, EC values were higher (>30 Ms/m) for the Kuruman Hills and Ghaap Plateau. A soil fertility gradient, together with a rainfall gradient, could thus be observed for GWC as indicated by the dendrogram of Jaccard Similarity based on sampled species (Figure 3).

Table 3. Mean concentrations with standard deviation of four elements and physical properties of soils associated with each mountain (n=8). LB=Langberg; AH=Asbestos Hills; KH=Kuruman Hills; GP=Ghaap Plateau.

	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)	Al (mg/kg)	Ca: Mg	pH	EC (Ms/m)	CEC cmol(+)/kg
LB	1347±921	2643±664	13741±1279	33868±3568	0.5±0.6	4.9±0.4	19.3±11.2	14.9±1.3
AH	4040±1237	3320±651	52437±10021	36318±4703	1.2±0.3	6.0±0.3	22.4±11.9	19.1±2.2
KH	3126±2573	2946±438	61660±19585	27055±5043	1.1±0.8	5.5±0.3	31.8±20.2	20.6±2.7
GP	11844±9241	5296±2790	18876+4721	30142±6981	2.2±3.2	7.6±0.6	32.6±14.2	20.2±3.1

Table 4. Comparison of field-collected (Field) data with historical herbarium records (Hist.) regarding taxa numbers represented in the flora of each mountain ecosystem of GWC. Unique species are those plant species that are not shared between mountain ranges.

	Langberg		Asbestos hills		Kuruman hills		Ghaap plateau	
	Hist.	**Field**	**Hist.**	**Field**	**Hist.**	**Field**	**Hist.**	**Field**
Families	65	39	75	40	83	38	73	45
Genera	192	89	252	93	287	89	223	94
Species	325	126	472	114	551	114	410	134
Species: Genus	1.69	1.42	1.87	1.23	1.92	1.28	1.84	1.43
Species/Family	5	3.23	6.29	2.85	6,64	3	5.62	2.98
N Unique Species	102	35	112	14	152	30	103	43
% Unique Species	31.38	27.78	23.73	12.28	27.59	26.32	25.12	32.09

Flora of GWC's mountain ecosystems

Sampling effort

A plant list of historical data records was compiled for each mountain system within GWC. As would be expected, historical data indicated higher taxa numbers than field data (based on eight Modified-Whittaker plots per system; Table 4). Restricted sampling effort resulted in certain taxa not being found (Spyreas 2016). However, each mountain flora was associated with unique plant species. These species were restricted to specific habitats and can be considered habitat specialists within GWC (Anderson and Ferree 2010; Williamson and Balkwill 2015). Comparing field data with historical data revealed that unique species of the Asbestos Hills were more restricted in distribution and difficult to locate, despite a comparable number of overall species recorded. The opposite was observed for the Ghaap Plateau with unique species seemingly widespread and easily recorded. The latest discovery of a new endemic plant species *Deverra rapaletsa* Magee & Zietsman, restricted to the Ghaap Plateau (Van Munster et al. 2019), emphasizes the unique flora of the Ghaap Plateau and the possibility of more species that are yet to be discovered. Floristic sampling on the Asbestos Hills was hampered due to poor rangeland conditions (overgrazing), which possibly favored common species tolerant to disturbance (Table 4). In contrast, sampling success for edaphic specialists was greater on the banded ironstone of the Kuruman Hills where the rangelands were managed responsibly.

Dominant plant families

Combined historical and field data revealed that the four most species-rich families across the four mountain landscapes were the Poaceae, Asteraceae, Fabaceae and Malvaceae in descending order (See supplementary, Table A4). These plant families are known to be of the largest and most widespread families, not only in southern Africa, but on a global scale. Members of these four families are known to occupy a variety of habitats and persist under various environmental conditions (Koekemoer et al. 2014). More specifically, the Asteraceae, Fabaceae, and Poaceae have been found to dominate plant communities on limestone and dolomite (Ludwig 1999; Siebert and Siebert 2005), banded ironstone (Jacobi and Do Carmo 2008; Markey and Dillon 2010; Gibson et al. 2012), as well as quartzite (Curtis et al. 2013; Neri et al. 2019). Since GWC is situated in the Savanna Biome, the representation by members of the Malvaceae can be ascribed to their preferred association and diversification in savanna landscapes (Koekemoer et al. 2014; Soares et al. 2015). The joined fifth most species-rich plant families in GWC, i.e. Cyperaceae and Scrophulariaceae, is respectively associated either with the lower rainfall (Langberg and Asbestos Hills) or higher rainfall mountains (Kuruman Hills and Ghaap Plateau). The Scrophulariaceae is widely distributed globally and is common in drier, open savanna-grasslands, as well as mountainous areas (Fischer 2004; Koekemoer et al. 2014). Furthermore, some taxa are habitat specialists since they prefer rocky and dry granitic outcrops and/or ferricretes and, hence are often drought tolerant (Clements et al. 2002; Fischer 2004; Koekemoer et al. 2014). Many Scrophulariaceae have also been found to be metallophytes and, hence able to tolerate heavy metals in soils especially copper (Cu) and cobalt (Co) in south-central Africa (Faucon et al. 2009). In contrast, the Cyperaceae is mostly found in moister habitats in savanna-grassland regions (Koekemoer et al. 2014). Since the Ghaap Plateau is underlain by dolomite and limestone, soils tend to be rich in lime (CaO), alkaline, high in clay content and poorly drained (Mustart et al. 1994). This provides a suitable habitat for taxa in the Cyperaceae. Ludwig (1999), as well as Swadek and Burgess (2012), conducted studies on North American limestones and found that the Cyperaceae was respectively the fourth and fifth most diverse plant family. Both studies recorded 17 taxa within the Cyperaceae, a number that corresponds to the number of taxa present on the Ghaap Plateau (See supplementary, Table A4). The Kuruman Hills and Ghaap Plateau are rocky habitats. Consequently, presence of rock crevices, drainage lines and shallow depressions where rainwater can collect, serves as microhabitats for the Cyperaceae to establish successfully (Porembski and Barthlott 2000; Jacobi and Do Carmo 2008).

Diversity on family- and species level

Most diverse families of the Asbestos Hills correlated significantly with the most diverse families of the Kuruman Hills (Table 5; $\rho=0.88$; $p<0.05$). Jaccard similarity, based on sampled plant species (Table 6), also revealed highest similarity between these two mountain landscapes (38%). Similarities between the Kuruman- and Asbestos Hills could be ascribed to the fact that both these mountains are characterized by banded ironstone (Van Wyk and Smith 2001) and the same vegetation type, namely the Kuruman Mountain Bushveld (Mucina and Rutherford 2006). Dendrograms of Spearman correlation (See supplementary, Figure B1) and Jaccard similarity (Figure 3) indicated that the floristic difference between the two banded ironstone habitats is most likely attributed to rainfall, since the Kuruman Hills receives higher rainfall than the southern lying Asbestos Hills (Table 1).

The Langberg family diversity was moderately correlated (Table 5) with the Asbestos Hills ($\rho=0.77$; $p<0.05$), and the least with the Ghaap Plateau ($\rho=0.56$; $p<0.05$). This is likely attributed to differences in pH values (low *vs.* high) since the Langberg has acidic soils and the Ghaap Plateau is alkaline (Table 3). Jaccard similarity indicated that the Asbestos Hills and Langberg share 34% of their species (Table 6), despite differences in geology. Both these landscapes are characterized by lower rainfall (Table 1), suggesting a shared drought-tolerant and/or resistant flora (Kimball et al. 2017).

The Kuruman Hills and Ghaap Plateau mountain systems revealed similar family diversity (Table 5; $\rho=0.72$; $p<0.05$). This finding could be attributed to the higher rainfall regime associated with these two systems within GW (Table 1). Therefore, the most species-rich plant families shared in high abundances, such as Cyperaceae, are adapted to these moister systems (See supplementary, Table A4). However, on species level, the Ghaap Plateau and Kuruman Hills had the lowest Jaccard similarity (Table 6; 22%) which indicates differing species-specific colonization on contrasting geological substrates. Spearman correlation (Table 5) revealed that the Ghaap Plateau and Asbestos Hills were also similar in their most diverse plant families ($\rho=0.70$; $p<0.05$), but even more so at species level (Table 6, 34.6%). This was unexpected since these systems differ in geology and rainfall regimes. The only meaningful explanation would be that the Ghaap Plateau and Asbestos Hills are in close proximity to one another (less than 50 km). Therefore, plant species may easily migrate between the two systems especially when species have wide niche breadths and are generalist plant species (Sklenář et al. 2014; Zhang et al. 2016).

Species composition

NMDS analysis of floristic sub-plot data revealed clustering according to mountain ecosystems (Figure 4). PERMANOVA analysis revealed that the clustering was significant (See supplementary, Table A5; Pseudo-F=9.138; $p<0.001$). Although Langberg plots were dispersed without a clear cluster, herbaceous assemblages differed significantly between mountains (See supplementary, Table A5). These findings are in accordance with studies which have found that plant communities underlay by banded ironstone (Jacobi et al. 2007; Gibson et al. 2012), dolomite and limestone (Siebert and Siebert 2005; Zietsman and Bredenkamp 2007; Mota et al. 2008) and quartzites (Wild et al. 1963; Schmiedel and Jürgens 2004) are distinct. In semi-arid savannas, soil nutrients and rainfall are of the most important factors determining vegetation dynamics, especially for the herbaceous layer (Siebert and Dreber 2019). Despite similar geologies, the separate clustering displayed by the Kuruman Hills and Asbestos Hills emphasizes the important role of rainfall in driving compositional differences, since both have the same rock type, but the latter is a drier system.

Each mountain system was characterized by certain commonly occurring species (See supplementary, Table A6) as indicated by the top 20 highest ranked taxa based on abundance values *per se*. Despite certain of these taxa being shared between different mountain systems, their relative frequency differed per system. For example, *Eragrostis nindensis* Ficalho & Hiern was shared between the Langberg, Asbestos Hills and Kuruman Hills, yet this grass species had the highest abundance values on the Langberg (See supplementary, Table A6). Indicator plant species (Table 7) are characterized by high relative frequency of occurrence in a specific mountain habitat (specificity) and thus were primarily found in that habitat in high numbers (Dufrêne and Legendre 1997). In contrast to common species, indicator plant species provide valuable ecological information on various species groups of different plant communities (Dufrêne and Legendre 1997), especially with respect to their habitat preferences and adaptations to persist under certain environmental conditions (Siebert et al. 2010).

The effects of rainfall and soil properties on indicator plant species were confirmed by CCA analysis (Figure 5). Explanatory variables accounted for 47.7% of the total variation. The first canonical axis explained 70.3% of total variation and the second axis 41% of the variance. The Ghaap Plateau was positively correlated with Ca: Mg ratio, soil pH and negatively correlated with Fe content (Figure 5), with a clear separation between the plots of the Ghaap Plateau and banded ironstone hills. Thus, indicator plant species of the Ghaap Plateau preferred alkaline soil with high Ca: Mg ratios. In contrast, those of the Kuruman Hills are adapted to more acidic soils with high Fe content. A study conducted by Li et al. (2015) in subtropical China, revealed separation of indicator plant species across a pH gradient in combination with other environmental variables. Therefore, soil chemical characteristics can be considered as one of the most significant factors driving floristic composition across mountain ecosystems (Boneschans et al. 2015) and explain the preferences of indicator plant species associated with each mountain (Soares et al. 2015).

The Langberg was positively correlated with higher soil sand content. The Ghaap Plateau, as well as Kuruman Hills, were positively correlated with MAP and CEC (Figure 5). Indicator plant species of the Langberg, with its low MAP, high sand content and low CEC values, were separated clearly from other wetter and more nutrient-rich mountain systems (Figure 5). Plots of the Asbestos Hills were clustered intermediately between those of the Ghaap Plateau and Kuruman Hills. There is thus evidence of niche partitioning (Naaf and Wulf 2012) and a filtering effect (Franklin et al. 2013) for herbaceous indicator plant species across the nutrient- and rainfall gradient. The two drier and nutrient-poor systems (Langberg and Asbestos Hills) were predominantly characterized by perennial species of only two life form types (dwarf shrubs and grasses; Table 7). In contrast, the regions of higher rainfall and nutrients (Kuruman Hills and Ghaap Plateau), consisted of both perennial and annual indicator plant species comprising four life form types (dwarf shrubs, forbs, grasses, and sedges; Table 7).

Table 5. Spearman rank correlation (ρ) test of the highest-ranked and most diverse plant families. All correlations were significant ($p<0.05$). ** highest correlation; * lowest correlation.

	Asbestos Hills	Langberg	Kuruman Hills
Langberg	0.77		
Kuruman Hills	0.88**	0.66	
Ghaap Plateau	0.70	0.56*	0.72

Table 6. Jaccard similarity coefficient measuring the degree of similarity of plant species between sampled mountain systems. Values are expressed as percentages. ** highest similarity; * lowest similarity.

	Langberg	Kuruman Hills	Asbestos Hills
Kuruman Hills	31.2	-	
Asbestos Hills	34.4	38.2**	-
Ghaap Plateau	24.3	21.7*	34.6

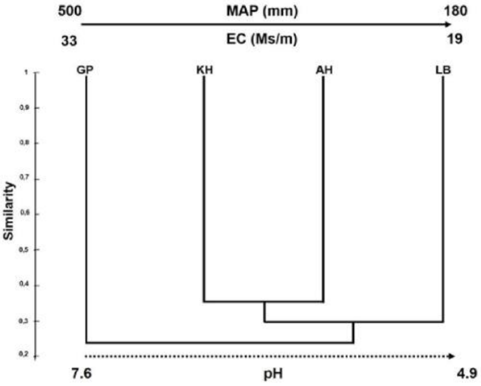

Figure 3. Dendrogram of Jaccard Similarity indicating the relatedness of each mountain ecosystem across the pH-, nutrient- and rainfall gradient. Clusters were based on presence and absence of sampled plant species.

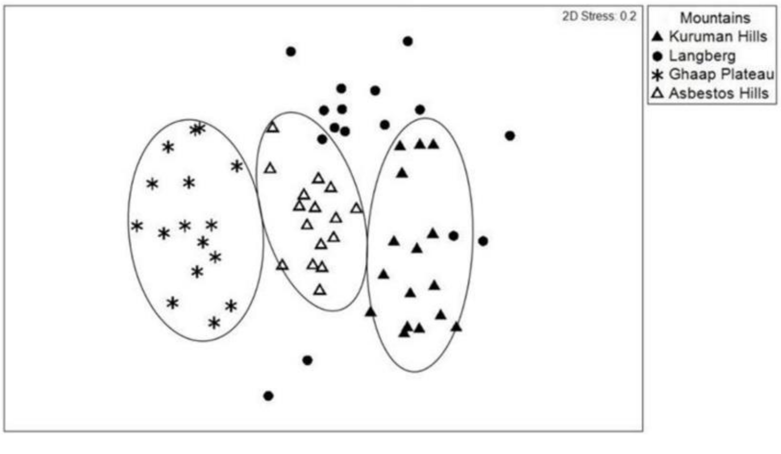

Figure 4. NMDS ordination of sampled sub-plots representing herbaceous species assemblages of the four mountain ecosystems.

Despite this study not following a trait-based approach, the larger variety of life forms and life history characteristics of indicator species associated with the Kuruman Hills and Ghaap Plateau, suggests that niches increase along a soil fertility and precipitation gradient (Schellenberger Costa et al. 2017). Since indicator species of wetter and more nutrient-rich habitats have more traits (i.e., different life forms and life histories), it can be ascribed to niche partitioning (Naaf and Wulf 2012). In contrast, nutrient-poor and drier mountains have indicator plant species with fewer traits (Wright et al. 2002; Shovon et al. 2020). Therefore, reduction of trait richness of indicator plant species in the drier Langberg and Asbestos Hills are ascribed to environmental filtering. Thus, these dominant traits provide species with competitive vigor and stress tolerance to persist in the associated extreme environmental conditions (Negreiros et al. 2014). This suggests habitat specialization of indicator plant species (Li et al. 2015).

Table 7. List of indicator plant species associated with each mountain as determined by indicator species analysis (Indval function of the labdsv package in RStudio).

Mountain	Family	Species	Indval	p-value	Frequency	Life history	Life form
Langberg							
	Poaceae	*Brachiaria nigropedata*	0.48	0.001	13	Perennial	Grass
	Convolvulaceae	*Evolvulus alsinoides*	0.44	0.001	7	Perennial	Dwarf shrub
	Poaceae	*Eragrostis nindensis*	0.32	0.019	14	Perennial	Grass
	Poaceae	*Eragrostis chloromelas*	0.2	0.037	6	Perennial	Grass
Asbestos Hills							
	Acanthaceae	*Glossochilus burchellii*	0.69	0.001	11	Perennial	Dwarf shrub
	Poaceae	*Tragus koelerioides*	0.59	0.001	21	Perennial	Grass
	Poaceae	*Aristida diffusa*	0.57	0.001	32	Perennial	Grass
	Poaceae	*Cymbopogon pospischilii*	0.54	0.001	28	Perennial	Grass
	Verbenaceae	*Chascanum pinnatifidum*	0.35	0.003	15	Perennial	Dwarf shrub
	Malvaceae	*Sida chrysantha*	0.32	0.007	11	Perennial	Dwarf shrub
	Malvaceae	*Corchorus aspelinifolius*	0.25	0.034	12	Perennial	Forb
	Lamiaceae	*Leucas capensis*	0.21	0.028	5	Perennial	Dwarf shrub
Kuruman Hills							
	Poaceae	*Diheteropogon amplectens*	0.81	0.001	13	Perennial	Grass
	Cyperaceae	*Bulbostylis hispidula*	0.67	0,001	15	Annual	Sedge
	Poaceae	*Cymbopogon caesius*	0.5	0.002	8	Perennial	Grass
	Euphorbiaceae	*Phyllanthus parvulus*	0.46	0.002	35	Perennial	Dwarf shrub
	Poaceae	*Brachiaria serrata*	0.45	0.001	14	Perennial	Grass
	Poaceae	*Elionurus muticus*	0.44	0.001	10	Perennial	Grass
	Asteraceae	*Pegolettia retrofracta*	0.32	0.003	7	Perennial	Dwarf shrub
	Verbenaceae	*Chascanuma denostachyum*	0.31	0.005	5	Perennial	Dwarf shrub
	Poaceae	*Anthephora pubescens*	0.31	0.008	17	Perennial	Grass
	Ebenaceae	*Euclea undulata*	0.19	0.046	3	Perennial	Dwarf shrub
	Polygalaceae	*Polygala hottentotta*	0.19	0.048	3	Perennial	Dwarf shrub
Ghaap Plateau							
	Cyperaceae	*Bulbostylis humilis*	0.3	0.001	25	Annual	Sedge
	Poaceae	*Enneapogon desvauxii*	0.69	0.001	11	Perennial	Grass
	Poaceae	*Fingerhuthia africana*	0.5	0.001	18	Perennial	Grass
	Oxalidaceae	*Oxalis depressa*	0.44	0.001	7	Perennial	Forb
	Poaceae	*Tragus racemosa*	0.44	0.001	7	Annual	Grass
	Euphorbiaceae	*Euphorbia inaequilatera*	0.42	0.002	14	Perennial	Forb
	Molluginaceae	*Limeum fenestratum*	0.38	0.002	6	Annual	Dwarf shrub
	Molluginaceae	*Limeum argute-carinatum*	0.34	0.003	7	Annual	Dwarf shrub
	Poaceae	*Eragrostis lehmanniana*	0.33	0.019	23	Perennial	Grass
	Cyperaceae	*Cyperus bellus*	0.31	0.002	5	Perennial	Forb
	Poaceae	*Oropetium capense*	0.25	0.008	4	Perennial	Grass
	Poaceae	*Eragrostis trichophora*	0.24	0.019	8	Perennial	Grass
	Poaceae	*Enneapogon scoparius*	0.19	0.045	3	Perennial	Grass

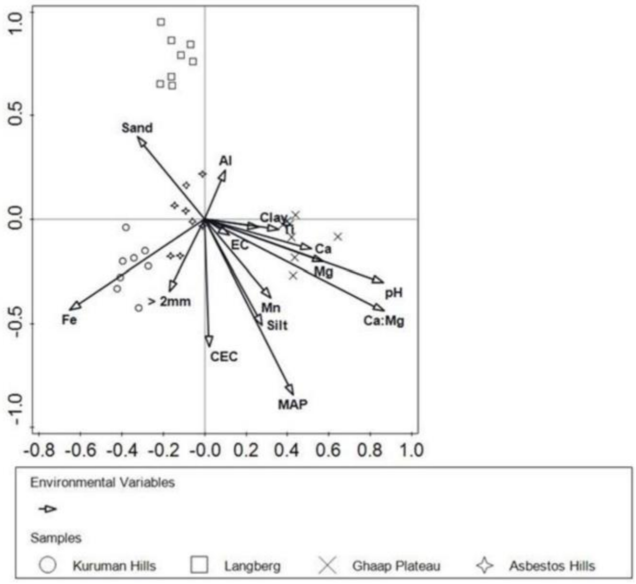

Figure 5. CCA biplot of indicator plant species per plot and associated environmental variables within each mountain system. Species included in the analysis are listed in Table 7.

Threatened and endemic species

The Ghaap Plateau hosted the highest number of GWC endemic plant species followed by the ironstone hills (See supplementary, Table A7). These findings are in accordance with several studies which revealed that limestone and dolomite (Ludwig 1999; Zietsman and Bredenkamp 2007; Mota et al. 2008), as well as banded ironstone (Gibson et al. 2012; Robinson et al. 2019) harbor high numbers of endemics. Six GWC endemic plant species (See supplementary, Table A7) can be considered narrow endemics since they are restricted to a single mountain range (Wild et al. 1963). Three of these restricted endemics were associated with the Ghaap Plateau that included a recently added species, *Nerine hesseoides* L.Bolus (See supplementary, Table A8), after an outlying locality was confirmed to be a different species. Two other endemics were associated with seasonal pans of the Ghaap Plateau. The ironstone hills harbor one narrow endemic, while the Langberg with its deeper, sandy soils harbors two species. Therefore, these plant species show an edaphic preference (Mason 1946; Rajakaruna 2004) and can be considered as rare (Stebbins 1942; Gaston 1997). Edaphic restricted endemic plant species may be prone to extinction (Harrison et al. 2009) due to low genetic variability (Stebbins 1942). Despite low genetic diversity, narrow resource use abilities and narrowed niche range (Gaston and Kunin 1997), these plants are highly specialized and thus edaphic specialists (Mason 1946; Anderson and Ferree 2010).

Eleven of the 24 GWC endemics were recorded during the field surveys. More commonly sampled endemics included *Blepharis marginata* (Nees) C.B.Clarke, *Calobota cuspidosa* (Burch.) Boatwr. & B.-E.vanWyk, *Glossochilus burchellii* Nees, *Searsia tridactyla* (Burch.) Moffett and *Tarchonanthus obovatus* DC. (Table 8). These endemic plant species are also associated with a wider distribution range within GWC and can be considered regional endemics (Cowling et al. 1994) with wider ecological niches compared to narrow endemics (Gaston and Kunin 1997). The random sampling approach of this study did not allow the targeting of rare species with patchy distributions and strict habitat specificity (Stohlgren et al. 2005). It is suggested that future studies must determine optimal sampling effort, sampling time and plot size to ensure more comprehensive data capturing of endemic species in GWC, especially at landscape scale (Zhang et al. 2014). By doing so, conservation efforts of endemic plant species can be promoted since all 24 endemic plant species are of conservation concern, irrespective that none of the endemics are currently regarded as endangered (South African National Biodiversity Institute 2019).

Table 8. List of GWC endemic plant species, number of individuals recorded during Modified-Whittaker plot surveys, mountains where it is known to occur, number herbarium QDG records and Red List category. AH-Asbestos Hills; GP-Ghaap Plateau; KH-Kuruman Hills; LB-Langberg.

Family	Taxon	Individuals recorded	Mountains	QDG records	Category
Acanthaceae					
	Barleria media	-	GP, KH	4	Vulnerable
	Blepharis marginata	51	AH, GP, KH, LB	12	Least concern
	Glossochilus burchellii	56	AH, GP, KH	10	Least concern
	Justicia puberula	4	GP, KH, LB	30	Least concern
Aizoaceae					
	Antimima lawsonii	-	AH, GP, KH	5	Rare
	Hereroa wilmaniae	3	AH, GP, KH, LB	15	Data deficient
	Lithops aucampiae subsp. *euniceae*	-	AH	2	Vulnerable
	Lithops bromfieldii	-	LB	4	Least concern
	Lithops lesliei subsp. *burchellii*	-	AH, GP	3	Near threatened
	Prepodesma orpenii	-	AH, GP, KH, LB	23	Least concern
Amaryllidaceae					
	Nerine hesseoides	-	GP	4	Least concern
Anacardiaceae					
	Searsia tridactyla	30	AH, GP, KH, LB	63	Least concern
Apiaceae					
	Deverra rapaletsa	-	GP	2	Not yet assessed
Asteraceae					
	Amphiglossa tecta	1	AH, GP, LB	3	Critically Rare
	Cineraria exilis	-	GP, KH	1	Data deficient
	Dicoma kurumanii	4	GP, KH	1	Least concern
	Eriocephalus ericoides subsp. *griquensis*	17	AH, GP, KH, LB	26	Least concern
	Gnaphalium englerianum	-	GP, KH	2	Least concern
	Pentzia stellata	-	GP	11	Near threatened
	Tarchonanthus obovatus	40	AH, GP, KH, LB	53	Least concern
Celastraceae					
	Maytenus ilicina	-	AH, GP, KH, LB	11	Least concern
	Putterlickia saxatilis	3	AH, GP, KH, LB	28	Least concern
Fabaceae					
	Calobota cuspidosa	23	AH, GP, KH, LB	45	Least concern
Poaceae					
	Brachiaria dura var. *pilosa*	-	LB	4	Data deficient

Note: QDG's were obtained from BODATSA (Ranwashe 2019). Categories for threats were based on the National Red List (South African National Biodiversity Institute 2019).

In conclusion, this study refined the borders of GWC which enabled the floristic description of the four, endemic-rich mountain landscapes within these new borders. These borders were based on an ecological model, which was constructed using presence and absence records of GWC endemics and environmental parameters. Distribution patterns of endemics were restricted to certain mountain landscapes and geologies which allowed for refinement of the model.

A clear soil fertility and rainfall gradient was identified for the GWC and, subsequently, each mountain flora was associated with different family- and species diversity, and composition. All four mountain landscapes were dominated by the Asteraceae, Fabaceae Malvaceae and Poaceae. Furthermore, the Scrophulariaceae dominated on the mountains of lower rainfall that are nutrient-poor (Langberg and Asbestos Hills), whereas the Cyperaceae were prominent on the two mountain systems of higher rainfall and which are more nutrient rich (Kuruman Hills and Ghaap Plateau). Indicator plant species explained the compositional differences since each mountain ecosystem was characterized by habitat specialists adapted to prevailing edaphic and climatic conditions. Primary drivers of the distribution of indicator species were soil pH, Ca: Mg ratios and rainfall. These drivers contributed to niche partitioning and environmental filtering (dry and nutrient poor *vs.* wet and nutrient rich).

From a conservation perspective, future botanical studies, and conservation and management strategies, should focus within the refined borders of GWC. The mountains are hotspots of endemics in GWC and should be considered as conservation priority areas. Especially the Ghaap Plateau and the ironstone hills since these systems harbour most of the GWC endemics. Special attention should be given to narrow endemic plant species with restricted distributions within GWC's borders as well as those species having a category of threat.

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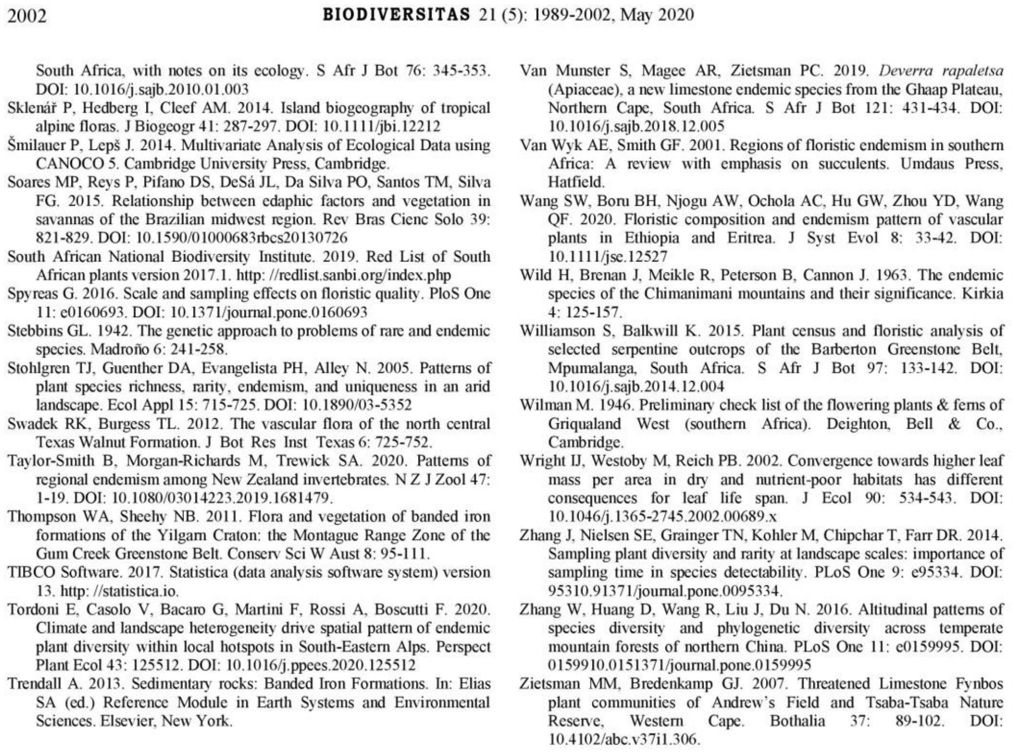

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