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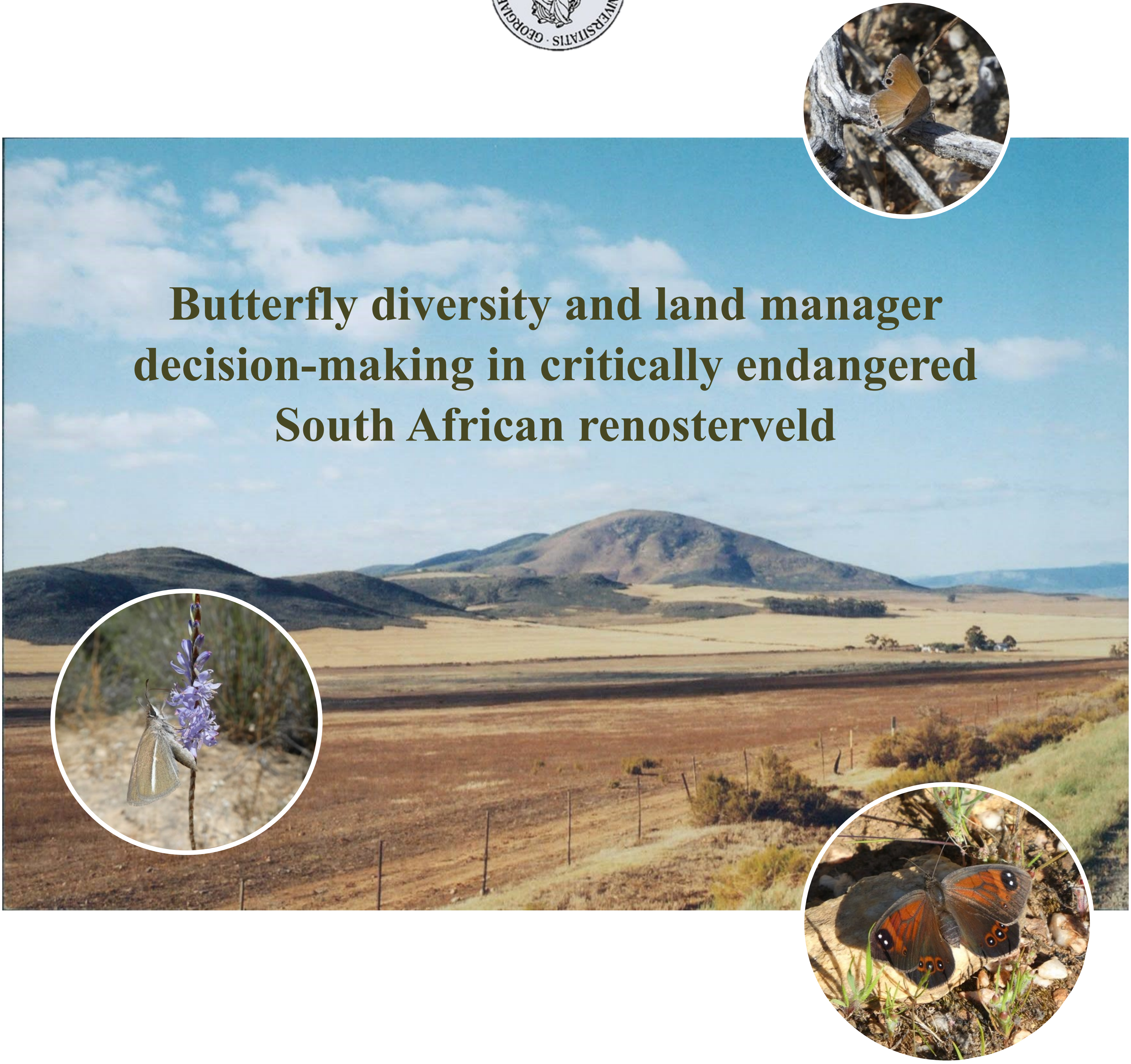

Butterfly diversity and land manager decision-making in critically endangered South African renosterveld

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Butterfly diversity and land manager decision-making in critically endangered South African renosterveld

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Summary

Addressing global biodiversity loss requires understanding complex human-nature relations. This is imperative in global biodiversity hotspots, areas that contain exceptional endemism and have lost significant amounts of natural habitat due to anthropogenic activities. In these areas, this understanding can be advanced through the assessment of both ecological and social components of the landscape. One such area is the Cape Floristic Region (CFR), which contains one of the most critically endangered ecosystems in South Africa: renosterveld. Renosterveld is a native fire-prone shrub-scrub ecosystem that has been extensively transformed to commercial agriculture in South Africa's Western Cape. Remaining renosterveld fragments are mostly in private ownership on areas which cannot be cultivated. These fragments foster remarkable biodiversity, primarily endemic plant diversity, but also insect diversity, including butterfly communities. This interdisciplinary thesis focuses on both ecological aspects, specifically butterfly diversity, and social aspects, including the decision-making context and climate change adaptation by land managers, of the agricultural landscape containing remnant renosterveld.

This thesis consists of six chapters including an introductory framework chapter and five original scientific manuscripts. In an introductory chapter (Chapter 1), I first introduce the thematic setting of the thesis, the study region, research questions and disciplinary approaches, along with more detailed chapter syntheses. I then provide a systematic literature analysis of renosterveld ecology and conservation (Chapter 2), where I synthesize renosterveld ecology and identify threats, barriers and recommendations for conservation. In the following two chapters, I present empirical studies into butterfly and vegetation responses to local and landscape variables in remaining renosterveld fragments among intensively managed agricultural land. In Chapter 3, I find that flower species richness and microhabitat type impact butterfly species richness and abundance, and that fragment size is a key determinant of butterfly species richness across the landscape. In Chapter 4, I find that fire is a key driver of renosterveld vegetation and butterfly abundance, while landscape context is important for butterfly species richness. In Chapters 5 and 6, I present empirical studies into the decision-making context for land managers of renosterveld and land manager perceptions and adaptation toward climate change in this landscape. Through interviews with renosterveld land managers and application of the Intergovernmental Panel for Biodiversity and Ecosystem Services' conceptual framework, I identify different decision-making contexts for renosterveld and associated nature's contributions to people (Chapter 5). I also ascertain different external and internal influences on climate change adaptation among farmers in the CFR, including institutional factors and cognitive biases (Chapter 6).

In summary, the results of my thesis shed light on some of the complex ecological and social processes at play in remnant renosterveld. Within the renosterveld remnants themselves, local environmental drivers such as floral resource availability and landscape level drivers such as fire and fragment size influence butterfly communities. Management for renosterveld plant conservation, including prescribed burns, may benefit renosterveld butterfly conservation through regeneration of plant diversity and removal of dominant shrub from otherwise unmanaged remnants. Land managers express a multitude of values related to renosterveld, including intrinsic, instrumental and relational values. Together with perceived rules and held knowledge, these values create the social decision-making context for renosterveld. Renosterveld is perceived by land managers to provide regulating, material and non-material nature's contributions to people, including place-specific benefits such as flower collecting. Farmers with renosterveld on their properties perceive different levels of risk associated with climate change, and adaptation strategies differ between wheat and wine grape farmers. In a landscape where most remaining fragments of biodiversity-rich renosterveld vegetation are privately owned, my thesis provides important evidence for insect diversity in these remaining fragments, and reveals the social context and priorities for land managers as well as their perceptions of renosterveld, which can support the safeguarding of renosterveld in the future.

Chapters 2-6 are presented in the format in which they were accepted for publication in international journals.

All photos by EN Topp unless otherwise stated.

List of abbreviations

AIC	Akaike Information Criterion
ANOVA	Analysis of variance
CFR	Cape Floristic Region
GIS	Geographic information system
GLM	Generalized linear model
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
LEK	Local-ecological knowledge
NCP	Nature’s Contributions to People
NMDS	Non-metric multidimensional scaling
ORCT	Overberg Renosterveld Conservation Trust
SABCA	Southern African Butterfly Conservation Assessment
SALCA	Southern African Lepidoptera Conservation Assessment
SANBI	South Africa National Biodiversity Institute
TARA	Transformative Adaptation Research Alliance
VRK	Values, Rules, Knowledge

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Chapter 1

Introduction

Remnants of exceptional biodiversity in a transformed agricultural landscape

Remaining renosterveld on a hilltop near Piketberg, 2017

Introduction

Humans are directly responsible for more than 60% of global land change (Song et al. 2018), primarily through transformation of natural ecosystems to agriculture (Tilman et al. 2001; Foley et al. 2005; Chaudhary et al. 2016). This loss of natural habitat and alteration of land cover is causing a severe global decline in biodiversity (Sala et al. 2000). Biodiversity, which includes the diversity within and between species and ecosystems, is essential for human existence and quality of life (IPBES 2019). Thus, protecting biodiversity and producing food to feed a growing global population is one of the major challenges of the 21st century (Tscharntke et al. 2012). Global biodiversity targets made during the last decade include ensuring by 2020 that all areas under agriculture are managed sustainably to secure conservation of biodiversity (Convention on Biological Diversity 2010). Future global targets seek to further these aims, such as the United Nations 2030 Agenda for Sustainable Development, which includes the commitment to protect biodiversity, ecosystems and wildlife (United Nations, 2015).

Regions with particularly high levels of biodiversity, including high endemism, and where more than 70% of natural habitat has been lost, have been designated as global biodiversity hotspots (Myers et al. 2000; Brooks et al. 2002; Sloan et al. 2014). In these areas, the need for effective biodiversity conservation is vital to mitigate biodiversity loss. This includes appropriate management of remaining fragments of natural habitat. However, there are great discrepancies between protected remaining habitat and habitat conversion (Hoekstra et al. 2005). In order to meet global conservation targets, privately owned remaining natural habitat is increasingly in focus alongside state-owned protected areas (Shumba et al. 2020). Even informal protection can be as effective for sustaining biodiversity as formal protection on private lands (Shumba et al. 2020) and enhance the resilience and connectedness of protected area networks (De Vos and Cumming 2019). In agricultural landscapes, biodiversity can be protected by retaining remaining natural habitat and increasing overall farmland heterogeneity, which may support some native species (Fischer and Lindenmayer 2007; Fahrig et al. 2011). Retained natural habitat may also provide a multitude of functions and services which enhance the capacity of the agricultural landscape to meet the needs of society (e.g. Plieninger et al. 2013; Fagerholm et al. 2020). This may be described as the multifunctionality of a landscape.

Agricultural landscapes are social-ecological systems, where human society and ecological processes are highly interconnected (Martín-López and Montes 2015). Tackling global biodiversity loss requires building resilient social-ecological systems; in other words, systems which can withstand disturbances while maintaining their identity (Walker and Salt 2006; Folke et al. 2010). In order to enhance system resilience, it is essential to understand underlying ecological and social patterns and drivers. For example, the regulation of land use on an ecosystem affects biodiversity, and the provision of benefits from the ecosystem affects the social system (Cumming et al. 2005). Plural human values may also be considered as indirect or direct drivers of change in agricultural landscapes (Arias-Arévalo et al. 2017).

Study of social-ecological systems therefore requires assessing multiple factors at multiple scales (Ostrom 2009). One factor may be the ecosystem, which can range from study at the local scale to the landscape scale. Another may be the knowledge of the ecosystem and the importance of the ecosystem to the user, (Ostrom 2009), which can be studied at the individual scale or the collective societal scale. In this thesis, I take a social-ecological systems lens to consider these specific factors within an agricultural landscape. My aim is to provide insights into biodiversity, specifically butterfly diversity, and the social decision-making context for land management of a highly threatened ecosystem in the Cape Floristic Region, a global biodiversity hotspot.

Study area

The Cape Floristic Region (CFR) is located on the southwestern tip of South Africa (Fig 1) and is renowned for its exceptional plant diversity, with over 9000 plant species found in native ecosystems such as fynbos (Goldblatt and Manning 2002), of which 70% are endemic (Linder 2005). Despite being relatively small in geographic area compared to other biodiversity hotspots (78, 555 km^2), the CFR has been designated a unique floral kingdom (Bergh et al. 2014) and is also recognized as a Centre of Plant Diversity and Global 200 Ecoregion (Olson and Dinerstein 2002). As well as plant diversity, the CFR is recognized for high faunal diversity including insects and birds (Grant and Samways 2007; Lee and Barnard 2016). The CFR contains five distinct natural vegetation types: Fynbos, Renosterveld, Subtropical thicket, Succulent karoo, and Forest types (Bergh et al. 2014). Estimates for remaining intact natural vegetation in the region vary between 20% and 32.9% (Sloan et al. 2014). Agriculture, urbanization and the spread of invasive alien plants have been the major drivers of habitat loss (Rouget et al. 2003) and viticulture expansion may also place additional pressure on remaining habitat (Fairbanks et al. 2004), which may be exacerbated by climate change (Hannah et al. 2013). Both formal and informal conservation agreements following conservation programs have contributed to CFR habitat protection, both for flora and some fauna such as mammals (Clements et al. 2019). However, meeting regional and global conservation goals such as those laid out in the Aichi targets is going to take longer than previously hoped (Von Hase et al. 2010).

One of the distinct vegetation types belonging to the CFR and to the fynbos biome is renosterveld. Renosterveld is a fire-prone shrubland found on relatively fertile, fine-grained soils (Bergh et al. 2014), distinguishing it from fynbos vegetation, which is found on more nutrient-poor soils. Broadly speaking, renosterveld is composed of semi-succulent, fine-leaved evergreen shrubs, a grassy layer and a high proportion of geophyte species (flowering bulbs). While there is debate over whether renosterveld can be considered a grassy shrubland or shrubby grassland (Curtis 2013), West Coast renosterveld generally contains more bulbs, whereas South Coast renosterveld contains more grasses (Krug 2004), making it more palatable for grazing. Similar to other Mediterranean-type biodiversity hotspots, fire is a strong driver of vegetation change in the CFR. Renosterveld is fire-adapted, with an estimated historic fire return interval (FRI) of 3-5 years, although for plant conservation, FRIs of 10-15 years are recommended for coastal renosterveld (Kraaj and van Wilgen 2014). Due to extensive conversion to agriculture, less than 10% remains of West Coast renosterveld (Newton and Knight 2010), making it one of the most critically endangered habitats in South Africa. More in-depth discussion of fragmentation, threats and conservation of renosterveld is the focus of the first part of the thesis and can be found in Chapter 2.

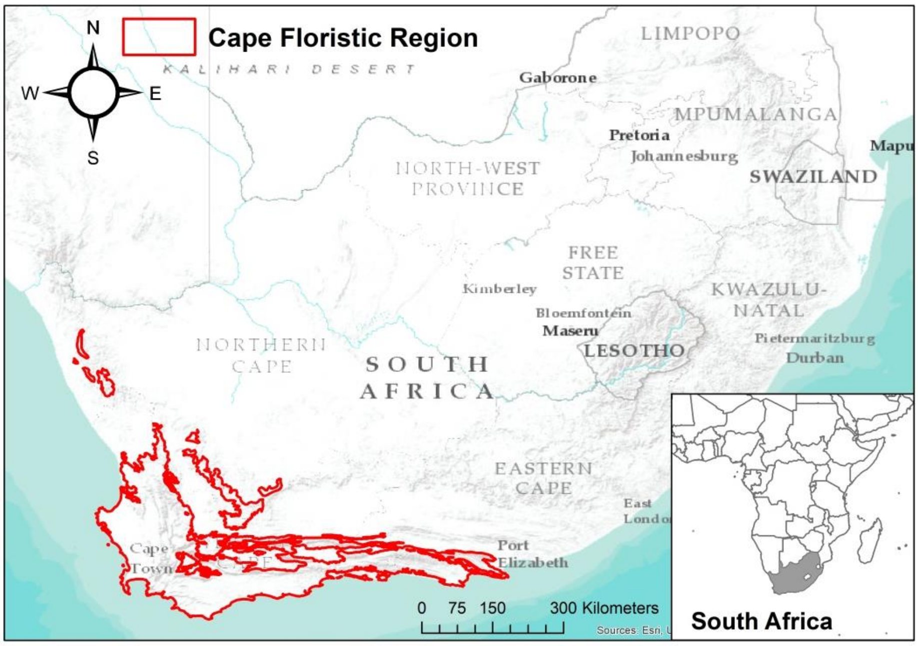

Figure 1: The Cape Floristic Region shown in red in the south-west of South Africa. The region covers the majority of the Western Cape province and extends partially into the Eastern and Northern Cape provinces.

One of the regions where most renosterveld has been converted to agriculture is the Swartland of South Africa's Western Cape, with less than 3% renosterveld remaining (Newton and Knight 2005a). Remaining renosterveld is highly fragmented, with isolated patches left in areas which are difficult to cultivate due to steep slopes or stony soils, and surrounded by homogenous, highly intensively managed grain and fruit farms (see Plate, Photo 1-2). Farms are mostly owned by white Afrikaans-speaking farmers of European descent. The most farmed crop is wheat, alongside other grains such as oats and barley, vines for wine and table grapes, and to a lesser extent, other fruit and vegetable production (e.g. nectarines, see Plate, Photo 6). Livestock farming including cattle and sheep is also common. Indeed, the region is one of the most important for South African agriculture, wherein remaining fragments of renosterveld are subject to different management. While some fragments are designated reserves, and may be state or privately managed, most renosterveld fragments are on privately owned farmland and are not managed for biodiversity conservation. Identifying the factors influencing decision-making of Swartland land managers is key to understand priorities and challenges for those responsible for renosterveld and support appropriate management of remaining fragments.

While habitat loss is well documented in the region (e.g. Newton and Knight, 2005b), and the implication of this fragmentation on plant diversity is known to some extent (e.g. Donaldson et al., 2002), the implications for insect diversity, including butterfly diversity, is less well known. Butterfly species are not as numerous in the fynbos biome as in other regions in South Africa. The average number of species one can expect to see in fynbos and renosterveld is 7-11 per day compared to 31-55 in savanna or forest biomes (Dobson 2018). Knowledge on the role of renosterveld remnants in the agricultural landscape and related environmental drivers such as fire is limited for insect diversity (Procheş and Cowling 2006). Historically, the Swartland has hosted endemic butterfly species such as the Moorreesburg Common Opal (*Chysoritis thysbe schloezae*) and Dickson's Brown (*Stygionympha dicksonii*) which have been classified endangered and have not been recorded since 2009 (Southern Africa Lepidoptera Conservation Assessment, 2017).

Methodological approach

Given that the Swartland is a complex social-ecological system, I have used both ecological and social science methods to address my research questions (Table 1). To investigate butterfly diversity I conducted field surveys using commonly practiced transect methods (Pollard 1977) adapted for the local landscape context (Terblanche and Edge 2011). This enabled me to make landscape-wide butterfly diversity records and check for endangered species. I used widely applied ecological statistical methods, including linear modelling and ordination, on spatial and survey-derived data to assess the effects of environmental drivers on renosterveld butterfly diversity. Butterflies show responses to landscape composition and configuration (e.g. Kormann et al., 2019; Krauss et al., 2003; Loos et al., 2014), they are relatively easy to identify and demonstrate different traits, such as mobility and resource preferences, thus are therefore a suitable taxon for investigating landscape wide biodiversity.

For my research questions on land-use decision making, I conducted semi-structured interviews with land managers for data acquisition. Using interviews provides advantages over, for example, surveys, in that it allows for contextualization of land-use decision-makers' responses (Soubry et al. 2020). For analysis of my interview data I chose to use conceptual frameworks emerging from social-ecological research disciplines. Conceptual frameworks can help us understand and perceive the relational between humans and nature. One example is to consider that the life support system provided by biodiversity consists of material (e.g., food), non-material (e.g., recreation experiences) and regulating (e.g. soil protection) services, which can be described collectively as Nature's Contributions to People (NCP)

(Pascual et al. 2017; Díaz et al. 2018). This framework is developed by IPBES and builds on the concept of ecosystem services to incorporate relational values, inclusive language and framing, and a context-specific perspective for nature assessments (Kadykalo et al. 2019).

Table 1. Overarching research questions for each chapter and corresponding methods used in this thesis.

Thesis chapter	Overarching research question	Main methods
2	What is the current state of knowledge on renosterveld ecology and conservation?	Systematic literature mapping
3	To what extent do local and landscape level variables influence butterfly diversity in critically endangered renosterveld?	Field surveys, linear modelling and multidimensional scaling
4	To what extent does fire and landscape context influence butterfly diversity in remaining renosterveld fragments?	Field surveys, linear modelling and multidimensional scaling
5	What interplay of values, rules and knowledge underpins decision-making for renosterveld, and what are the related Nature's Contributions to People (NCP)?	Semi-structured interviews and qualitative content analysis
6	How do farmers perceive climate change and what are the factors influencing climate change adaptation in South Africa's Western Cape?	Semi-structured interviews and qualitative content analysis

In addition to the IPBES framework, I adapted the Transformative Adaptation Research Alliance (TARA) approach which consists of the values-rules-knowledge (VRK) perspective. This perspective helps to identify aspects of societal decision-making concepts (Colloff et al. 2017). Essentially, decision-makers for land management are often constrained or supported by specific VRK. Embedded into the VRK perspective is a plurality of values approach, whereby an individual's valuing of nature includes not only intrinsic and instrumental values but also relational values (Chan et al. 2016; Arias-Arévalo et al. 2017). Relational values refer to relationships between humans and nature which are not instrumental and can be held by individuals, unlike cultural values which may be shared collectively (Chan et al. 2018). Plural value assessments are gaining traction through initiatives such as the IPBES global assessments, as nations try to reach global conservation targets and find ways to address the global biodiversity crisis. Relational values in particular are emerging as means to define human relationships with land in agricultural systems, and offer: "a nuanced perspective that can deepen our understanding of farmer values and subsequent decision making" (Allen et al., 2018, p1).

For the analysis of interview data related to climate change, I adapted a commonly used conceptual framework specifically addressing influencing factors on climate change adaptation behaviour (Grothmann and Patt 2005). These factors include internal factors, such as risk perception, and external factors which act as barriers or support to adaptation. I combined this framing with the identification of implemented strategies to address climate change and set this in the wider context of the Swartland social-ecological system. Below I synthesize the findings of each investigation presented in this thesis.

Chapter syntheses

Systematic literature mapping can give overviews of an evidence base by describing scope and focus of relevant studies, thereby identifying knowledge gaps and research needs (Bernes et al. 2015). This is particularly important for supporting environmental decision-making (Pullin and Knight 2009; Fardila et al. 2017). In Chapter 2: *Fragmented landscape, fragmented knowledge: A synthesis of renosterveld ecology and conservation*, I map and synthesize the state of knowledge on renosterveld ecology and conservation. Based on systematic searches of scientific literature, I assessed 132 relevant studies and identified the key threats to renosterveld, the barriers to and recommendations for its conservation. I found that the majority of articles focused on plant ecology as opposed to other taxa and many studies took place in larger, more intact and often protected renosterveld fragments, which means that the contribution of privately owned renosterveld fragments to biodiversity and ecological processes is largely unknown. I conclude that conservation implementation in the CFR is piecemeal and citizen science is a promising solution to some barriers.

In Chapters 3 and 4 I conducted empirical studies into the role of remaining renosterveld fragments for butterfly diversity. In Chapter 3: *Local and landscape level variables influence butterfly diversity in critically endangered South African renosterveld*, I quantified the influence that local level environmental variables, such as floral abundance and microhabitat, and landscape level environmental variables, such as fragment size and adjacent crop type, have on butterfly diversity in renosterveld remnants among an intensively managed agricultural landscape. The majority of butterfly surveys took place on privately owned farmland, providing insights into the role of these remnants for supporting biodiversity. I found that flower species richness and microhabitat type impact butterfly species richness and abundance and patch size is a key determinant of butterfly species richness across the landscape. In Chapter 4: *Fire and landscape context shape plant and butterfly diversity in a South African shrubland*, I specifically focused on fire as an ecological driver and investigated the effect of fire alongside landscape context on renosterveld plant and butterfly diversity. I found that fire drives plant diversity and structure in renosterveld remnants, which are important factors for butterflies (Pywell et al. 2004). Lack of fire is correlated with lower butterfly

Plate Photos 1-2: Renosterveld remnants on the upper slopes of wheat fields. Photo 3: Spring flowering in a lowland, overgrazed renosterveld remnant with almost no shrub layer. Photo 4: Protea Emperor butterfly (*Charaxes pelias*). Photo 5: Farmers burning the wheat stubble in a field adjacent to remaining renosterveld. Photo 6: Checking the quality of nectarines following an interview with the farmer at one farm with mixed production including fruit, livestock and wheat. Photo 7: Joining the farmers for wheat harvesting. Photo 8: A yellow airplane (background) sprays a mix of fungicide and pesticide onto young wheat in front of the sheep shearers' pen, next to a large, recently burned renosterveld remnant on the hillside. All photos E.Topp species abundance and the landscape level, while the amount of natural habitat in the landscape surrounding the focal remnant is also important for butterfly species richness. High mobility butterfly species appear to be more associated with renosterveld remnants with a longer time since previous fire, and linear modelling suggests that low mobility species and habitat specialists are more likely to be negatively affected by lack of regular fire. I conclude that sensitive management of renosterveld remnants with fire would benefit not only renosterveld plant but also butterfly diversity, and there are opportunities to implement this alongside existing agricultural practices in the CFR.

In ascertaining important ecological drivers for renosterveld diversity it is possible to make recommendations to land managers for renosterveld conservation. However, successful conservation depends upon the decisions of land managers. Renosterveld conservation is often not a priority of farmers in the CFR, who have historically viewed this ecosystem as 'uitvalgrond' [Afrikaans] or 'waste ground' and either left unmanaged any remaining renosterveld which was not previously cleared or used it to graze livestock in fallow periods, when pasture is not available. Chapter 4 presents a qualitative investigation into the factors underpinning land manager decision-making in the context of renosterveld: *Decision-making for nature's contributions to people in the Cape Floristic Region: the role of values, rules and knowledge*. I interviewed 30 land managers across the Swartland who had renosterveld remnants on their land to reveal their held values, rule and knowledge (VRK) types. I then clustered these VRK into three decision-making narratives, Bottom-up Conservation, Top-down Conservation and Utility, each of which corresponded with different NCP derived from renosterveld. I found that a Bottom-up conservation narrative is associated with non-material NCP, such as family ties, and unique relational values, such as sense of place. All narratives are associated with regulating values, such as soil protection, contributing to evidence that stakeholders identify intangible benefits from landscapes (Martín-López et al. 2012). The prevalence of relational values reveals the rich ongoing interactions between renosterveld biodiversity and people, and determining perceived NCP reveals the multifunctionality of remaining renosterveld fragments in the agricultural landscape.

Successful renosterveld conservation is not the only challenge facing land managers and farmers in the CFR. Climate change is a powerful threat to current farming practices and its effects are already clear in South Africa's Western Cape, which has recently seen extreme drought (2015-2017) that caused economic impacts through crop losses (Araujo et al. 2016; Archer et al. 2019). As they say often in the Swartland, "'N boer maak 'n plan" [Afrikaans], or "A farmer makes a plan". The fifth chapter of this thesis: *Farmers' perceptions of climate change and adaptation strategies in South Africa's Western Cape* is set in the climate change adaptation and risk perception literature and deals with Swartland farmers' perceptions and actions to address climate change. Through analysis of semi-structured interviews we found that farmers largely rely on technological approaches for handling climate change which often overlap with conservation agriculture approaches, and adaptation is influenced by exposure to impacts and cognitive biases. Farmers' strong perceptions of uncertainty regarding climate change impacts, and related strategies, have knock-on effects for rural livelihoods and the Swartland landscape.

Major findings

- Renosterveld is highly fragmented, faces a range of current threats, and the role for privately owned fragments to landscape-wide biodiversity is largely unknown. Renosterveld conservation implementation to date is piecemeal.
- Remaining renosterveld fragments in a commercially farmed landscape support butterfly populations. At the local scale, floral resources and microhabitat are important for renosterveld butterflies, and at the landscape scale, larger patches support more butterfly species, including habitat specialists.
- Fire is an important driver of plant and butterfly diversity in remaining renosterveld fragments, particularly butterfly abundance and low mobility species, whereas the amount of natural habitat in the surrounding landscape is more important for butterfly species richness.
- The social context for land manager decision-making for renosterveld can be grouped into three narratives: Bottom-up conservation, Top-down conservation and Utility, which are characterized by different values, rules and knowledge.
- Remaining renosterveld fragments are multifunctional, providing a diverse range of nature's contributions to people. These may be regulating, material or non-material, and can also be beneficial or detrimental.
- Relational valuing of renosterveld is prevalent among land managers.
- Farmers' adaptation to climate change in the Swartland is influenced by previous experience of climatic stresses, economic considerations and cognitive processes, including risk perception, perceived adaptive capacity and cognitive biases.

Concluding remarks

If I may give a personal perspective, I find that renosterveld is a complex ecosystem which is full of contradictions and surprises. Ecologically, the renosterveld is capable of sustaining many stresses, as it is full of plants adapted to drought, fire and grazing, which provide valuable resources for insects and other life in a challenging environment. Following long periods of succession and dormancy, fire can reveal multiple flowering species, which may be adapted to germinate or release seeds when exposed to heat and smoke. Despite its extremely severe fragmentation and the changes that are starkly visible across the landscape, each remaining fragment may contain unique plant species, even ones which have previously been thought extinct and have been rediscovered (Kemper et al. 1999; Cousins 2017). In terms of social systems, renosterveld has been largely devalued from a farming perspective, although it is used by a variety of stakeholders from different parts of society. Bluntly put, it is a tough ecosystem but full of beauty.

Another strong contrast is in the limited albeit growing knowledge that Western science has on this unique and ancient ecosystem compared to the highly efficient, intensive commercial farming which has taken its place. Some European farming landscapes have seen this type of farming for far longer than the relatively recently transformed CFR and therefore the edges between semi-natural habitat and farmland do not seem so severe. In the Swartland of South Africa, with vast fields of winter wheat or net-covered vines lapping at the edges of renosterveld fragments, on the one side is modernity, and on the other side, mystery. This makes determining the ecological value and nature's contributions to people of renosterveld all the more important.

And yet, the renosterveld is both ecologically and culturally a defining habitat of its region. The name 'Swartland' is derived from either the black-grey colour of the renosterveld from a distance, which conceals its multi-coloured array of flowers and insects seen at close-range, or to the black hide of the now-extinct black rhinoceros, which used to graze the area in pre-colonial times. The remaining fragments are important features of the agricultural landscape which provide a multitude of functions for its people and continue to support biodiversity, the like of which is not found anywhere else on Earth.

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Chapter 2

Fragmented Landscape, Fragmented Knowledge: A Synthesis of Renosterveld Ecology and Conservation

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Environmental Conservation (2019)
The final publication is available at:
https://www.cambridge.org/core/journals/environmental-conservation/article/fragmented-landscape-fragmented-knowledge-a-synthesis-of-renosterveld-ecology-and-conservation/6BBBB3D06DD6135B50827CE199661D67



L-R: Spider lily (*Ferraria uncinata*); recently burned renosterveld; Gladiolus (*Gladiolus alatus)*

Summary
Knowledge of ecological patterns and processes is key to effective conservation of biodiversity hotspots under threat. Renosterveld is one of the most critically endangered habitats in the biologically unique Cape Floristic Region, South Africa. For the first time, we map and synthesize the current state of knowledge on renosterveld ecology and conservation. We investigated 132 studies for the themes, locations and taxa of renosterveld research and the fragmentation, threats, recommendations and barriers to renosterveld conservation. More studies focused on plants than any other taxa (48% of articles) and are conducted mostly in larger intact renosterveld fragments. The most commonly identified threat to renosterveld was agricultural intensification; conservation recommendations spanned improved farming practices, formal protection and local patch management. Conservation implementation has been piecemeal and depended largely on the goodwill of landowners, which can be constrained by costs of conservation measures and a lack of suitable restoration means. Citizen science is a promising potential solution to some barriers. Fragmented knowledge in such a transformed and relatively densely populated region highlights the scale of knowledge gaps for other biodiversity hotspots and has implications for ongoing conservation work.

Keywords: Cape Floristic Region; Farmland expansion; Fire regime; Fragmentation; Fynbos; South Africa; Global biodiversity hotspot; Mediterranean ecosystem; Value perception.

Introduction
For more effective global biodiversity conservation, priority areas with high levels of habitat loss and endemism have been designated biodiversity hotspots (Myers et al, 2000). In total, these biodiversity hotspots contain more than 44% of the world´s plant species and 35% of its vertebrate species, in only 2.3% of the earth´s surface (Critical Ecosystem Partnership Fund, 2017). Despite their high conservation priority, only parts of these areas are legally protected, and implementation can be ineffective. Consequently, flora, fauna and ecosystem functions in biodiversity hotspots continue to suffer from habitat fragmentation and degradation through land use change, which is still the main cause of biodiversity decline globally, leading to half of all hotspots comprising 10% or less of their original natural habitat (Soulé 1991; Sala et al, 2000; Foley et al, 2005; Sloan et al, 2014). Effective conservation is underpinned by improved understanding of ecological patterns and processes at a landscape scale, including landscape composition and configuration (Fischer & Lindenmayer, 2007, Fahrig et al, 2011, Tscharntke et al, 2012). For biodiversity hotspots, it is thus vital to understand the state of knowledge at a landscape scale and identify possible barriers to furthering and applying this knowledge.

The Cape Floristic Region (CFR) in South Africa is recognized as a global biodiversity hotspot and contains some of the most transformed habitat in South Africa due to agriculture, urbanization and the spread of invasive alien plants (Newton & Knight, 2005a; Rouget et al, 2003b). Despite covering a relatively small geographic area (78,555 km^2), the CFR contains more than 9000 vascular plant species (Goldblatt & Manning, 2002), of which 70% are endemic (Linder, 2005; Giliomee, 2006), many of which are geophytes. Globally the region represents approximately 2% of all known plant species (Myers et al, 2000) and has high levels of faunal endemism, particularly reptiles, birds, amphibians and invertebrates, such as dragonflies and butterflies (Grant & Samways, 2007, Critical Ecosystem Partnership Fund, 2017). For these reasons, the region is recognized as a Centre of Plant Diversity, an Endemic Bird Area, and a Global 200 Ecoregion (Olson & Dinerstein, 2002). The exceptional biodiversity of the CFR is globally acknowledged, as is the serious need for conserving its threatened habitats and species.

Renosterveld is one of the most critically endangered habitat types within the CFR (Cowling & Heijnis, 2001; Rouget et al, 2003b, Newton & Knight, 2005b). While considered part of the fynbos biome, renosterveld differs from fynbos vegetation in that it occurs mostly on moderately fertile clay-rich soils, has a significant grass understorey, and shares few species with fynbos, although they often grow adjacent to one another (Goldblatt & Manning, 2002; Musil et al, 2005; Mucina & Rutherford, 2006), leading some authors to call for renosterveld to be recognized as a unique vegetation type rather than a subset of fynbos (Bergh et al, 2014). The richer substrate on which renosterveld occurs, and its largely accessible topography, makes it more prone to clearance for agriculture than fynbos (Cowling et al, 1986; Rouget et al, 2014), increasing the threat of transformation to this vegetation type over other habitat types in the CFR, with related consequences for fauna and flora (Fig S1A & S1B). Renosterveld contains the highest concentration of threatened plant species in South Africa, of which 25 are endemic to the Swartland shale renosterveld vegetation type (SANBI Red List, http://redlist.sanbi.org). Renosterveld ecology is subject to diverse ecological drivers, not only land-use change, but also fire, drought, grazing regimes and invasive species. These drivers may have individual as well as interacting effects on specific taxa, with related implications for conservation planning.

Given both the high endemism rate and the acute landscape changes in renosterveld (e.g. Halpern & Meadows, 2013), a synthesis of scientific understanding of its ecology and conservation to date is needed to inform targeted conservation measures. Here, we present the first systematic literature map and synthesis of renosterveld ecology and conservation. Systematic mapping allows for identification and collation of existing research but does not include analysis of collected data as in meta-analyses (McKinnon et al, 2016; Randall & James, 2012).We conducted our synthesis on two levels to cover both a broad overview and identify research gaps in this particular ecosystem through systematic mapping and, more specifically, generate a synthesis of the available scientific knowledge. Our first-level question asked: What are the dominant themes, taxa and locations of renosterveld research? Our second-level questions asked: What is known about the state of fragmentation in renosterveld; what are the principal imminent and general threats to it; what are the main recommendations for its conservation and what are the barriers to conservation? We thus synthesized the existing knowledge and identified gaps and potential wider implications for evidence-based conservation.

Material and Methods

We focused this synthesis on literature specifically relating to renosterveld. We define renosterveld as dense fire-prone shrubland, delineated in the following broad habitat units (BHU) outlined by Cowling and Heijnis (2001): coastal renosterveld, inland renosterveld and fynbos/renosterveld mosaic. While renosterveld relates to an ecological habitat type, we did not exclude any search results from outside ecological and environmental sciences. We did not impose any constraints on year or language of publication on the database searches. We searched two peer-reviewed publication databases: Elsevier´s Scopus and Thompson Reuters´ Web of Science, both of which cover natural and social sciences. The search term 'renosterveld' was applied in both databases on May 23 2017. We also searched both databases for the term 'renosterbos' which refers specifically to the species *Elytropappus rhinocerotis*, a shrub typically associated with renosterveld. Additionally, we included the first 50 hits from Google Scholar, excluding theses and citations. We added relevant additional articles that were cited in identified articles. Our search, while comprehensive, was not exhaustive.

All search results were exported into the bibliography software Mendeley and after exclusion of duplicates, subsequently exported to Microsoft Excel. We documented our procedure as recommended by Moher et al (2015) (Fig. 1). To address our first-level research questions, we examined the title and abstract of each search result to determine the research theme, study location, and studied taxa. All articles were assigned to one of 12 broad research themes (Table S1). If this information was not available in the title and abstract, we searched the full text. To address our second-level research questions, we read the titles and abstracts of each article to determine its relevance to the following themes of interest: fragmentation and landscape ecology, threats, and conservation. We rejected articles of these themes that were i) not specifically about renosterveld, but dealt with one or more of these themes at a national scale; ii) about characteristics or traits of a single species unless directly related to conservation. The resulting articles formed the basis for an in-depth qualitative analysis.

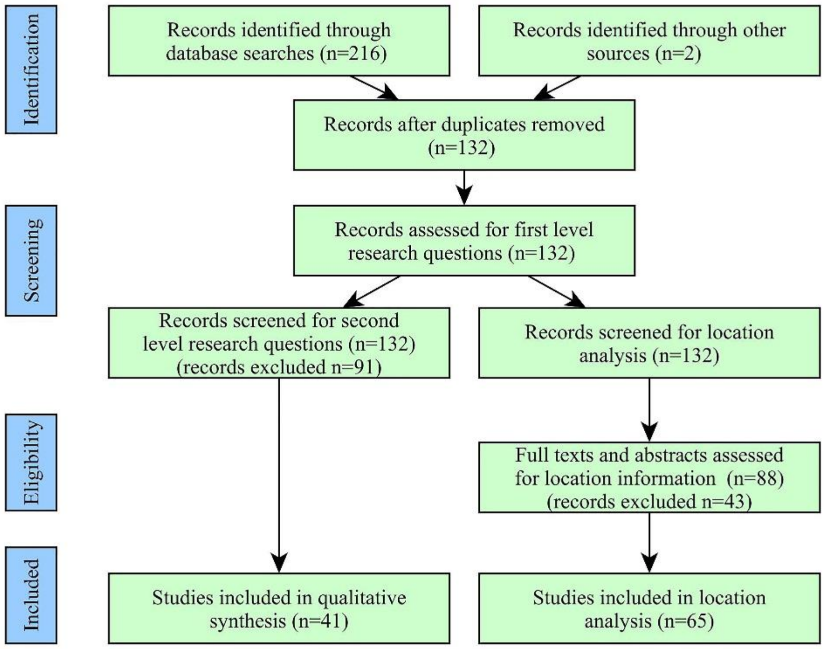

Figure 1: PRISMA literature search flow diagram. Adapted from PRISMA flow diagram (Moher & Liberati, 2009).

To map renosterveld study locations, we screened the titles and abstracts of all records and rejected those that were i) not within the CFR and ii) without geographical field sites. To further determine eligibility, we searched the full texts of the resulting records for location data, excluding i) studies using bird atlas data ii) historical or archeological study sites and iii) experimental studies. For every article with geographic information available, we collected study locations and mapped them as accurately as possible to give a broad indication of the spatial distribution of renosterveld studies. Information on fragment size was collected for those studies which intersected with existing fine-grain spatial data of fragments (von Hase et al, 2003).

First-Level Analysis

What are the dominant themes, locations and taxa of renosterveld research?

In the 132 articles that were relevant to the synthesis, the most popular research theme was plant ecology (n=35), followed by animal ecology (n=33) and botany (n=20). The majority of articles appeared in the journals *South African Journal of Botany* (n=20), *Biological Conservation* (n=7) and *Bothalia* (n=7); articles were published between 1981 and 2017. The number of publications increased after 2003, peaking in 2011 (n=16).

Renosterveld study sites showed a high concentration in the Cape Wineland and Boland municipal districts to the north east of Cape Town (Fig. 2). Of 136 total mapped locations, 70 were located within 60 km of Cape Town (51%). Coastal renosterveld appears to have been studied more than inland renosterveld and, in west coast renosterveld, clustered in larger fragments on the edges of the Swartland region. There have been fewer studies in the south coast renosterveld, where renosterveld conservation priority clusters are larger and more numerous. Of 65 mapped studies, 44 contained locations in protected areas (67%). Studied fragments ranged from less than one hectare to 4233 hectares in size (mean 393 ha).

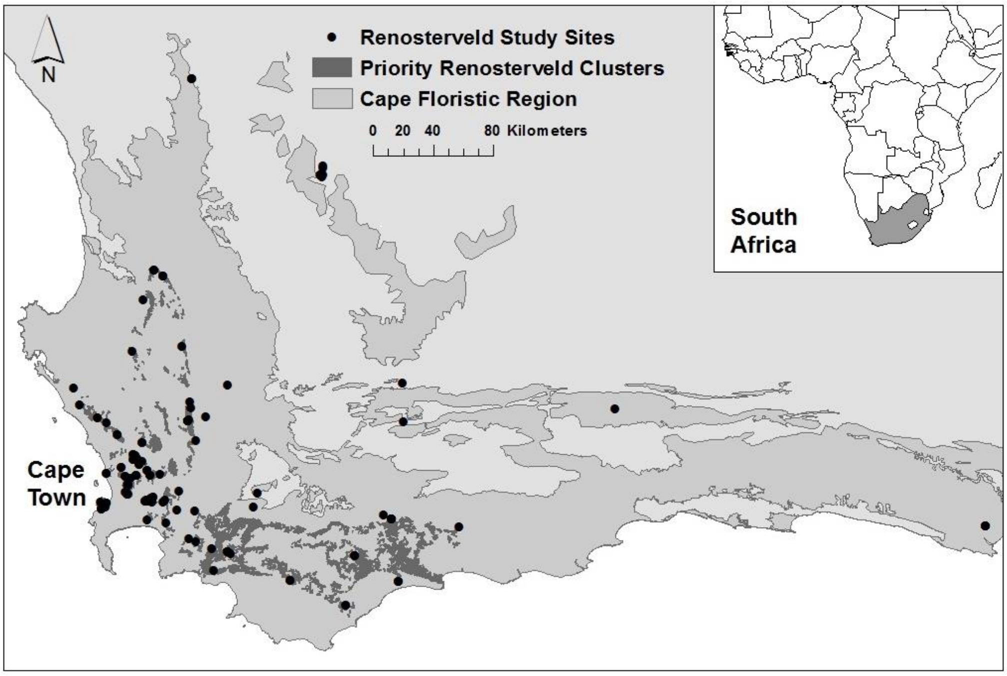

Figure 2: Regional distribution of renosterveld studies (n=65) within the Cape Floristic Region which investigated ecological phenomena with field study sites. Priority renosterveld clusters as mapped in the Cape Lowlands Renosterveld Project (von Hase et al, 2003) are shown in dark grey.

The most studied were plant communities (n=38), followed by individual plant species (n=25), together accounting for 48% of all study taxa (Fig. 3). The least studied taxa were reptiles, amphibians and birds (n<5). Invertebrates were the most highly studied animal taxa from all articles (n=16), although this included three articles from the same study identifying a new type of leafhopper (Theron, 1984a, 1984b, 1986). Other invertebrates studied included species of the gall midge, termites, longhorn beetle, springtail, oil-collecting bee, earthworm and pollen wasp. Seven articles studied invertebrates as part of ecological processes (Donaldson et al, 2002; Garnas et al, 2016; Leinaas et al, 2015; O’Farrell et al, 2010; Pauw, 2006; Pauw & Hawkins, 2011; Picker et al, 2007). Trophic interactions were studied for plant-pollinator relationships, such as between oil-collecting bees and geophytes (Coryciinae) (Pauw, 2006), and revealed that fragmentation does not necessarily limit pollinator diversity (Donaldson et al., 2002). Mammals were studied in relation to fire regime and seed dispersal in dung (Kraaij & Novellie, 2010; Shiponeni & Milton, 2006), but otherwise not at a community or trophic level. Nine studies considered direct effects of fire on renosterveld ecology and nine studied the impact of invasive species.

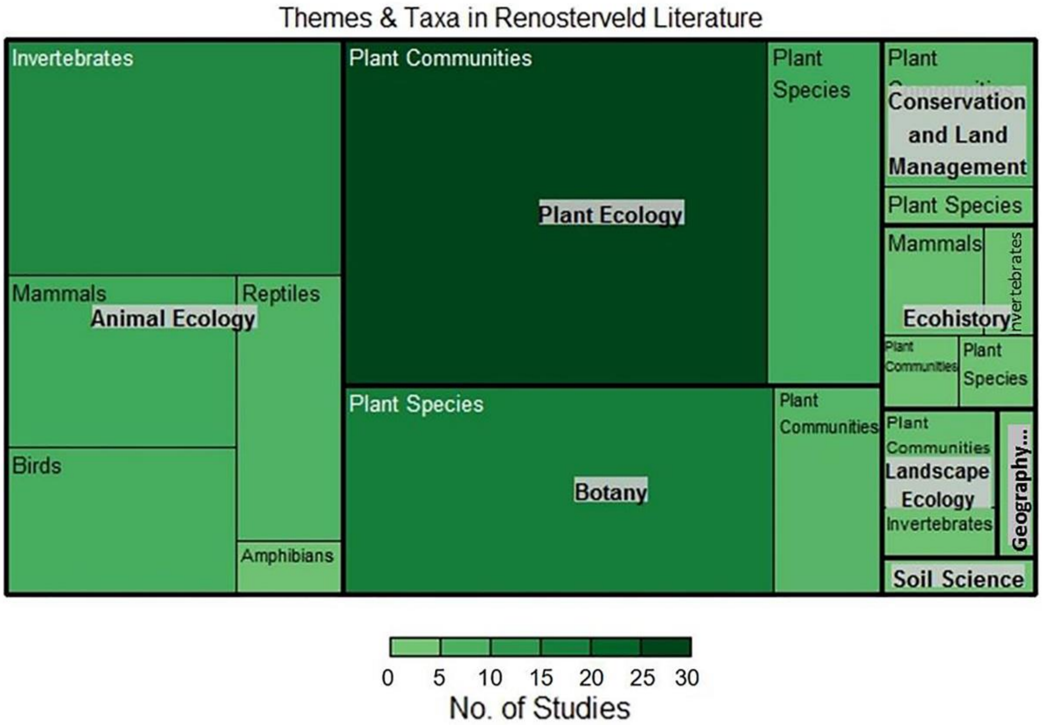

Figure 3: Renosterveld studies grouped by study taxa (labels in top left of boxes), and different research themes (in bold greyed text), as a proportion of all studies of taxa (n=101). Thick white lines distinguish between thematic groups. Size of box represents number of studies relative to total. Created using Treemap package, R Software (Tennekes & Ellis, 2017).

Second-Level Analysis

Of the 132 articles from our first-level analysis, we found 48 articles to be relevant for our second-level analysis. More of these articles appeared in the journals *Biological Conservation* (n=7) and the *South African Journal of Botany* (n=7) than any other journals. These 48 articles we were able to provide answers to our second-level research questions:

What is the state of fragmentation in renosterveld?

Renosterveld is a highly fragmented landscape, with only 15% of coastal renosterveld and 3% of West Coast renosterveld remaining (McDowell & Moll, 1992). In the Cape Lowlands region, less than 10% of original lowland renosterveld remains (Von Hase et al, 2003). In the Swartland, renosterveld cover changed from 11.23% in 1960 to 2.5% in 2010 (Halpern & Meadows, 2013). Of four regions of West Coast renosterveld studied by Newton and Knight (2005a), the Kapokberg region in the Swartland (33’24’54”S; 18’23’53”E) underwent the greatest transformation from 1938 to 2000, losing 47.6% of renosterveld vegetation. The lesser fragmentation observed in the South Coast renosterveld compared to West Coast renosterveld is likely due to its retention for grazing, owing to higher grass cover as a result of greater summer precipitation (Cowling 1984, cited in Kemper et al, 2000). The west coast renosterveld is not as palatable for grazing and thus has less direct value for agriculture than artificial grasslands. As a consequence, the majority has been transformed to arable land rather than pasture (McDowell & Moll, 1992). Topography is the strongest predictor for patterns of renosterveld loss

(Kemper et al, 2000). Remaining fragments exist on areas less suited to agriculture due to steep slopes and rocky soils. Most fragments in the Cape Lowlands region are less than half a hectare (Von Hase et al, 2003). Nonetheless, renosterveld fragments contain highly localized species and between fragments there is very high species turnover (Kemper et al, 1999; Newton & Knight, 2010). Such high heterogeneity of floristic composition among fragments suggests that loss of fragments in plains may lead to higher extinction rates than previously assumed, when larger hillside fragments are those most likely to be conserved (Newton & Knight, 2010).

Fragmentation in renosterveld produced more losers than winners. Fragmentation and agricultural intensification have been beneficial for some species such as the blue crane (*Anthropoides paradiseus*), which favours artificial grassland habitat (McCann et al, 2007). However, pollinators have been shown to be negatively impacted (Donaldson et al, 2002; Pauw, 2006), and abundance and species richness of petaloid monocotyledonous plants and ferns show edge effects (Horn et al, 2011). Even small renosterveld fragments (<1ha) may support vegetation that is similar to large fragments (>30ha) (Kemper et al, 1999) and do not always experience pollinator deficits (Donaldson et al, 2002). Other indigenous renosterveld plants, such as *Nemesia barbata*, did not show any correlation with fragment size or distance (Heelemann et al, 2014; Heelemann et al, 2015). Black harriers (*Circus maurus*) were found to be displaced from lowland renosterveld following transformation to cereal agriculture (Curtis et al, 2004). In general, severe implications stem from the loss of species diversity from such a unique global biodiversity hotspot due to land transformation drivers (Meadows 1998).

What are the principal imminent and general threats to renosterveld?

We identified threats and their frequency from the literature and grouped them according to four major types: socio-economic (n=29), biological (n=9), climatic (3) and attitudinal (n=6). Socio-economic threats included agricultural expansion for pasture and crops, which was the most commonly identified imminent threat to renosterveld overall (n=18). Other commonly identified socio-economic threats were urbanization and industrial expansion (n=8) with tungsten mining specifically identified as a more localized threat (Steiner, 2011). Invasive plant species such as Port Jackson willow (*Acacia saligna*) are the principal biological threat to South Africa, occurring particularly where land is already modified, such as road verges and agricultural lands, and their presence could impact rich renosterveld flora that attract visitors to the region (Musil et al, 2005). The biological threat of alien species converges with poor land management. For example, overgrazing changes the shrub species composition and deteriorates renosterveld (Kemper et al, 1999), allowing for the spread of invasive species and of hardy pioneer shrubs such as the kraalbos (*Galenia africana*) (Bengtsson et al, 2011).

Climate change is associated with serious risk to the entire CFR; for example, certain Proteaceae may lose all bioclimatically suitable range by 2050 (Midgley et al, 2002; 2003), predominantly through the lack of precipitation (Yates et al, 2010). Specific potential impacts of climate change on renosterveld were identified in the literature (n=4), particularly for invertebrates and associated ecosystem functions. For example, termite mounds play an important role in generating renosterveld species diversity and as a food source, and could be impacted by changing rainfall and vegetation patterns (Picker et al, 2007). Additionally, the great number of ant-dispersed plant species in the CFR are unlikely to be capable of migrating sufficiently quickly (Cowling et al, 2003; Newton & Knight, 2010). Climate change is also linked to fire and drought cycles, key natural drivers of environmental change in renosterveld. We found one study of renosterveld-fynbos diversity baseline data for monitoring climate change impacts, conducted on protected land (Agenbag et al, 2008). Although we did not find many very recent papers overall, Curtis et al (2013) state that the most prevalent ongoing threat to renosterveld remains illegal land conversion and poor land management. Despite legislation prohibiting ploughing virgin soils (Conservation of Agricultural Resources Act, 1983 Act 43 and the National Environmental Management Biodiversity Act of 2004), conversion continues to take place in areas outside of formal protection.

What are the main recommendations for conservation in renosterveld?

Recommendations for conservation of renosterveld can be grouped into four types: governance and formal protection, farming practices and incentives, renosterveld patch management and managing perceptions. Formal protection includes the recommendation to increase purchase of renosterveld by government, adding 52% of additional extant habitat to existing reserves, and reclassifying quartz shale renosterveld as critically endangered (Curtis et al., 2013) in order to meet conservation targets established by Cowling et al (2003). Our synthesis showed that large renosterveld fragments are more likely to be conserved legally, whereas in west coast renosterveld, where fragments are generally smaller than south coast renosterveld, fragments are largely in private ownership and unprotected (McDowell & Moll, 1992; McDowell et al, 1989; von Hase et al, 2003, 2010).

Recommendations for improvement of farming practices address both local threats, such as overgrazing, through well-managed grazing regimes for example, and also include large-scale strategies, such as the development of management plans to allow for coexistence of species in agricultural landscapes (Cowling et al, 1986; McCann et al, 2007). Agricultural expansion should take place in areas of former agriculture as opposed to areas of high biodiversity (Fairbanks et al, 2004), in order to achieve the vision of a biodiversity-friendly landscape posited by Giliomee (2006). Within renosterveld patches themselves, recommendations include managing for heterogeneity to increase pollinator richness (Donaldson et al., 2002), and enlarging Swartland shale renosterveld patches to more than 600m in width to avoid edge effects (Horn et al, 2011). Mills et al (2013) advocate for carbon credits as a means of incentivizing farmers to protect marginal agricultural land in renosterveld. In order to manage perceptions and address misconceptions, several authors recommend increased, careful engagement with landowners to enhance understanding of the value of renosterveld (Giliomee, 2006; McDowell et al, 1989; Winter et al, 2007).

The Cape Lowlands Renosterveld Conservation Project published a technical report on its conservation planning for renosterveld (Von Hase et al, 2003). Principal recommendations included avoiding transformation of all fragments in priority clusters and river corridors. Ecological processes and functions are incorporated into planning, with mapping of edaphic interfaces, riverine corridors, upland-lowland interfaces and habitat connectivity. This plan, along with the conservation plan for the CFR (Cowling et al, 2003), represents the most comprehensive conservation assessment of renosterveld ecology to date, with a goal of effective protection by 2020, in line with global Aichi biodiversity targets (https://www.cbd.int/sp/targets/), although it is likely to take much longer to implement than originally planned (von Hase et al, 2010).

What are the barriers to conservation of renosterveld?

The main barrier to conservation has been farmer attitudes to retaining renosterveld, which is not perceived as economically advantageous (McDowell et al, 1989; O'Farrell et al, 2009; Von Hase et al, 2010; Winter et al, 2005, 2007). The fact that most vulnerable fragments are in private ownership, albeit protected under national law, limits conservation activity. External 'structural' factors, such as financial pressures and government policies, are arguably the most influential factors deciding farmers' conservation behaviour (Winter et al, 2005). A prevailing notion is that financial responsibility for conservation should come from government, and while farmers have welcomed potential incentives, such as assistance with fencing and direct financial assistance, many are sceptical of these incentives being implemented (Winter et al, 2007). Lack of institutional capacity and collaboration between conservation agencies is another barrier to conservation (Cowling et al, 2003). Other barriers include high costs of conservation measures, such as removal of invasive species (Musil et al, 2005) and the costs and administrative burdens for fire management. Nonetheless, some landowners conduct controlled burns in collaboration with local authorities to reduce fuel load and promote regeneration of renosterveld (S. Cousins, Department of Conservation Ecology and Entomology, University of Stellenbosch, pers. comm).

Other barriers to conservation action include the lack of awareness of the importance of biodiversity (Cowling et al, 2003; Giliomee, 2006). Certain benefits of biodiversity on farmland, such as wild plant potential and biological pest control, are not experienced to a significant degree by farmers (Giliomee, 2006), although the benefit of maintaining ecological processes such as soil formation is acknowledged. Our mapping showed potential for restoration in targeted areas such as the Peninsula Shale renosterveld in Cape Town (Waller et al, 2015, 2016; Cowan & Anderson, 2014), but a lack of suitable measures for restoration of degraded renosterveld or integration of renosterveld with farming practices in the wider landscape (Fourie, 2014; Heelemann et al, 2012, 2013; Shiponeni & Milton, 2006). For example, native renosterveld species have been unsuitable as winter cover crops (Fourie, 2014) and artificial bird perches have been ineffective in enhancing seed dispersal and establishment in degraded renosterveld (Heelemann et al, 2012), thereby limiting the opportunities for farmers to perceive material benefits from retaining renosterveld.

Discussion

Renosterveld research is thematically and geographically biased, with notably less focus than other fragmented ecosystems worldwide, despite higher levels of habitat loss than other biodiversity hotspots (Geri et al, 2010; Sloan et al, 2014). For example, a rapid search for Mediterranean grasslands in scientific literature databases returned many more studies than we retrieved for renosterveld. Compared to other ecosystems in the CFR, such as mountain fynbos, renosterveld is more likely to be transformed and less likely to be protected, due to its occurrence on lowland fertile soils (Rouget et al, 2014). We find fragmented knowledge in both an overview of renosterveld studies to date and among the intricacies of renosterveld conservation. We discuss our findings according to our two-level analysis.

Themes, Location and Taxa

Plant ecology and botany are perhaps unsurprisingly the most studied research themes in renosterveld. The geographic clustering of studies in coastal renosterveld, close to Cape Town, and in larger fragments of greater connectivity, indicates that ecological knowledge on more isolated, smaller fragments is lacking. At the same time, proximity to urban areas makes these fragments more prone to resource extraction at unsustainable rates (Van Wilgen & McGeoch 2015). Fewer ecological studies have taken place in south coast renosterveld despite there being significantly more and larger remaining fragments, suggesting this region requires additional focus. Renosterveld has the smallest proportion of overall area covered by protected areas of any BHU in the CFR (Rouget et al, 2003a). We found that over half of ecological studies have taken place in protected areas, despite the majority of renosterveld falling outside of protected areas. This discrepancy creates gaps in knowledge; for example, all mammal studies in renosterveld took place inside protected areas, indicating that the role of privately owned renosterveld remnants for sustaining mammal populations is unknown.

It appears that research on renosterveld fauna is generally lacking as no single taxa was studied exhaustively (Giliomee, 2006; Von Hase et al, 2003). While invertebrates were the most highly studied fauna in our synthesis, the link between invertebrates and fragmentation in renosterveld is still unclear. Detailed information on the species richness, the distribution, the community composition, the habitat requirements and the patterns of faunal endemism of invertebrates in the CFR are still deficient (Colville et al, 2014).

Given these knowledge gaps, improved understanding of renosterveld-dependent fauna would be a key addition to a revised conservation assessment. To overcome resource limitations in terms of staff, time and money, citizen science can function as a key societal initiative that targets neglected organisms for research (Troudet et al, 2017), and can also target understudied locations, particularly unprotected areas. There are strong citizen science initiatives in the CFR for a wide variety of understudied taxa, such as Lepidoptera, mammals, fungi, Odonata, and arachnids (e.g. the Animal

Demography Unit Virtual Museum, University of Cape Town, www.vmus.adu.org.za). These initiatives offer a potential ‘way out’ of the problems of a lack of long-term monitoring on multiple small and large fragments, and address the lack of awareness of biodiversity by engaging communities and landowners. The resulting datasets from such initiatives offer opportunities for future scientific research, conservation, and science outreach (Silvertown, 2009; Braschler et al, 2010).

Fragmentation, Threats and Recommendations

Renosterveld plant diversity is relatively well understood, and plant diversity can act as proxy for other taxonomic diversity within the CFR (Kemp & Ellis, 2017). However, fragmentation studies demonstrate that renosterveld plant species can be highly localized, and therefore one renosterveld fragment cannot act as an ecological proxy for all others (Kemper et al, 1999). For such a fragmented landscape, renosterveld studies focused on fragmentation are surprisingly few (12% of all articles) and those that quantify and consider the qualities of surrounding land are limited. Both single large and many small fragments have been shown to promote landscape-wide biodiversity across taxa (Rösch et al, 2015) which increases the importance of studying individual fragments at a landscape scale. Fire and grazing regimes add complexity to fragmented renosterveld ecology and threats, such as climate change and invasive species, are also likely interlinked. Given the likelihood of increasing drought and fire occurrence in the face of climatic and human population changes in the CFR, a lack of knowledge on functional ecology could impede effective conservation. Thus, ecological studies on the responses of species to these drivers are needed.

Threats to renosterveld are both varied and persistent. Habitat loss is stark, and the current level of loss is uncertain (Rouget et al, 2014). While agricultural intensification is the most imminent threat, studies documenting the incentives and attitudes behind intensification are dated and there is little information on policy, governance structures or other socio-economic factors potentially acting as drivers. South African agricultural policy is set in a complex, shifting post-colonial context within which biodiversity conservation must be navigated (Crane, 2006). For renosterveld, arguably the most critically endangered habitat in South Africa (Newton & Knight 2005b), identification of policy tools and appropriately adaptive management strategies are crucial, particularly given diverse ecological drivers and threats. Adaptive management integrated with regional biogeographical knowledge is important for conserving large-scale production landscapes (Kay et al, 2016), such as the CFR, wherein the agricultural mosaic must be considered as a significant contributor to the compositional biodiversity of the region (Vrdoljak & Samways, 2014), and management plans are developed alongside landowners to allow for coexistence of species in these landscapes (McCann et al, 2007).

Landowner perception of lack of utility is one of the most important historical and current factors determining renosterveld conservation failure. We found only one article which explicitly investigated potential ecosystem services of renosterveld (O’Farrell et al, 2009), an approach which could address this lack of valuation. Erosion control is a particularly important ecosystem service, given the history in the Western Cape of severe erosion on agricultural lands (Giliomee, 2006). Control measures, such as contours, have been implemented on farmland following the Agricultural Resources Act of 1983. Winter et al (2007) found that erosion control was the fourth most important use of renosterveld to farmers in south coast renosterveld. Our review showed that pollinator networks have been studied to some extent in renosterveld and surrounding agricultural landscapes, although the use of pollination as an ecosystem service is limited as the monoculture crops grown in the CFR, primarily cereals (73% of land cover) and wine grapes (7% of land cover), do not require pollination by wild pollinators (Crop Estimates Consortium, 2017). Fragmentation does not necessarily limit pollinator diversity (Donaldson et al, 2002), and therefore, as farmers in the CFR potentially diversify in response to market demand and environmental changes, a wider variety of crops in the CFR may allow for a higher perceived value of renosterveld fragments as important pollinator sources. More studies involving direct landowner engagement and addressing farmer valuation of nature could provide collaboratively derived ideas for conservation which, matched with ecological knowledge, could help to meet detailed conservation targets, such as those laid by Cowling et al (2003), particularly as so many remaining fragments are privately owned. The unique and highly complex biological, evolutionary and socio-political history of renosterveld and the CFR contrasts with conservation elsewhere, such as in Europe, where political structures differ, and tools such as agri-environment schemes are more widespread (Crane, 2006; Vrdoljak & Samways, 2014). One key limitation is the capacity to attract external conservation investment. However, renosterveld managers may learn from other Mediterranean-type ecosystem hotspots, such as the Californias, where conservation easements target native species and habitats on private, working landscapes (Cox & Underwood, 2011); an approach which is implemented by the Overberg Renosterveld Conservation Trust (ORCT) in south coast renosterveld, with notable successes (www.overbergrenosterveld.org.za).

Articles focused on renosterveld conservation have not substantially increased since publication of the Cape Lowlands Renosterveld Conservation Plan in 2003, and many articles containing recommendations are already relatively dated (Von Hase et al, 2010). We recognize that only mapping scientific literature does not capture all conservation progress, particularly when many land stewardship agreements are informal (Von Hase et al, 2010). The loss of some nuance and detail is inevitable in a synthesis; however, we tried to capture the meaning or principal recommendations of all studies included. Despite comprehensive landscape-scale conservation assessments, conservation approaches are piecemeal, consisting of differently managed protected areas, farmer initiatives and NGO partnerships, such as the former Biodiversity and Wine initiative (https://www.sanbi.org/documents/biodiversity-and-wine-initiative-bwi/), which are constrained by external funding cycles. While the majority of the CFR falls under the Western Cape administration, policy and planning implementation is complex (Rouget et al, 2014). Current understanding of landowner attitudes, additional options for conservation and restoration of renosterveld within an adaptive, evidence-based approach remain priorities for future research.

Conclusion

We demonstrated that, to date, renosterveld articles contain thematic, spatial and taxonomic biases. Ecological understanding of the effect of fragmentation on renosterveld is limited and lacks insights from long-term observations. Renosterveld remnants continue to be at risk and conservation targets are not being met (von Hase et al, 2010). The impact of threats on much existing renosterveld is unknown; therefore, continued research efforts are necessary, particularly on smaller, understudied fragments, as is continued, creative engagement with landowners to reshape attitudes toward renosterveld.

The gaps identified in our understanding of renosterveld have implications for the wider comprehension of biodiversity hotspots. Renosterveld exists in a relatively densely populated and highly transformed area of global biological significance, with existing citizen science initiatives. In contrast, limited ecological understanding of other highly biologically diverse, more sparsely populated regions could impact our capacity to effectively conserve these ecosystems and potential associated ecosystem services. Due to converging land-transformation drivers, Mediterranean and grassland ecosystems are considered the most threatened ecoregions in the world (Sala et al, 2000). Systematic mapping of ecology and conservation knowledge, including threats and barriers to conservation, for these regions and other biodiversity hotspots could similarly identify preferences, gaps and research priorities of value to researchers and conservation practitioners.

Supplementary material

Fig S1A: Wheat farming extending up slope into renosterveld, Swartland, South Africa. Distance from viewer to first contour approximately 180m. **Fig S1B:** Wheat fields surrounding renosterveld fragment on hilltop, Swartland, South Africa. Distance from viewer to hilltop renosterveld fragment approximately 3km. Photos: E. N. Topp 2017.

Table S1: Frequency and definitions of research themes as found in the systematic literature synthesis.

Research Themes	Definition of theme (unless evident)	Frequency
Plant Ecology	Plant distribution, abundance, community structures, interactions with other organisms or communities	35
Animal Ecology	Wildlife, faunal studies, vertebrates, invertebrates, interactions with other organisms	33
Botany	Specific plant species characteristics, plant biology, new species	20
Conservation and Land Management	Land planning and management, socio-economic studies, conservation targets	18
Landscape Ecology	Fragmentation studies, landscape-scale studies	11
Ecohistory	Broad term to incorporate types of environmental history, including paleobiology, archaeology, geochemistry, historical biogeography	9
Soil Science	-	3
Geography and Hydrology	-	2
Information Technology	Modelling studies, innovative technologies	1
Total		**132**

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Conflict of Interest
None

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Chapter 3

Local and landscape level variables influence butterfly diversity in critically endangered South African renosterveld

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L-R: Cape black-eye (*Leptomyrina lara*); Spring widow (*Tarsocera cassus*); Dull copper (*Aloeides pierus*)

Abstract
Severe losses in biodiversity hotspots reduce global insect diversity. Renosterveld is a critically endangered and biologically diverse ecosystem occurring only in the fynbos biome of the Cape Floristic Region (CFR), a recognized global biodiversity hotspot. Following agricultural intensification, less than 5% natural renosterveld vegetation remains in the Swartland of South Africa's Western Cape. Remaining renosterveld is highly fragmented and confined to land less suited to agriculture, including steep slopes and rocky outcrops. These fragments vary in their environmental conditions at the local (e.g. microhabitat, floral diversity and density) and the landscape (e.g. patch size, habitat connectivity and surrounding crop cover) level. The influence of these environmental variables on butterfly diversity at a landscape scale in the CFR is not fully understood. We selected 32 sites across the Swartland and surveyed for butterflies to determine the effect of environmental variables on butterfly diversity, specifically butterfly species richness, abundance and composition. Overall, we found 2861 individuals of 27 species. Our findings suggest that crop cover in the surrounding landscape affects butterfly diversity at a small landscape scale (<500m radius) in the CFR. Flower species richness and microhabitat type impact species richness and abundance. Patch size is a key predictor of species diversity particularly for endemics and site quality may influence species composition. All renosterveld patches regardless of size and site quality can be considered valuable for butterflies in this highly fragmented landscape.

Keywords
Agricultural intensification; biodiversity hotspot; Cape Floristic Region; fragmentation; Lepidoptera; viticulture

Introduction
The global decline of insects is linked to landscape degradation and fragmentation (Erhardt 1985; Thomas et al. 2004; Wenzel et al. 2006; Burns et al. 2016; Lebeau et al. 2016; Hallmann et al. 2017). Insect diversity has declined severely in global biodiversity hotspots (Fonseca 2009), areas which have lost at least 70% native vegetation cover often as a result of agricultural intensification and where conservation is prioritized (Brooks et al. 2006). Butterflies in particular have been studied widely in agricultural landscapes and are useful indicators of agrobiodiversity (Erhardt 1985). Butterfly populations have suffered severe declines either due to loss of habitat connectivity through fragmentation, or to land management practices outside of protected areas in areas such as farmland (Wenzel et al. 2006; Burns et al. 2016; Lebeau et al. 2016). The identification of influential biotic and abiotic landscape features is therefore vital to shape butterfly conservation on farmland (Dennis 2004; Gillespie and Wratten 2012).

One of the most biologically unique and threatened regions in the world is the Cape Floristic Region (CFR) of South Africa's Western Cape province, where agricultural intensification is one of the key drivers of landscape degradation and fragmentation. This region is a recognized global biodiversity hotspot (www.cepf.net) with over 9000 plant species found in native ecosystems such as renosterveld (Goldblatt and Manning 2002). Renosterveld is a fire-prone scrub-shrub habitat belonging to the fynbos

(Afrikaans for "fine-bush") biome. The botanical value of renosterveld is in the many grasses, annuals, herbaceous perennials and flowering geophytes, of which some are still being discovered and rediscovered after being classified extinct (Cousins 2017). As well as floristic value, the Cape Floristic Region is considered to have high levels of endemism in invertebrates (Picker and Samways 1996). This high plant and insect species diversity is represented across different land use types within the CFR, including semi-transformed and remnant patches of natural vegetation, suggesting that the agricultural mosaic makes a significant contribution to the compositional biodiversity of the region (Vrdoljak and Samways 2014).

Less than 5% renosterveld remains in the Swartland municipality north of Cape Town in the CFR (Halpern and Meadows 2013). This landscape is characterized by intensively farmed monocultures of grains, primarily winter wheat (62% of total agricultural land) alongside vineyards (6%) and grazing lands (27%, Crop Estimates Consortium, 2017). Vineyard expansion is likely to threaten remaining renosterveld given favourable wine-producing conditions in the region (Fairbanks et al. 2004). Organic farms are few in the Swartland, although organic vineyards occur in the south in the Cape Winelands region, and are found to support more insect-flower interactions than conventional farms, likely due to reduced pesticide use (Kehinde and Samways 2014). Municipal or state-owned protected renosterveld areas are few within the Swartland municipality as the majority of remaining renosterveld patches are in private ownership (McDowell and Moll 1992; Von Hase et al. 2010). Many renosterveld patches have been subject to intense grazing from domestic herbivores, and those on municipal land are degraded due to other uses such as landfill and motocross networks. Particularly when it has been subject to fire suppression, renosterveld can become dominated by the Rhinoceros bush renosterbos (*Elytropappus rhinoceritis)*. Other pioneer shrub species such as kapokbos (*Eriocephalus africanus),* and kraalbos (*Galenia africana*) establish post disturbance. Remaining renosterveld patches therefore vary not only in size and distribution across the landscape but also in habitat quality due to previous and current management practices (Fig 1).

Fig. 1 A) Natural renosterveld with vineyard expansion on the mountain slopes B) Renosterveld following intense grazing pressure C) Renosterveld with light grazing pressure D): Degraded renosterveld, Swartland, Western Cape, South Africa. All photos ©/ by EN Topp

Little information is available on the effect of these environmental variables on regional butterfly populations. As part of the fynbos biome, the Western Cape is not the most diverse region for butterflies in South Africa. Butterfly and insect diversity in general is considered to be lower than plant diversity in fynbos and renosterveld, which may be due to the sclerophyllous nature of many plant species and their lack of suitability for insect food, as well as the lack of sufficient plant structure, regular fire occurrence, and lack of speciation via environmental factors or coevolution with plants (Giliomee, 2003). However, Proche and Cowling (2006) suggest that parallelism has resulted in insect species richness and insect diversity in fynbos is in fact not richer or poorer than can be expected for the latitude of the CFR. According to the Lepidopterists' Society of Africa Species Diversity Index, the average expected number of observed butterfly species per day in the fynbos biome is 7-11, compared to 31-55 in the Lowveld savanna or forest biomes (Dobson 2018). Some fynbos species include the Moorreesburg Common Opal (*Chysoritis thysbe schlozae*) and Dickson's Brown (*Stygionympha dicksonii*), which are classified as critically endangered according to Red List criteria in the South African Butterfly Conservation Assessment (SABCA) (Mercenero et al. 2013) and have not been recorded by local experts in the Swartland region since 2009 (Southern African Lepidoptera Conservation Assessment, 2017).

Both habitat quality and metapopulation dynamics can explain butterfly species loss or gain in fragmented landscapes (Thomas et al. 2001). Suboptimal habitat reduces species survival, and increasing fragmentation and isolation of habitat across landscapes reduces habitat connectivity. Butterfly responses to these changes have been found widely. In the US, for example, grazing and fire management regimes on grasslands influenced species composition (Panzer and Schwartz 2000; Bendel et al. 2018). Butterfly diversity is affected by landscape level variables such as the proportion of arable land in the surrounding agricultural matrix (Krauss et al. 2003; Pocewicz et al. 2009), by microhabitat variables such as nectar availability (Lebeau et al. 2016; Collinge et al. 2003), or by a combination of landscape and microhabitat level variables (Rundlöf et al. 2008). Although butterfly monitoring data for the region is available through active citizen science programs such as Lepimap (www.lepimap.adu.org.za) and the recent SABCA (Mercenero et al. 2013), landscape variables have not yet been linked to butterfly populations in the Swartland. Understanding butterfly responses to such variables will be informative not only for butterfly conservation but for renosterveld biodiversity conservation more widely, given that butterfly communities are understudied among renosterveld insect taxa compared to, for example, hymenoptera and coleoptera (e.g. Pauw, 2006; Kehinde and Samways, 2014).

Considering the critical status of renosterveld, we investigated which environmental variables impact renosterveld butterfly diversity and may increase the conservation value of these patches within the agricultural mosaic. Our overarching research question was: How do local and landscape variables impact butterfly diversity in the renosterveld remnants of the Swartland? Our hypotheses were that the characteristics of both the renosterveld patches themselves and the surrounding agricultural land would affect butterfly diversity (including species richness, composition and abundance). For example, we expect that a greater proportion of agricultural land in the area surrounding each renosterveld patch may decrease butterfly diversity. Specifically, we investigated the influence of both habitat quality and landscape configuration on two levels: the microhabitat level and the landscape level, using a replicable, systematic butterfly surveying approach which could provide data suitable for linear modelling.

Methods

Study Sites

The study location was the Swartland municipality, Western Cape, South Africa, approximately 50 km north of Cape Town (Fig 2). We surveyed 32 renosterveld patches ranging between 0.36 and 1049 ha in size across the Swartland municipality (approximately 3707 km² plus a 5 km buffer). We selected patches using a stratified random approach to cover a balanced range of environmental variables (Table 1), from the GIS layer 'Remnants of natural vegetation', accessed via the South Africa National Biodiversity Institute (SANBI) GIS repository (http://bgis.sanbi.org) and ground-truthed in September 2017. We included information on historic sightings of endangered species into our site selection to survey patches known to have hosted endangered species in the past. All surveyed patches were on privately owned farmland except for three on municipal land. Farms ranged from approximately 400 –

2000 ha in size. The majority of surveyed patches had a single owner although several patches spanned multiple farm boundaries. Farms were intensively managed monocultural croplands and vineyards, although they may differ in individual farming practices such as timing and method of agrochemical application and grazing stock levels. Floral and faunal diversity was known to the farmers to some extent in private and municipal nature reserves but largely unrecorded on private land.

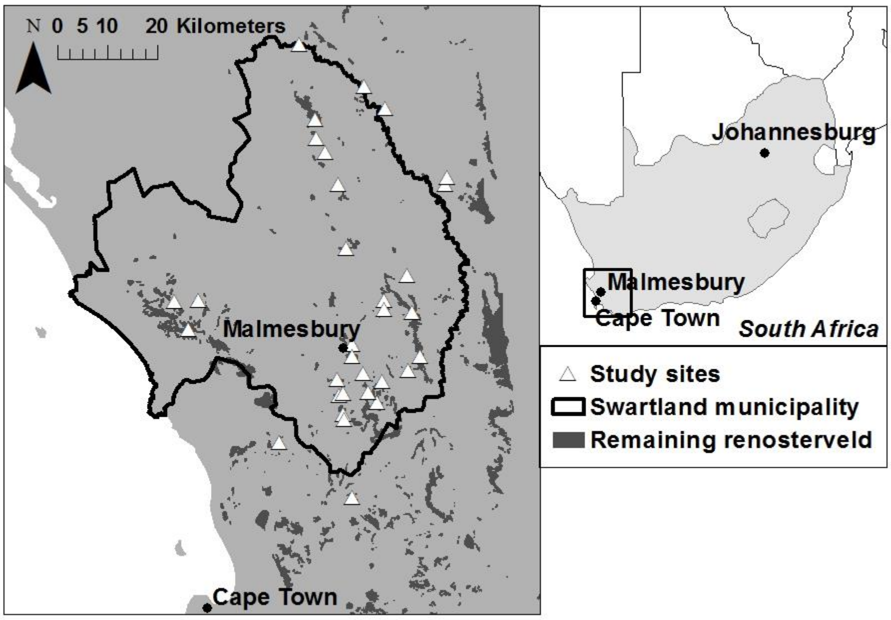

Fig. 2 The 32 study sites in the Swartland municipality (plus a 5 km buffer), Western Cape, South Africa. The majority of remaining renosterveld is in the mountainous region to the east of the Swartland and along the western coastal edge of the municipality

Butterfly Recording

We visited the 32 patches 4 times during the spring-summer season between September 2017 and January 2018 to maximize the opportunity to detect species of different flight periods and voltinism. Two fieldworkers walked separate transects at a steady pace (Pollard 1977) of five minutes in duration (as in Krauss et al. 2003, following Colwell 1997) on days with ≥ 17 °C temperatures and extended periods of sunshine. Number of transects per site accorded with site size class (Table 1), i.e., the larger the size of the patch, the longer the amount of time spent observing butterflies. Survey times consisted of the following: small sites = 3 transects (15 minutes total), small-medium sites = 6 transects (30 minutes total), medium-large sites = 9 transects (45 minutes total), and large sites = 12 transects (60 minutes total). During every five minute transect, we recorded all butterflies seen along with environmental variables (Table 1). Where possible, we recorded butterflies to species level while on the wing. Where the species was uncertain, particularly with the genus *Aloeides*, the individual was captured, photographed and later identified by a local expert.

Environmental Variables

We collected environmental variables at two spatial scales (Table 1). At the microhabitat level, we visually estimated floral species richness and density at the beginning of each transect. We collected microhabitat information for each transect and classified into the following six categories for analysis:

1. Koppies - rocky outcrops, often quartz or silcrete shale, generally with less vegetation than other areas in renosterveld patches although can host *Aloe* spp. and other hardy fynbos species.
2. Mature Veld - renosterveld dominated by renosterbos (*E. rhinoceritis)*, with a wide range of geophytes at ground level and other common herbaceous and flowering species such as kapokbos (*E. africanus*).
3. Track – farm tracks through renosterveld patches or alongside field margins. Telecom towers are often found in Swartland renosterveld patches due to their hilltop locations, for which well-maintained access tracks are required. Track edges were observed to contain relatively high flower diversity.
4. Burned – fires are frequent in Swartland renosterveld, often caused by human negligence but also by intentional land management. The majority of recently burned sites had been subject to medium intensity fires which removed structural vegetation in contained areas within the overall patch. Burned microhabitats were classified by the presence of blackened stalks and shrubs and the visible absence of mature renosterveld vegetation in comparison to surrounding renosterveld. The estimated burn age for all recently burned microhabitat was 0-3 years.
5. Overgrazed – microhabitats of two definitive structural levels: grazed areas of short grasses, often with common flowering species remaining in the soils such as chinkerenchee (*Ornithogalum thyrsoides*) and *Cyanella hyacinthoides*; and medium to large bushes (S*ersia spp*, *Pteronia spp*.) left by grazing livestock.
6. Other – areas unable to be classified into the above, often degraded, including areas used as landfill, or areas overgrown with invasive species such as Port Jackson trees (*Acacia saligna*).

At the landscape level, we visually estimated overall site quality and confirmed this in discussion with landowners. We calculated other landscape level variables including patch size, adjacent crop type and connectivity using GIS.

Table 1: Environmental variables recorded at two spatial scales.

Microhabitat Level	
Variable	**Description and Scale**
Microhabitat	Classification of immediate surroundings into one of five microhabitats (as described in text).
Floral species richness	The number of different plants in flower, estimated visually for the length of each transect on a scale from 0-4. 0 – No flowering species, 1 – 1-2 flowering species, 2 – 3-5 flowering species, 3 – 5-10 flowering species, 4 – More than 10 flowering species
Floral density	The proportion of floral cover in the surrounding vegetation estimated visually for the length of each transect on a scale from 0-4. 0- No floral density, 1 - <10% cover, 2 – 10-50% cover, 3 – 50-75% cover, 4 – 75-100% cover.
Aspect	Recorded as N, NE, E, SE, S, SW, W, NW, NS-ridge
Landscape Level	
Variable	**Description and Scale**
Patch size	Calculated in hectares in GIS and placed into one of the following classes: Small: <1 ha, Small-Medium: 1-10 ha, Medium-Large:10-100 ha and Large: >100 ha
North/South position	Estimated visually in GIS whether sites were located north or south of Malmesbury, the approximate geographical centre of the Swartland municipality.
Adjacent crop type	Vineyards or Other crop (Primarily wheat, also lucerne (*Medicago sativa)*, barley, oats, pasture).

Burn age	Years since previous burn according to local landowners and other local knowledge sources (e.g. other neighbouring landowners, citizen scientists).
Site quality	Classification of the entire patch into one of the following types: LG – lightly grazed, OG – Overgrazed, UM – Unmanaged, DEG – Degraded (e.g. previously used as landfill). This classification was estimated visually by fieldworkers and confirmed in interviews with the land manager.
Connectivity	Calculated using the Hanski Index (Hanski et al. 2000) $$CI_i = \sum_{j \neq i} exp\left(-\propto d_{ij}\right) A_j^{\beta}$$ Where A_j is the area of neighbouring fragment j (in square metres) and d_{ij} is the edge to edge distance (in metres) from the focal fragment i to the neighbouring fragment j. α is a species-specific parameter that describes a species' dispersal ability and β is a parameter that describes the scaling of immigration. As we did not have species specific dispersal information available, both parameters were set to the commonly used value of 0.5 (e.g. Rösch et al. 2015).
Per cent crop cover in the surrounding landscape	Calculated in GIS as the percentage of agricultural land (both vineyard and cereal cropland) surrounding each renosterveld remnant at 500m, 1500m and 2500m scales.

Statistical Analyses

To address our research question on butterfly diversity in renosterveld patches, we considered butterfly species richness, species abundance and species composition as different components of butterfly diversity. Species richness was measured as the total number of species recorded in each transect, species abundance was measured as the total number of individuals recorded per transect, and species composition as the identity of species recorded at each site, which we considered by illustrating whether species occurred together in ordination space. We performed analyses of variables according to our two spatial scales: microhabitat and landscape level. In microhabitat level analyses, we investigated the effects of different explanatory variables on species richness and abundance with generalized linear mixed models including site as a random factor (Poisson distribution). We used backwards stepwise selection to retain variables with a p-value of <0.1.

In landscape level analyses, we first recalculated renosterveld patch size from the original spatial data layer (http://bgis.sanbi.org) by using most recent available spatial data on cropland (Crop Estimates Consortium, 2017) and removing overlaps in order to increase accuracy of patch area. We used this spatial information to explore correlation of different spatial scales with species diversity. Second, we pooled species and environmental variable data for use in generalized linear models (Poisson distribution). Sampling adequacy was assessed by plotting species accumulation curves for the different size classes of study sites. In order to account for the additional survey effort given to larger sites, we calculated the Chao species richness estimate (Chao and Chiu 2016) as the response variable for each site. Patch size was correlated with habitat connectivity (0.69, Pearson's test) and therefore we tested for both variables separately in our models. We log transformed patch size and the Hanski habitat connectivity index to achieve a normal distribution and performed backwards stepwise selection to retain variables with a p-value of <0.1. We selected the best fitting model according to the lowest Akaike Information Criterion (AIC) score. We also performed analysis of variance (ANOVA) and post-hoc tests (Tukey) to test for significant differences of site qualities on species richness and abundance.

Likewise, we modelled the sum of abundance of species endemic to the region compared to globally widespread species. Third, to investigate differences in species composition across differing site qualities and size classes, we used non-metric multi-dimensional scaling (NMDS) and used a permutation test to fit the correlation of environmental variables within the ordination. We performed all analyses in R using the packages vegan and lme4 (Oksanen et al. 2016, R Core Team, 2017).

Results

We recorded a total of 2861 individuals of 27 species from five families (for full species list see Appendix 2). The species of highest abundance was the Spring Widow (*Tarsocera cassus*) (n=647), followed by the Tulbagh sylph (*Tsitsana tulbagha*) (n=489) and the Boland Brown (*Melampias huebneri*) (n=487). Eleven species were endemic to the western and northern Cape region of South Africa, whereas the other species were more globally widespread according to the Conservation Assessment of South Africa, Lesotho and Swaziland (Mercenero et al. 2013) and local experts. Despite specific efforts to survey sites known to host endangered species, we did not observe any endangered species. We recorded one observation of the Wineland Blue (*Lepidochrysops bacchus*), which is known to be a rare habitat specialist, and recorded one colony of the Boland Skolly (*Thestor protumnus*) which occurs in highly localized colonies symbiotically with *Anoplolepis* ant colonies (Woodhall 2005). Otherwise all species seen were of least concern (LC) globally according to Red List criteria, common for the Western Cape and known to occur in renosterveld. Species abundance peaked in the beginning of October 2017 and species richness peaked between October and November 2017. The site with the highest richness in butterflies contained 17 species (mean 6.09, +/-3.02). The most widespread species was *Vanessa cardui*, appearing on 29 sites, followed by *Aloeides pierus* on 25 sites and *Melampias huebneri* on 20 sites (see Appendix B). The species with the observed highest fidelity to plant type was the Tulbagh Sylph (*Tsitsana tulbagha*), which was found only in sites where *Merxmuellera* grass, a known larval food plant, was present.

Microhabitat Level Analysis

At microhabitat level, flower species richness significantly predicted butterfly species richness and abundance (Table 2). Microhabitats classified as 'overgrazed' had significantly higher species abundance than other microhabitats and those classified as 'other' had significantly lower species richness and abundance.

Table 2. Significant environmental variables in the generalized linear mixed models of species richness and abundance at microhabitat level with site as a random factor.

Microhabitat Level	Estimate	*Z*	*P*-value
Species Richness			
Intercept	-0.91		
Flower Species Richness	0.47	10.36	<0.001
Microhabitat "Other"	-0.96	-2.62	<0.01
Species Abundance			
Intercept	-0.49		

Flower Species Richness	0.61	20.84	<0.001
Microhabitat "Overgrazed"	0.69	4.93	<0.001
Microhabitat "Other"	-0.67	-2.85	<0.01

Landscape Level Analysis

In order to understand at which spatial scale landscape effects were strongest we plotted correlations of species richness and per cent crop cover (the percentage of agricultural land in the surrounding landscape) at different scales (Fig 3a & 3b). Per cent crop cover was more strongly negatively correlated with both species richness and abundance at the local scale (500m) (Fig 3a). Widespread species were more negatively correlated at the local scale whereas endemic species showed more stable correlation across differing spatial scales (Figure 3b). More endemic species were observed in larger sites with more endemic species overall, although at least one endemic species was present even in small sites with relatively few total species (Fig 4).

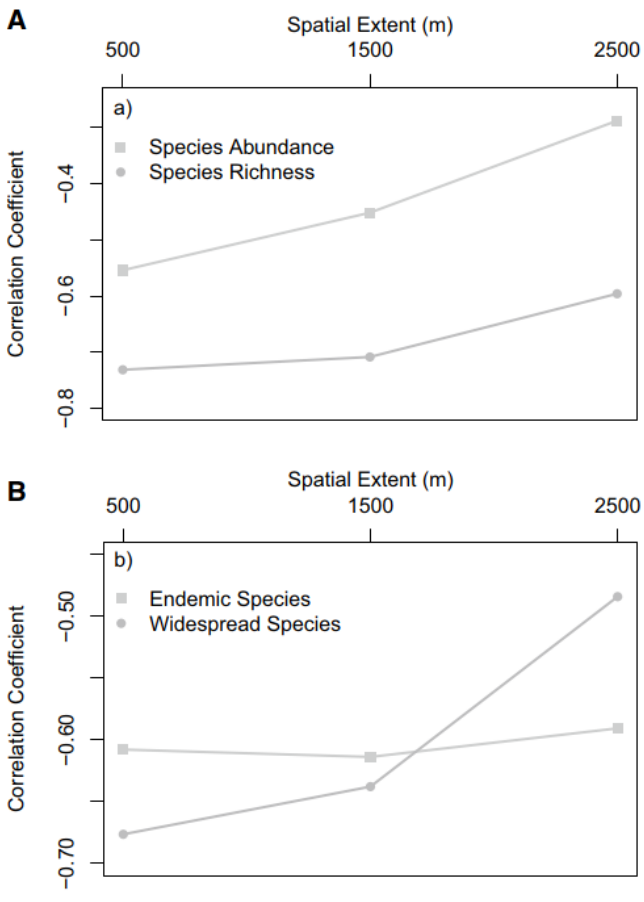

Fig. 3 (a) Correlation between per cent crop cover and species diversity at widening spatial scales (b) Correlation between per cent crop cover and endemic vs. widespread species richness at widening spatial scales

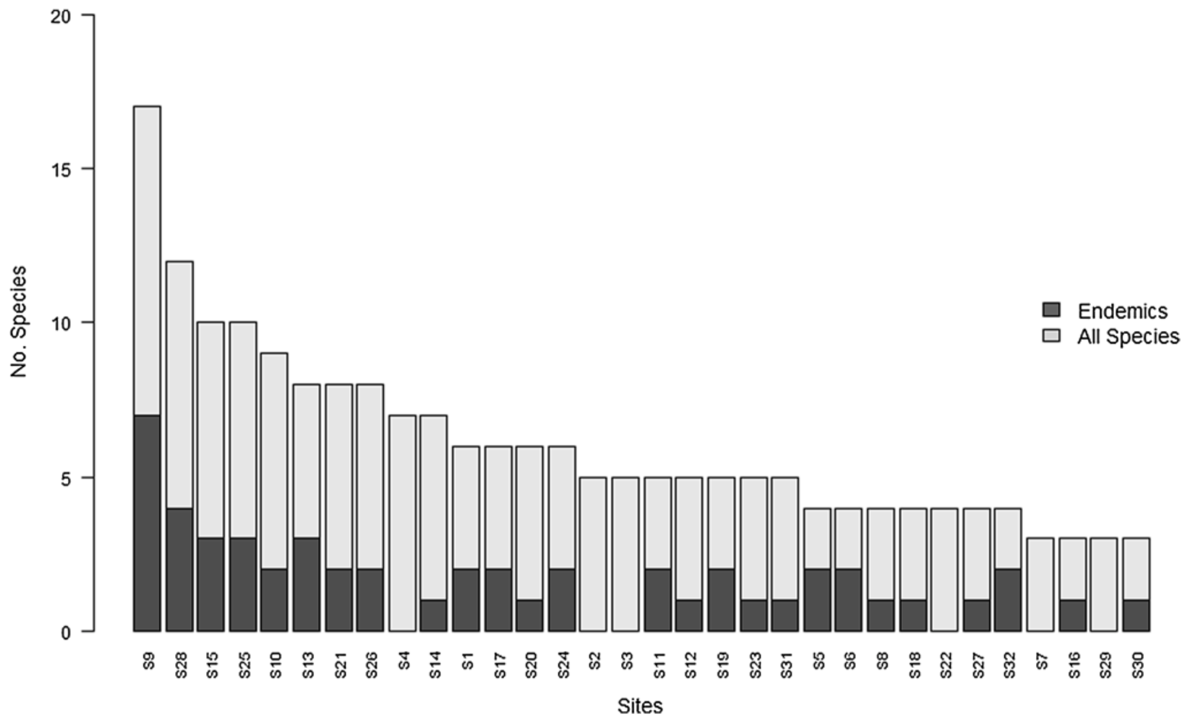

Fig 4 Endemic and total species distribution across sites. Higher numbers of endemic species were observed in sites with more species overall although endemics occurred in nearly all sites (n=26)

Species accumulation curves (Appendix C) suggest that species saturation was not reached in our sampling for large sites, although may have been reached for small sites with noticeable levelling off at approximately 50-100 transects. The Chao estimate for species richness was slightly higher than observed species richness for nearly all sites. Considering that increasing proportion of crop cover correlated negatively with species diversity, we expected habitat connectivity to have a positive effect on species diversity. In subsequent generalized linear models (Table 3) we found patch area to be the only significant explanatory variable of species richness for both endemic and overall species. The model for endemic species fitted better (AIC 92.055) than for overall species richness (AIC 146.38).

Table 3. Significant environmental variables in the generalized linear models of species richness at site level after backwards stepwise selection

Model **Site Level**	**Estimate**	***z***	***P*-value**
Chao Species Richness Estimate			
Intercept	1.5		
Log(patch area)	0.13	4.35	<0.001
Endemic Species Richness			
Intercept	-0.35		
Log(patch area)	0.23	3.83	<0.001

NMDS analysis showed that species composition overlapped among site qualities (Fig 5) suggesting that site quality is not driving large differences in species composition, although some separation in ordination space occurred between overgrazed sites and lightly grazed sites (Fig 5, polygons b&c).

Unmanaged sites contained most species (Fig 5, polygon a). Nine species were found only in large sites: *Aloeides almeida, Aloeides apicalis, Capys alphaeus, Charaxes pelias, Lepidochrysops bacchus, Mylothris agathina, Phasis thero thero, Pieris brassicae* and *Thestor protumnus.* Of these species, seven are endemic to the Cape region and two are habitat specialists, *Lepidochrysops bacchus* and *Thestor protumnus*. Six sites contained no species endemic to the region. We observed species such as *Cacyreus marshalli*, *Aloeides pierus* and *Tarsocera cassus* in almost all size classes and site qualities. When environmental variables were added to the ordination, patch size and per cent crop cover significantly influenced species composition (p<0.1).

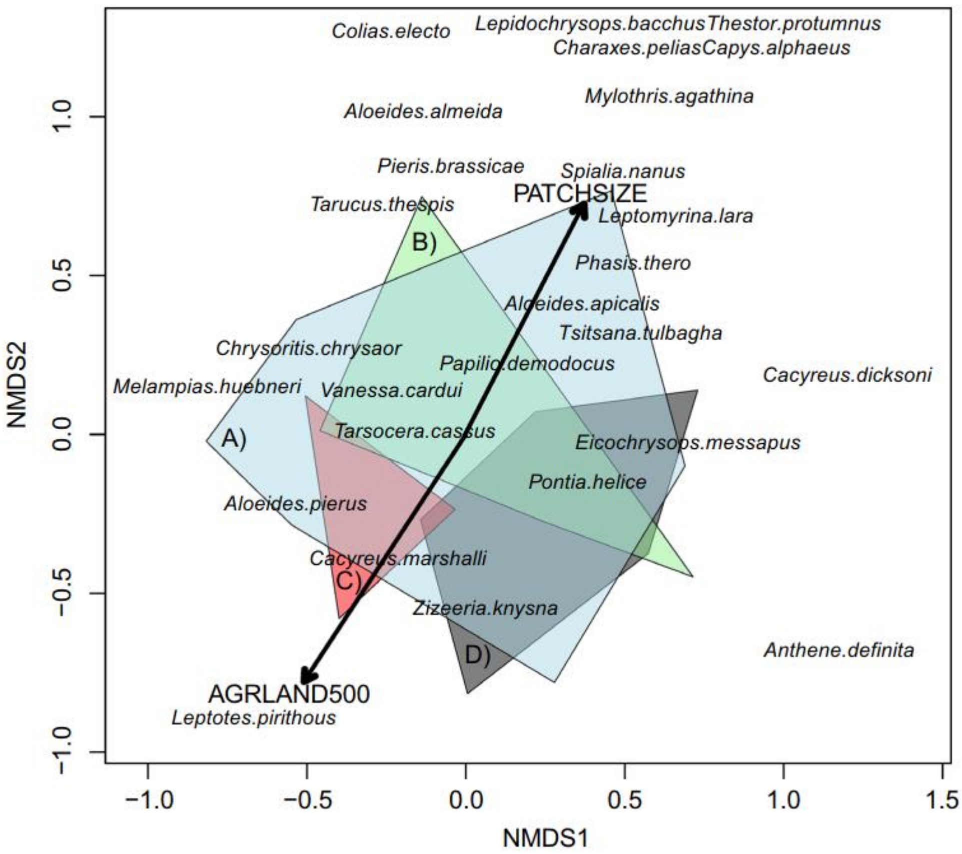

Fig 5 NMDS ordination of species composition with influence of environmental variables superimposed (black arrows, p<0.1). Coloured polygons show grouping of sites according to site quality: A) blue – unmanaged, B) green – overgrazed, C) red – lightly grazed, D) black – degraded, corresponding to photos A, B, C and D in Figure 1 respectively. Species composition changes along a gradient from low to high proportion of crop cover (AGRLAND500 = percentage of agricultural land in the surrounding landscape within a 500m radius)

Discussion

Our findings suggest that environmental variables influence butterfly diversity in the Swartland at both the local and landscape level. The fairly low numbers of species recorded overall (n=27) may have caused that the difference in species richness between patches was not great in relative terms, although our analyses suggested that species saturation was not reached in all sites. Many of the species observed were within the historically recorded centre of their ranges and yet we found low abundance in our surveys. We summarize the interpretation of our findings into the following three themes: i) the importance of floral richness in microhabitat; ii) the importance of patch size and connectivity for endemic species and iii) the effect of land management on species composition.

Importance of floral richness in microhabitat

Within highly fragmented renosterveld patches, different microhabitats host a range of butterfly diversity. Our finding that floral richness is key for species richness and abundance echoes similar studies of agricultural mosaics (Pywell et al. 2004; Gillespie and Wratten 2012; Wallisdevries et al. 2012; Loos et al. 2014). Expanding the sampling period into the late summer and autumn period (March-April) may have unraveled insights into the richness patterns of Satyrinae species, however this time and duration was selected to represent the flight period of the majority of species present in the area. This period also covered the spring renosterveld flowering. While we found an effect of overgrazing on butterfly abundance at the microhabitat level, we did not find a similar effect at the landscape level. Some sites maintained relatively high floral richness despite grazing pressure, and the vegetation structural complexity resulting from grazing differs from unmanaged sites dominated by renosterbos (*E. rhinoceritis*), which could benefit butterflies provided larval host plants are present. Domination of renosterbos can be mitigated by fire management, as regular fires reduce the fuel load of the shrub layer, promote regeneration of geophytes, and enable new insect species to enter the ecosystem (Donaldson et al. 2002; Pryke and Samways 2012). Burning patches every 10-15 years is recommended to landowners (Esler et al. 2014). Although we found no effect of burn age on diversity in this study, fire management recommendations have implications for butterfly diversity in Swartland renosterveld particularly as pollinators respond more conservatively to fire than other invertebrates in the CFR (Pryke and Samways 2012). The impact of degraded microhabitats (classified "other") on butterfly species richness and abundance suggests continued development and disturbance within renosterveld patches is likely to negatively impact butterflies. Additionally, recent severe drought in the CFR is likely to impact natural vegetation and annual floral richness and density with cascading effects on invertebrate populations. Data from one field season is not sufficient to draw conclusions on the impact of drought on Swartland butterfly populations although local experts reported a drop in observed numbers during this period (Dobson 2018).

Importance of patch size and connectivity for endemic species

Species diversity is well known to relate to different spatial scales. Our findings of stronger correlations between crop cover in the surrounding landscape and species diversity at the small scale corroborates other studies in the CFR, which find plant and insect diversity to be significantly positively correlated at the local scale (up to 3 km) but not at the regional scale (15-70 km) (Kemp and Ellis 2017). While in-depth species population assessments require targeted investigation, we found seven of eleven endemic species only occurred in large patches, including populations of two rare habitat specialists *Lepidochrysops bacchus* and *Thestor protumnus*. These highly localized species may be more sensitive to further renosterveld fragmentation or alteration of habitat quality. While larger patches with more stable conditions may support rare and specialized species (Rösch et al. 2015), smaller fragments are known to support insect conservation by covering a wider geographic area and enabling spreading of beta diversity and species dispersal among fragments (Tscharntke et al. 2002b). While greater patch area and connectivity was important for overall species diversity, we found small, isolated and overgrazed or otherwise disturbed patches still contained up to six butterfly species, similar to findings for other invertebrates in small patches within agricultural mosaic landscapes (Donaldson et al. 2002; Tscharntke et al. 2002a; Vrdoljak and Samways 2014). Low shrub cover and associated high floral density may explain pollinator diversity in small renosterveld patches compared to larger patches (Donaldson et al. 2002). While we found widespread species diversity is more strongly correlated to per cent crop cover at smaller scales, widespread southern African species such as *Zizeeria knysna* and *Spialia nanus* were present across a wider range of habitats in our study, which may be explained by the life-history traits of the butterflies such as individual mobility and nectar source preference. Large patches appear important for endemic species and habitat specialists as they likely harbor a greater diversity of appropriate microhabitats, larval food plants and symbiotic ant colonies, and therefore require special attention for monitoring butterfly populations.

Effects of land management on species composition

While we did not find significant effects of site quality on species diversity in generalized linear models at the landscape level, some difference of species composition between grazing regimes is indicated in ordination space. Other studies found a similar lack of clear patterns between butterfly and floral diversity and landscape management in North American grasslands (e.g. Bendel et al. 2018), contrary to clear effects of fire and grazing on butterfly species composition in some areas (e.g. Vogel et al. 2007). Compared to agricultural landscapes with less intensive production, cereal and vine production in the Swartland creates large areas relatively hostile to butterflies. Pesticide spraying of crops is frequent and chemicals are often applied by airplane, particularly following rainfall, which can increase drift and subsequently impact renosterveld patches and associated insect populations. It may be intuitively believed that within these hostile areas, unmanaged, undisturbed renosterveld hosts higher levels of biodiversity than sites subject to disturbance such as grazing; however, we found that sites subject to disturbance still supported butterfly diversity. For example, despite being widespread species, our only observations of *Anthene definita* and *Colias electo electo* were in relatively small, overgrazed patches, suggesting that renosterveld patches of varied quality are of conservation value for butterflies, and highlighting further the importance of landscape heterogeneity, host plant distribution and microhabitat for butterflies moving through the landscape (Rundlöf et al. 2008; Pocewicz et al. 2009).

Conclusion

Renosterveld in the Swartland is among the most fragmented and critically threatened habitat in South Africa. Local and landscape environmental variables including patch size, floral richness and grazing regime affect Swartland renosterveld butterfly populations. Renosterveld fragments of varying conditions support butterfly diversity and must be considered as part of the overall biodiversity value of this highly transformed agricultural mosaic. Agri-environment schemes in South Africa are more prevalent for wine grape production than cereal farmers, unlike many countries in Europe, the US and New Zealand. Biodiversity conservation, wildlife-friendly farming and the retention of natural vegetation is therefore reliant upon government agencies and the will of private landowners. Subsequently, dissemination of knowledge of impacts of farming and landscape practices on agrobiodiversity including local butterfly populations is of high priority within regions such as the Swartland, where crop production is the most common type of agricultural land cover. Future research priorities may include specific host plant-butterfly relationships, further investigation into the effects of fire history and fine grain habitat mapping for improved species-specific knowledge, as well engagement with landowners on the wider value of insect conservation to address the critical status of this unique global biodiversity hotspot.

Conflict of interest: The authors declare that they have no conflict of interest.

Ethical statement: This study was performed in compliance with ethical standards and received ethical clearance from Georg-August University Göttingen. Fieldwork was conducted with permission from Cape Nature (Permit No. 0035-AAA004-00100).

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Appendices

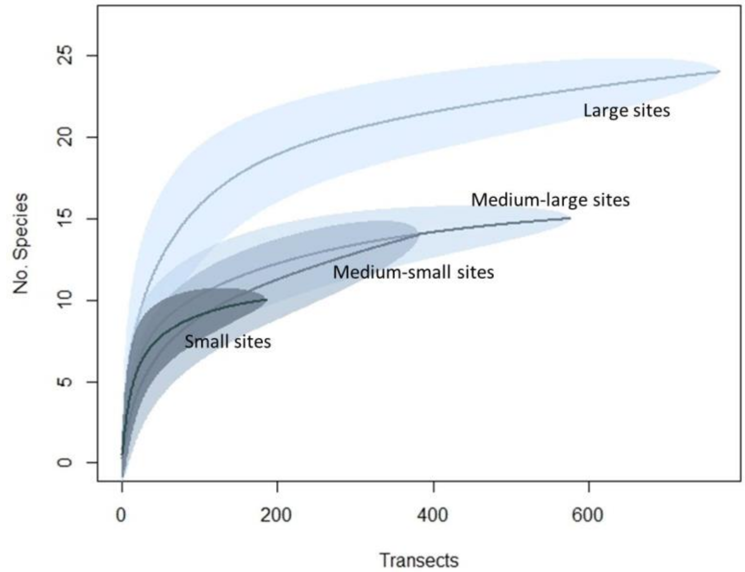
A) Study Sites

Site Code	Area (ha)	Longitude (Decimal Degrees)	Latitude (Decimal Degrees)
S1	51.17	18.69	-33.10
S2	3.28	18.95	-33.15
S3	9.24	18.78	-32.99
S4	22.63	18.95	-33.17
S5	0.27	18.73	-33.28
S6	11.88	18.76	-33.50
S7	2.17	18.81	-33.39
S8	30.99	18.74	-33.45
S9	1401.05	18.79	-33.55
S10	17.83	18.36	-33.36
S11	13.02	18.86	-33.50
S12	1.41	18.58	-33.62
S13	863.62	18.87	-33.39
S14	8.98	18.86	-33.33
S15	1036.50	18.67	-33.04
S16	1.45	18.71	-33.51
S17	26.96	18.72	-33.57
S18	3.25	18.72	-33.58
S19	96.27	18.71	-33.54
S20	38.72	18.73	-33.72
S21	60.77	18.67	-33.08
S22	14.71	18.64	-32.91
S23	464.92	18.89	-33.47
S24	3.37	18.41	-33.36
S25	227.94	18.74	-33.47
S26	112.80	18.72	-33.16
S27	2.07	18.81	-33.37
S28	446.13	18.39	-33.42
S29	1.41	18.82	-33.03
S30	0.92	18.80	-33.51
S31	7.10	18.77	-33.53
S32	9.25	18.72	-33.54

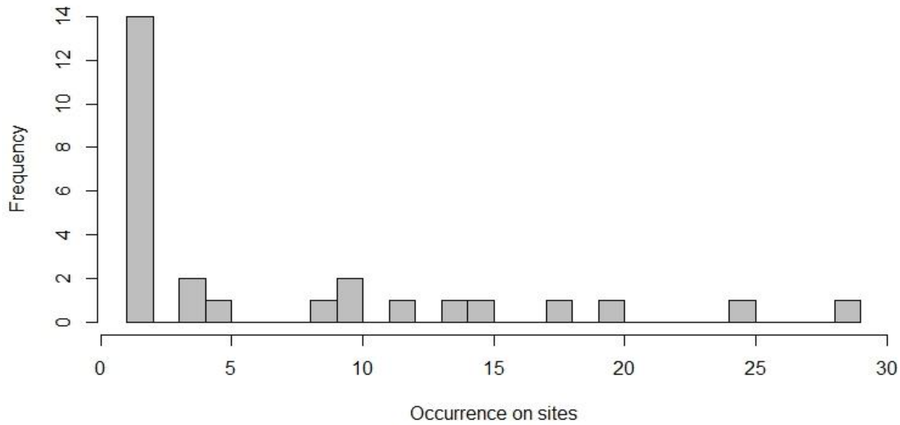
B) List of observed species

Common Name	**Latin Name**	**Family**	**SABCA Classification** (Mercenero et al. 2013)	**No. of sites where observed**
Almeida Copper	*Aloeides almeida*	LYCAENIDAE	Endemic	1
Pointed Copper	*Aloeides apicalis*	LYCAENIDAE	Endemic	1
Dull Copper	*Aloeides pierus*	LYCAENIDAE	Widespread	25
Common Hairtail	*Anthene definita definita*	LYCAENIDAE	Widespread	1
Dickson's Geranium Bronze	*Cacyreus dicksoni*	LYCAENIDAE	Endemic	1
Common Geranium Bronze	*Cacyreus marshalli*	LYCAENIDAE	Widespread	10
Orange-banded Protea	*Capys alpheus alpheus*	LYCAENIDAE	Endemic	1
Protea Emperor	*Charaxes pelias*	NYMPHALIDAE	Endemic	1
Burnished Opal	*Chrysoritis chrysaor*	LYCAENIDAE	Widespread	5
African Clouded Yellow	*Colias electo electo*	PIERIDAE	Widespread	1
Cupreous Blue	*Eicochrysops messapus messapus*	LYCAENIDAE	Widespread	12
Wineland Blue	*Lepidochrysops bacchus*	LYCAENIDAE	Endemic	1
Cape Black-eye	*Leptomyrina lara*	LYCAENIDAE	Widespread	4
Common Zebra Blue	*Leptotes pirithous pirithous*	LYCAENIDAE	Widespread	1
Boland Brown	*Melampias huebneri*	NYMPHALIDAE	Endemic	20
Common Dotted Border	*Mylothris agathina agathina*	PIERIDAE	Widespread	2
Citrus Swallowtail	*Papilio demodocus demodocus*	PAPILIONIDAE	Widespread	9
Silver Arrowhead	*Phasis thero thero*	LYCAENIDAE	Endemic	1
Cabbage White	*Pieris brassicae*	PIERIDAE	Widespread (Exotic)	2
Common Meadow White	*Pontia helice helice*	PIERIDAE	Widespread	18
Dwarf Sandman	*Spialia nanus*	HESPERIIDAE	Widespread	2
Spring Widow	*Tarsocera cassus*	NYMPHALIDAE	Endemic	15
Vivid Blue (Fynbos Blue)	*Tarucus thespis*	LYCAENIDAE	Endemic	10
Boland Skolly	*Thestor protumnus protumnus*	LYCAENIDAE	Endemic	1
Tulbagh Sylph	*Tsitana tulbagha tulbagha*	HESPERIIDAE	Widespread	4
Painted Lady	*Vanessa cardui*	NYMPHALIDAE	Widespread	29
African Grass Blue	*Zizeeria knysna*	LYCAENIDAE	Widespread	14

C) Species accumulation curve for four different size classes of renosterveld patch. Shaded areas shows standard deviation of estimate.



Appendix D) Histogram of species numbers across all 32 sites. Fourteen species were observed at 1-2 sites, and one species observed at 29 sites (*Vanessa cardui*).



Chapter 4

Fire and landscape context shape plant and butterfly diversity in a South African shrubland

Emmeline Topp, Teja Tscharntke and Jacqueline Loos

Diversity and Distributions (2021)

Special Issue: Fire ecology for the 21st century: conserving biodiversity in the age of megafire
Full article available here: Topp, E. N., Tscharntke, T., & Loos, J. (2021). Fire and landscape context shape plant and butterfly diversity in a South African shrubland. *Diversity and Distributions*, *28*(3), 357–371. https://doi.org/10.1111/ddi.13257

Controlled burn near Riebeek Kasteel, April 2019. Photograph © Fiona Hellman

Abstract

Aim: To understand effects of fire history and landscape composition on butterfly diversity in a fragmented agricultural landscape.

Location: We studied critically endangered renosterveld remnants within the fynbos biome in the Swartland municipality, Western Cape, South Africa, a global biodiversity hotspot.

Method: We selected survey sites on renosterveld fragments in the agricultural landscape along a gradient of fire history to test the response of biodiversity patterns to fire and landscape composition. We surveyed butterfly species richness, abundance and community composition as well as vegetation structure in five survey rounds on 58 sites between August 2018 and April 2019. We analysed data through linear modelling and multidimensional scaling.

Results: Fire was associated with reduced shrub and understorey plant cover and with increased plant species richness. Butterfly species richness was three to four times higher when natural habitat increased in the surrounding landscape (within a 2 km radius), while butterfly abundance was negatively associated with increasing time since fire, with approximately 50% fewer individuals after 9 years. Fire was indirectly associated with increased butterfly species richness and abundance through the alteration of vegetation structure, particularly through removal of shrubs and enhanced plant diversity. Low-mobility butterfly species were more positively associated with less vegetation cover than were high mobility butterfly species, which were more associated with sites characterized by long absence of fire.

Main conclusions: Our findings suggest that species respond differently to fire, so a diversity of fire frequencies is recommended. Partially burning areas approximately every ten years may benefit particularly low-mobility butterfly species through gap creation and fostering plant diversity. Hence, including fire into management activities can benefit butterfly and plant populations alike in critically endangered renosterveld.

Keywords:

Cape Floristic Region, fire management, fragmentation, fynbos, natural disturbance

Introduction

For effective management and conservation of natural habitat, it is essential to consider natural disturbance regimes. Fire is a key natural disturbance, which alters vegetation and affects animal movement in landscapes (Nimmo et al., 2019). In fragmented fire-prone landscapes, the spatial context and composition of remaining habitat fragments shape the outcomes of the fire regime (Parr & Andersen, 2006). Remaining natural habitat fragments within agricultural landscapes are important refuges for insect diversity, including butterfly diversity. In biodiversity hotspots, these natural remnants are particularly important for maintaining biodiversity, and are thus conservation priorities in the face of global insect decline (Brooks et al., 2006; Fonseca, 2009; Hallmann et al., 2017). While habitat loss is widely accepted as a principal driver for declining insect populations, quality of habitat is a further key factor determining species survival (Henderson et al., 2018). In fire-prone biodiversity hotspots, which experience strong colonization-extinction dynamics (Cleary & Mooers, 2006; Fernández-Chacón et al., 2014; Schurr et al., 2007), the role of remaining habitat in the landscapes may be more important for insect conservation than in landscapes characterized by more stability.

Landscape context, fire and habitat quality are all drivers of butterfly diversity. While traditional species-area relationships have been observed for butterflies in many fragmented landscapes (e.g. Bruckmann et al., 2010), multiple small habitat fragments can support butterfly populations in agricultural mosaics (Fahrig, 2020; Rösch et al., 2015; Tscharntke et al., 2002). Landscape context attributes, such as the amount of natural habitat in the focal landscape, are increasingly recognized as a driver of arthropod diversity (Aviron et al., 2005; Hendrickx et al., 2007), particularly for mobile taxa such as butterflies (Krauss et al., 2003). Butterfly populations also respond to fire in grasslands and shrublands (Henderson et al., 2018; Moranz et al., 2014; Vogel et al., 2007). The effect of fire may be direct, through loss of individuals, or indirect, as fire regimes can alter host plant availability and vegetation structure, which provide important resources for butterflies (Pywell et al., 2004; Vogel et al., 2007). In addition, butterflies with differing traits may respond differently to drivers at different spatial scales (Loos et al., 2015). For example, low-mobility butterflies and habitat specialists may require specific habitat retention in intensively managed landscapes (Toivonen et al., 2016), and may require targeted fire regimes to enhance population survival (Schultz et al., 2018). However, highly mobile butterflies may be able to move far distances through a fire-prone landscape to make use of available resources (Baum & Sharber, 2012).

The renosterveld ecosystem of the Cape Floristic Region (CFR), a global biodiversity hotspot, is a fire-prone shrub-scrub ecosystem belonging to the fynbos biome, which is now one of the most critically endangered habitats in South Africa (Bergh et al., 2014). Approximately 95% of West Coast renosterveld in the Western Cape has been lost to agricultural transformation and urbanization, much of which occurred throughout the 20^{th} century (von Hase et al., 2003; Newton & Knight, 2005).

Renosterveld is considered a fire-driven ecosystem which becomes more shrub-dominated in the absence of fire, although it contains fewer fire-adapted plant species than fynbos (Heelemann, 2010; Kraaij & van Wilgen, 2014). In pre-colonial times, native herbivores would also have driven renosterveld diversity patterns, given the abundance of palatable grasses. Several studies have shown the combined effects of fire and grazing on renosterveld vegetation dynamics. For example, many renosterveld annual and geophyte species are vulnerable to grazing once they regenerate following fire (Curtis, 2013; Helme & Rebelo, 2005; Kraaij & van Wilgen, 2014) and grazing following fire can enhance the dominance of shrub (Radloff, Mucina, & Snyman, 2014). Remaining renosterveld patches are mostly privately owned and often not managed for their biological value, but either left unmanaged by land managers or used for grazing of cattle and sheep (Winter et al., 2007). While being known primarily for its exceptional plant richness, particularly geophytes, renosterveld also fosters high insect diversity (Stander, 2016; Vrdoljak & Samways, 2014), including endemic and rare species. For optimal plant regeneration and removal of dominant shrub, it is recommended that renosterveld patches are burned approximately every 10-15 years (Esler et al., 2014; Kraaj & van Wilgen, 2014). Limited understanding of insect ecology in renosterveld (Topp & Loos, 2019a) makes it difficult to assess how fire regimes may impact insect diversity in the fynbos biome (Procheş & Cowling, 2006), although it has been shown that bees may benefit from flower abundance resulting from regular burns in the CFR (Adedoja et al., 2019) and ecologically appropriate fire management is key to support diverse butterfly populations elsewhere in South Africa (Gaigher, Pryke, & Samways, 2019). Given the importance of understanding management impacts and ecological processes in renosterveld (Topp & Loos, 2019a) and the inclusion of habitat and landscape conservation as key strategies for butterfly conservation in South Africa (Edge & Mecenero, 2015), our intention was therefore to investigate the relationship between fire in renosterveld and butterfly diversity in the CFR.

Renosterveld fragments are known to foster diverse butterfly populations (Topp & Loos, 2019b), even though their species richness is lower than in lowveld savannah or forest biomes of South Africa (Dobson, 2018). On average, a total of 7-11 butterfly species per day are expected to be observed in the fynbos-renosterveld biome (Dobson, 2018). West Coast renosterveld fragments have previously supported endangered species including the Moorreesburg Common Opal (*Chysoritis thysbe schlozae*) and Dickson's Brown (*Stygionympha dicksonii*), although none have been recorded since 2009 (Southern African Lepidoptera Conservation Assessment, 2017). These highly localised and rare species, as well as many other species occurring on renosterveld, are polyphagous species (Woodhall, 2005). Many species' larval host plants can be found in similar South African biomes such as fynbos and succulent karoo (SALCA, 2017). While no butterfly species are known to feed on plants exclusively found in renosterveld, some species can be relatively uncommon or found in a limited geographical region which includes renosterveld, including the aforementioned endangered species, and non-threatened species such as the Tulbagh Sylph (*Tsitana tulbagha tulbagha*) (SALCA, 2017). Other renosterveld-occurring butterfly species of the Lycaenidae family are myrmecoxenous, meaning the larvae rely on or benefit from feeding and shelter in ant colonies. Such species include the Boland Skolly (*Thestor protumnus)*, the Pan Opal (*Chrysoritis pan)*, the Dull Copper (*Aloeides pierus*) and the Pointed Copper (*Aloeides apicalis*). Colonies of these butterfly species may only occur in restricted ranges of up to 100m in diameter (SALCA, 2017). Suitable ant species colonies for associative or obligatory relationships with these butterflies may be found in areas of natural habitat. Thus, renosterveld remnants may provide some of the only suitable conditions for some species with specific habitat requirements in otherwise transformed landscapes of the CFR, where much natural habitat is lost. Bowie & Donaldson (1999) emphasized the importance of connectivity of remnants for the Cupreous Blue (*Eicochrysops messapu*s), which occurs in the CFR and more widely through South Africa (Woodhall, 2005). Both local and landscape scale attributes of renosterveld can therefore play a role for renosterveld butterflies (Topp and Loos, 2019b), although to date we are not aware of studies that have focused specifically on the response of butterflies to fire in renosterveld at a landscape scale.

Our overarching research question is: How does butterfly diversity vary along a disturbance gradient of time since last fire and landscape context in remaining renosterveld fragments? In addressing this question, we also aim to derive management recommendations for effective conservation of butterfly diversity in fragmented and fire-prone renosterveld. We first investigate the relationship between time since the last fire and vegetation diversity and structure in order to assess the link between fire history and potential plant and floral resources. We then investigate the relationships among vegetation diversity and structure, time since last fire and landscape context with butterfly diversity, in terms of butterfly species richness, abundance, and composition. Previous studies in other grassland ecosystems have shown that recently burned sites had similar or higher butterfly abundances to fire-excluded sites (e.g. Henderson et al, 2018; Panzer and Schwarz, 2000) which is in contrast to the hypothesis that butterfly abundance would be higher in fire-excluded sites (Panzer and Schwarz, 2000). We hypothesized that recently burned renosterveld sites would have higher plant diversity and, correspondingly, higher butterfly species richness and abundance than unburned sites. We also hypothesized disturbance through fire to be more strongly negatively associated with low mobility species than high mobility species, which should be able to move more freely through the landscape and make use of patches of varying burn ages. Nearby natural habitat is an important factor for butterflies and in a fire-prone landscape could potentially enable butterflies to recolonize recently burned areas. We therefore hypothesized that more natural habitat in the surrounding landscape would also benefit butterfly diversity in focal fragments.

Materials and methods

Study region

Our study area was the Swartland municipality and its close surrounding, Western Cape, South Africa, approximately 60km north of Cape Town (Fig 1). The region has a Mediterranean-type climate with winter rainfall and hot, dry summers. The land use is predominantly grain farming, including wheat, oats and barley, along with livestock, wine grape and vegetable production. The majority of the remaining renosterveld is West Coast renosterveld, which grows on relatively fertile soils which are also nearly always clay-rich (Henning, Terblanche & Ball, 2009). Renosterveld is comprised of small-leaved, evergreen shrubs with an understory of grasses and high proportion of geophytes (Bergh et al., 2014). Remaining renosterveld fragments are mostly privately owned and occur on steep hillsides, which cannot easily be cultivated. Fragments vary greatly in size, with the majority of larger fragments on the borders of the Swartland municipality, although several large (>1000ha) fragments remain within the agricultural landscape. It is common for Swartland grain farmers to annually burn the wheat stubble fields during autumn (March-April). These burns are normally closely controlled and any adjacent renosterveld is seldom burned. Fires in remaining renosterveld may be either accidental due to human negligence (e.g., sparks from farming machinery) or, more rarely, in fragments which are managed as reserves, deliberately initiated by the land manager to remove shrubs and regenerate floral diversity. Renosterveld fragments which have not been subject to fire in the previous ten to fifteen (approximate) years are often dominated by mature bushes such as renosterbos (*Elytropappus rhinocerotis*), kraalbos (*Galenia africana*) or kapokbos (*Eriocephalus africanus*). Some renosterveld fragments are grazed in either high or low intensity, mostly by sheep and cattle, although renosterveld is rather seen as supplementary grazing provision for when croplands are growing and cannot be used for grazing (Curtis, 2013).

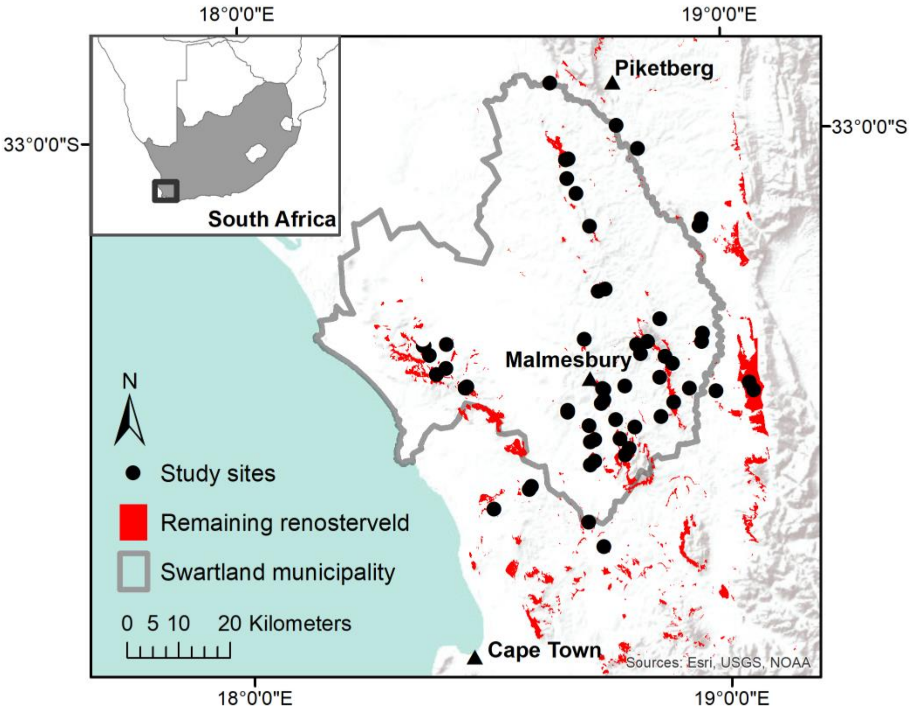


Figure 1 : Map of the study region. The 58 study patches lie within the Swartland municipality and its close surrounding and are shown as black circles. Notable towns and cities are shown as black triangles.

Site selection

We selected 50 renosterveld fragments across the Swartland as study sites to cover a gradient of time since the previous fire and a range of different fragment sizes (between 0.7 ha and 4227.6 ha, median 22.6 ha). Thirty-two of our study fragments were selected from a previous study on butterflies in renosterveld (Topp and Loos, 2019b). Eight of our study fragments were designated nature reserves under either private or public ownership and 42 were privately owned. Eight study fragments contained patches of different fire ages (Fig 2a-c), so we considered these as separate sites and sampled them separately, resulting in 58 sampled renosterveld sites overall. We identified the time since previous fire for each site by checking two GIS datasets: all fires on Cape Nature properties from 2016-17 (Western Cape Nature Conservation Board, 2017) and the Moderate Resolution Imaging Spectroradiometer (MODIS) data for the Swartland municipality from 2002-2018 (MODIS Collection 6, 2018). We also checked sites visually using freely available historical satellite imagery (Google Earth Pro Version 7.1.8.3036). We confirmed time since last fire and grazing regime with local experts and the land owner or manager. Study sites of known burn age ranged from 1 to 16 years since last fire and may have burned accidentally or through prescribed burning.

For sites of more than 16 years since the last fire, we could not be certain of the exact year due to lack of accurate remote-sensing data and approximate information by landowners, and therefore we categorized these sites separately as 16+ years. We did not include these sites in the subset of data for linear modelling of fire on vegetation and on site-level butterfly diversity (*n* sites = 21). We categorized grazing regime into three types: heavily grazed, lightly grazed and non-grazed. We obtained information on fragment sizes from the South African National Biodiversity Institute (SANBI) spatial data layer of mapped remaining renosterveld fragments, accessed through the SANBI GIS repository (http://bgis.sanbi.org). To investigate the landscape context, we calculated the amount of natural habitat (renosterveld and non-renosterveld vegetation) within a 2km radius of the survey location in each site. In lieu of detailed information on butterfly dispersal in our study area, we selected this distance as it is known to allow for dispersal of butterflies in other fire prone landscapes (Henderson et al., 2018). However, we acknowledge that butterfly dispersal can be highly variable. Furthermore, we investigated the landscape context through the number of neighbouring fragments within a 5km radius, in GIS using the same renosterveld fragment data layer. We measured a 2km radius from the centroid of butterfly sampling GPS points, and thus the amount of natural habitat in the surrounding 2km included the selected fragment itself (Rand & Tscharntke, 2007; Spiesman, Bennett, Isaacs & Gratton, 2017). Therefore, larger selected fragments by definition had larger amounts of natural habitat in the surrounding, but smaller selected fragments may also have large amounts of natural habitat in the surrounding if they were located within 2km of other natural habitat fragments. The amount of natural habitat in the surrounding 2km from the surveyed locations ranged between 1.41 ha and 1224.9 ha (median 91.34 ha).

Figure 2a – Koringberg (-33.045718, 18.673489), one of the larger renosterveld study sites in the Swartland region, with both recently burned (3 years prior to study, light green young growth, left hand side of photo) and unburned (more than 30 years since last fire, dark green woody vegetation, in foreground and on right hand side of photo) patches. 2b - The lower east-facing slope of Contreberg (-33.450922, 18.465570) which has not burned in more than 20 years, and 2c - the upper part of the slope, which burned accidentally in 2017. Photos: E. Topp 2018.

Butterfly and vegetation recording

We visited each of the 58 renosterveld sites five times in total; four times during the spring-summer period of August-December 2018 and once in the autumn period of March-April 2019, to maximize the opportunity to detect species of different flight periods and voltinism. We conducted surveys on days with a temperature of at least 17°C and extended dry periods between 9.30 am and 5 pm (Pollard, 1977; Terblanche & Edge, 2011). During each round, we changed the time of day that we surveyed each site to capture temporal variation in butterfly activity. Two fieldworkers each walked four separate random transects through the renosterveld of 5 minutes in duration, so that each site was surveyed a total of 40 minutes per survey round. Fieldworkers walked at least 20m apart to cover different areas of the site, while remaining within eyesight of each other. Each fieldworker walked at a steady pace, slow enough to spot butterflies which may be moving low to the ground, surveying the area approximately 4m either side of the transect, similar to Leone et al. (2019) and recommended by Terblanche & Edge (2011). During each transect walk, we counted and recorded all butterflies seen and aimed not to record the same individual twice. Where possible, we recorded butterflies to species level in flight. Where the butterfly species was uncertain, we captured, photographed and released the individual, which was later identified by a local expert (see Acknowledgements). At the end of each five-minute transect, each fieldworker sampled a representative 2m x 2m vegetation plot, in which the species richness of plants and vegetation structure-related variables were recorded (Table 1). As we walked random transects during each visit, we sampled the vegetation on every visit, resulting in a total of 2320 transects (40 plots/site).

Data analyses

We analysed the data in five steps. We first investigated how fire is related to vegetation at the transect level, where each transect was an individual observation in the dataset. To this end, we calculated generalized linear mixed models for each vegetation variable (Table 1) as a response variable, using time since fire as an explanatory variable. We used the subset of the data with time since last fire as a continuous variable (*n* sites = 21), treating fragment and survey round as random factors. In this subset, two sites were heavily grazed, two were lightly grazed and 17 were not grazed, thus we did not have an optimal number of observations per grazing category to include grazing as a random effect. We therefore included grazing as an explanatory variable to account for possible correlations, although we did not design the study to test this variable. As we had few sites with very large amounts of natural vegetation and many sites with small amounts of natural vegetation in the surrounding, we square-root transformed the amount of natural habitat to account for this imbalance (e.g. Steffan-Dewenter & Tscharntke, 2000). This step also takes into consideration the species-area relation, which saturates following a steep incline. For shrub height, we first used a binomial model to see if fire was associated with the presence of shrub or not, and then modelled a subset of the data where the height was greater than zero.

Table 1. Vegetation variables sampled in each plot in each renosterveld study site (40 plots per site in total).

Vegetation variable	**Description**
Number of plant species	We counted the number of different plant species present in the plot. We verified plant species counts by having two fieldworkers make separate counts of the same plot.
Number of flowers	We pooled the number of flowers of all plant species in the plot. We considered one floral unit as a visible single head of a flower. Where species had multiple small flowers in clusters, for example *Hymenolepis spp*, we estimated the number of flowers in a single cluster and multiplied by the number of clusters. Where there were too many flowers to accurately and efficiently count (>500) we approximated by counting a smaller area of the plot and scaling up to the plot area (4m²).
Shrub height	We placed a 2-metre ruler at five random locations in the plot and measured the shrub height. We determined shrub as vegetation having woody stems and usually identified as *Elytropappus rhinoceritis, Galenia africana*, *Eriocephalus africanus* or *Searsia spp*. We later summed and averaged these five measurements to get the mean shrub height for each plot.
Non-shrub vegetation height	We did the same as above for all other vegetation in the plot, including graminoids and forbs.
% vegetation cover	The estimated proportion of the sample plot covered by vegetation, the remainder being bare soil.

Second, we investigated the association between vegetation and butterfly diversity at the transect level, using the full dataset (*n* sites = 58). Our response variables were butterfly species richness and butterfly abundance per transect and our explanatory variables were the vegetation variables (Table 1). We used generalized linear mixed models with a Poisson distribution for species richness and a negative binomial distribution for species abundance (Warton et al., 2016), treating fragment, survey round and grazing regime as random factors. Where species richness data were underdispersed, we used a generalized Poisson distribution (Harris et al., 2012). We observed very high abundances of Painted Lady (*Vanessa cardui)* in several sites due to migration, thus removed this species from our analyses to reduce anomaly (Öckinger & Smith, 2007). We classified butterfly species into high and low mobility using information taken from the literature on body and wing size (Mercenero et al., 2013; Woodhall, 2005) and expert consultation (Table S1), and then applied the same analyses for high and low mobility butterfly species separately.

Third, we investigated the association between time since last fire and landscape context with butterfly diversity. Each site was treated as an individual observation, using the same subset of the data as in step 1, with time since last fire as a continuous variable (*n* sites = 21). Our response variables were pooled butterfly species richness and pooled species abundance data at the site level, and our explanatory variables were time since last fire and natural habitat in the surrounding landscape. We again included grazing as an explanatory variable rather than a random effect, although we did not design the study to test this variable. We chose to use the amount of natural habitat in the surrounding landscape as an explanatory variable because butterflies are a generally mobile taxon and many species are able to cross different habitat types. This variable was highly correlated with fragment size (0.89 Pearson's correlation coefficient); therefore, we did not include fragment size into the models. As before, we used generalized linear mixed models with a Poisson distribution for species richness and a negative binomial distribution for species abundance, treating fragment and grazing regime as random factors. We tested for interactions between time since fire and landscape context. We also tested for a unimodal relationship of time since last fire by including a quadratic term in the model equations. We then applied the same analyses for high and low mobility species separately. In all models for steps 1-3, we checked for correlation between explanatory variables and where variables were considered to be correlated (>0.5 Pearson's correlation coefficient), we included only one variable in the model. We also made backwards stepwise selection to include only variables with statistically significant predictive power in our final models. We used the R package glmmTMB (Brooks et al., 2017).

In a fourth step, we analysed the six fragments which contained both a recently burned site (less than six years ago) and long-since burned site (more than 16 years ago). We tested differences in butterfly species richness and abundance between the paired sites with a Student's *t*-test. This enabled us to check the effect of fire on butterfly diversity without additional inter-fragment variability.

Lastly, to see if species composition was associated with fire and landscape context, we performed non-multi-dimensional scaling (NMDS) analysis and fitted site-level environmental variables (i.e., time since last fire and natural habitat in the surrounding area) with a permutation test using the function *envfit* in the vegan package in R (Oksanen et al., 2019). We used a 'Bray-Curtis' dissimilarity index to indicate dissimilarity among sites. In order to include all observed species in the ordination, we included all surveyed sites (n=58) and for sites in which fire occurred more than 16 years ago, we considered them as 20 years since last fire. We performed all analyses in R Version 3.6.1 (R Core Team, 2020).

Results

We observed 6131 butterfly individuals (excluding *Vanessa cardui*, 9273 individuals) during the survey period from a total of 29 species and five families (for full species list see Supplementary Material 1). Butterfly abundance was highest in the second survey round (2598 individuals), from 27/09/18 - 17/10/18. The highest number of species observed at one site was 14, the lowest was two and the median was six. We did not observe any species classified as Endangered, Vulnerable, Near Threatened or Rare according to Red List criteria (SALCA, 2017). Thirteen species were considered to be of high mobility and 17 considered to be of low to medium mobility.

We found that time since the last fire was significantly associated with all sampled vegetation variables except for number of flowers (Table 2). While increased time since fire was negatively associated with our observed plant species diversity, we found a positive association of time since fire with the presence of shrub, shrub height, the height of non-shrub vegetation and the proportion of vegetation cover within the plot. We also found a negative association of grazed sites with presence of shrub (Table 2).

Vegetation variables had mixed relationships with butterfly species richness and abundance (Table 3). We found a positive association between plant species richness and butterfly species richness and abundance at the transect level, for both high and low mobility butterfly species. For low mobility butterfly species richness, we found a negative association with the proportion of vegetation cover. The number of flowers was significantly positively associated with butterfly species abundance, and to a lesser extent with butterfly species richness. We found a significant positive association between the height of non-shrub vegetation and our observed butterfly abundance, and a negative association with increasing vegetation cover. At site level, the amount of natural habitat in the surrounding landscape was positively associated with species richness (Fig 3) and to a lesser extent, low mobility butterfly species abundance (marginally statistically significant). We found no association with the number of neighbouring fragments within a 5km radius of our study sites and no interactive association of fire and natural habitat in the surrounding landscape. We found a negative association between time since last fire and low mobility butterfly species richness, whereas we found a positive association of time since last fire with high mobility species richness (Fig 3). Time since last fire was also significantly negatively associated with total butterfly species abundance. We did not find a significant relationship for a quadratic term of time since last fire and, therefore, could not confirm a unimodal relationship of time since last fire and butterfly diversity. These patterns were observed for up to 16 years but could not be confirmed for sites of more than 16 years, where variability in butterfly diversity may be driven by unknown successional age or other unknown factors.

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Table 2. Summary table of predicted effects of fire on renosterveld vegetation at transect level. Each row corresponds to one model. Highly statistically significant p-values are shown in bold. Levels of significance are indicated by stars (.<0.1; *<0.05; **<0.01; ***<0.001). “na” = not available, “ns” = non-significant. Z values are shown except for linear models where the t-value is shown. Intercept for site level models includes first level of grazing effect, i.e. non-grazed sites.

	Model performance		**Model coefficients**																
			(Intercept)				Time since last fire				Grazing Lightly grazed				Grazing Heavily grazed			
Response variable	R^2 cond.	R^2 marg.	Est	SE	z	p	Est	SE	z	p	Est	SE	z	p	Est	SE	z	p
No. plant species	0.49	0.05	2.43	0.12	20.63	**<0.001*** **	-0.02	<0.01	-5.11	**<0.001*** **				ns				ns
No. flowers	0.28	<0.01	4.31	0.32	13.27	**<0.001*** **				ns				ns				ns
Presence of shrub	0.63	0.46	-0.63	0.41	-1.51	0.13	0.41	0.06	6.56	**<0.001*** **				ns	-2.1	1.02	-2.06	0.04*
Shrub height	0.43	0.34	38.42	2.47	10.44(t)	**<0.001*** **	2.83	0.27	10.44(t)	**<0.001*** **				ns				ns
Non-shrub vegetation height	0.19	0.07	21.43	1.32	16.24	**<0.001*** **	0.56	0.1	5.45	**<0.001*** **				ns				ns
Vegetation cover (%)	0.47	0.3	0.38	0.03	12.6(t)	**<0.001*** **	0.03	<0.01	12.22(t)	**<0.001*** **				ns				ns

Table 3. Summary table of predicted effects of vegetation (transect level) and landscape (site level) predictor variables on butterfly species richness and abundance. Effects were generated from generalized linear mixed models selected following backwards stepwise selection, so final models included only statistically significant variables. Each row corresponds to one model with included predictor variables. Highly statistically significant p-values (***<0.001) are shown in bold. Levels of significance are indicated by stars (.<0.1; *<0.05; **<0.01; ***<0.001). "na" = not available; "ns" = non-significant. Intercept for site level models includes first level of grazing effect, i.e. non-grazed site

		Model performance		**Model coefficients**																							
		R^2		(Intercept)				No. of plant species				No. of flowers				Shrub height				Non-shrub vegetation height				Vegetation Cover			
	Response variable	cond.	R^2 marg.	Est	SE	z	p	Est	SE	z	p	Est	SE	z	p	Est	SE	z	p	Est	SE	z	p	Est	SE	z	p
Transect	Butterfly species richness (total)	0.29	0.03	-0.53	0.22	-2.34	0.02*	0.04	<0.01	5.73	**<0.001*** **	<0.01	<0.01	1.86	0.06.				ns				ns	<-0.01	<0.01	-2.58	<0.01**
	High mobility species richness	0.52	<0.01	-1.12	0.5	-2.25	0.02*	0.02	<0.01	2.81	<0.01**				ns				ns				ns				ns
	Low mobility species richness	0.37	0.03	-1.87	0.43	-4.35	**<0.001*** **	0.06	0.01	4.96	**<0.001*** **				ns				ns				ns	<-0.01	<0.01	-4.86	**<0.001*** **
	Butterfly abundance (total)	0.5	0.06	-0.14	0.3	-0.46	0.64	0.05	<0.01	6.95	**<0.001*** **	<0.01	<0.01	4.83	**<0.001*** **				ns	<0.01	<0.01	3.87	**<0.001*** **	<-0.01	<0.01	-2.09	<0.05*
	High mobility species abundance	0.71	0.01	-0.71	0.65	-1.08	0.28	0.03	<0.01	3.93	**<0.001*** **	<0.01	<0.01	3.89	**<0.001*** **				ns	<0.01	<0.01	2.91	0.02**				ns
	Low mobility species abundance	0.49	0.06	-1.94	0.52	-3.73	**<0.001*** **	0.09	0.01	6.19	**<0.001*** **				ns				ns	0.01	<0.01	2.72	0.01**	-0.01	<0.01	-6.28	**<0.001*** **
		R^2		(Intercept)				Natural habitat (sqrt)				Time since last fire				Grazing Lightly grazed				Grazing Heavily grazed							
		cond.	R^2 marg.	Est	SE	z	p	Est	SE	z	p	Est	SE	z	p	Est	SE	z	p	Est	SE	z	p				
Site	Butterfly species richness (total)	na	0.44	1.65	0.18	9.31	**<0.001*** **	0.02	<0.01	2.37	<0.02*				ns				ns	-0.7	0.43	-1.7	0.09.				
	High mobility species richness	0.79	0.53	0.41	0.16	2.52	**0.01***	0.02	<0.01	2.89	<0.01**	0.03	0.01	2.13	0.03*	0.41	0.22	1.85	0.06.				ns				
	Low mobility species richness	na	0.39	1.35	0.21	6.29	**<0.001*** **	0.03	0.01	2.46	<0.05*	-0.06	0.02	-2.25	0.02*				ns				ns				
	Butterfly abundance (total)	na	0.41	5.11	0.17	29.35	**<0.001*** **				ns	-0.06	0.02	-2.57	0.01*				ns	-0.6	0.37	-1.7	0.08.				
	High mobility species abundance	na	0.17	4.66	0.19	23.42	**<0.001*** **				ns	-0.05	0.03	-1.71	0.09.				ns				ns				
	Low mobility species abundance	0.96	0.53	3.18	0.39	8.18	**<0.001*** **	0.04	0.02	1.74	0.08.	-0.08	0.01	-5.3	**<0.001*** **				ns	-1.5	0.69	2.1	0.04*				

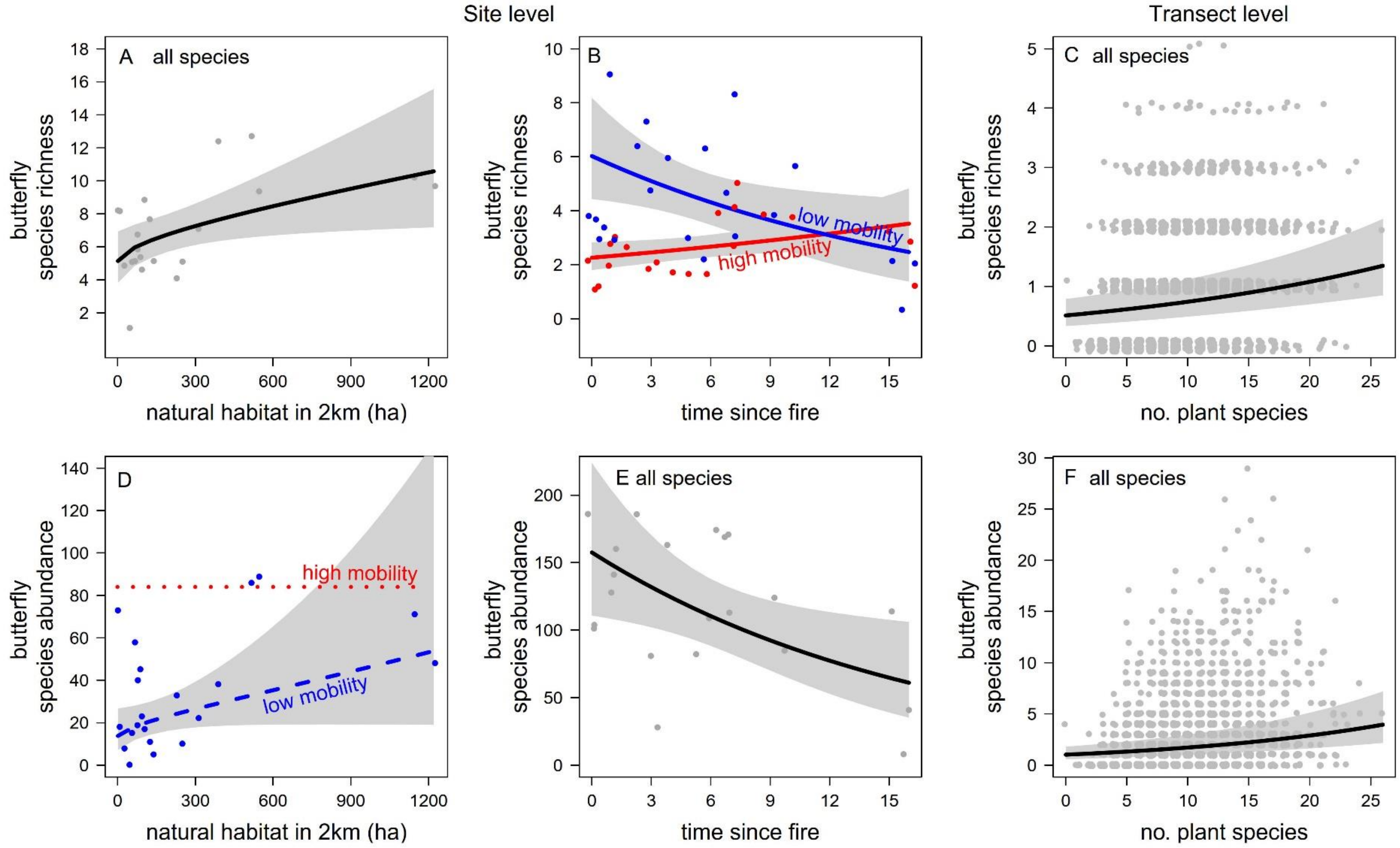

Figure 3. Predicted effects from the fitted generalized linear models for the amount of natural habitat in the surrounding landscape; the time since last fire and the number of plant species on butterfly richness (top row) and abundance (bottom row). Only relationships that were statistically significant are shown. Points show individual observations. Grey bands show 95% confidence intervals. Site level model graphs (panels A, B, D and E) show total butterfly species richness and abundance per site; transect level model graphs (panels C and F) show butterfly species richness and abundance per transect. Black lines refer to total butterfly species; red lines refer to high mobility butterfly species and blue lines refer to low mobility butterfly species. Red dotted line (panel D) shows mean high mobility species abundance across all sites for comparison with modelled low mobility species abundance (blue dashed lines, $p<0.1$)

We found that butterfly species richness and abundance differed between pairs of recently burned and old sites in the same fragment (Fig 4). Across all pairs, butterfly species abundance was significantly lower in sites where fires occurred more than 16 years ago (t=2.62, p=0.046), whereas species richness did not differ significantly between paired sites (t=0.73, p=0.49). Median butterfly species richness was 5 in sites 0-6 years and 6 in sites of 16+ years. Median butterfly abundance was 106.5 in sites of 0-6 years and 98.5 in sites of 16+ years.

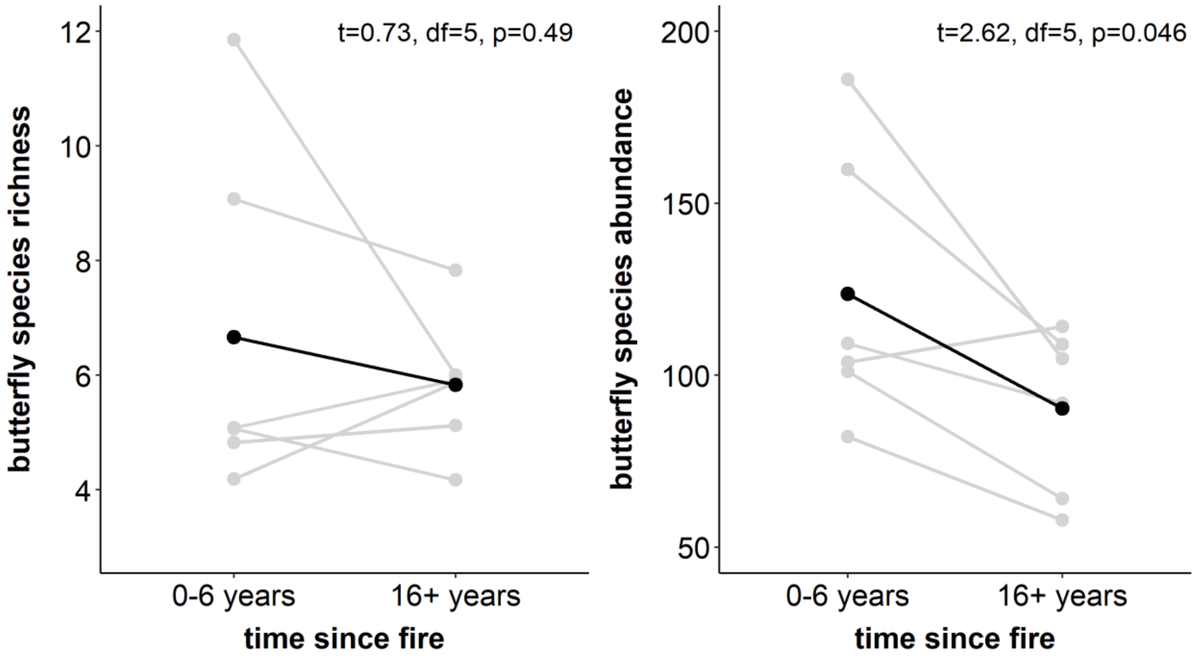

Figure 4. Difference in total butterfly species richness (left) and abundance (right) between pairs of sites in the same fragment (n=6). Sites were burned either 0-6 years ago or more than 16 years ago. The difference for abundance between pairs of sites was significant in a paired t-test (p<0.05). Means are shown as black circles and linked with black lines. Original data points are shown as grey points. Grey lines link data points from pairs of sites and indicate general direction of trend.

The NMDS suggests that renosterveld butterfly composition is also associated with time since last fire and the amount of natural habitat in the surrounding landscape (Fig 5). There appears to be little clustering of species according to mobility, although high mobility species including the Common meadow white (*Pontia helice)*, the Painted Lady (*Vanessa cardui)* and the Boland Brown (*Melampias huebneri*) appear to be more associated with increased time since fire. Certain species appear to be associated with sites with more natural habitat in the surrounding landscape, such as the Boland Skolly (*Thestor protumnus)* and the Protea Emperor (*Charaxes pelias)*. Other low mobility species were scattered across even small or isolated sites without much natural habitat in the surrounding. The divergence of the fitted variables (time since last fire and surrounding natural habitat) suggests compositional dissimilarity among sites where fires occurred more than 16 years ago and sites with more natural habitat in the surrounding landscape; both fitted variables were significant at p<0.05.

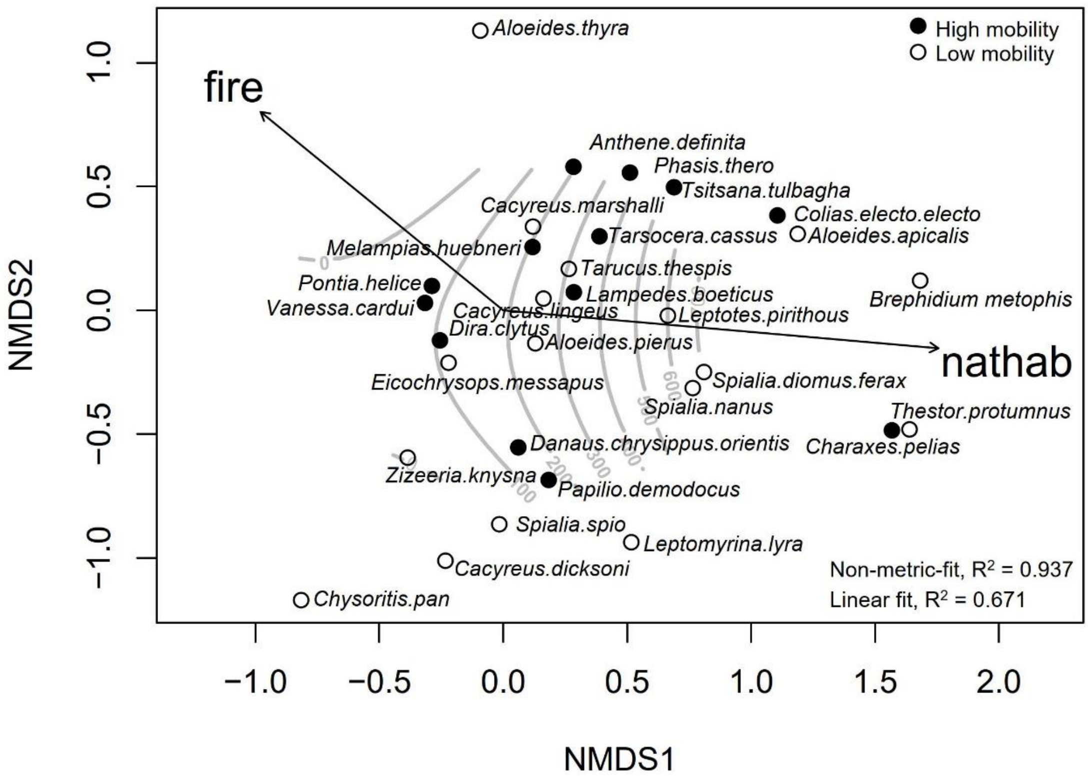

Figure 5. Non-metric multidimensional scaling of butterfly species with fitted environmental variables (significant at <0.05), "fire" = time since the last fire in years, "nathab" = amount of natural habitat in the surrounding 2km from the survey location. Contours of modelled natural habitat amount (hectares) are shown in grey, increasing from left to right (0 to 600 ha) in the ordination.

Discussion

Our results showed that fire plays a role for vegetation and butterfly diversity in renosterveld fragments at both the local and landscape level. Fire was consistently associated with vegetation change in our study, which demonstrates the transformative effect of fire in the renosterveld ecosystem (Cousins et al., 2017; Curtis et al., 2013; Kraaij & van Wilgen, 2014). We hypothesized that fire would be positively related to renosterveld plant diversity, which in turn may be associated with higher butterfly diversity through the emergence of attractive floral resources and larval food plants. Indeed, the associations we observed between vegetation and butterfly species richness and abundance demonstrate how fire may be indirectly related to renosterveld butterfly diversity through vegetation. At the transect level, plant diversity was positively associated with both butterfly species richness and abundance, while flower abundance was important for butterfly abundance, although it was not associated with fire. Fire adaptation among renosterveld plant species is complex, due to the exceptional endemism and wide range of reproductive traits including re-seeding and sprouting, which may be fire-adapted through responses to heat and smoke (Cousins et al., 2017). For example, *Protea* spp. are present in many renosterveld-fynbos transitional areas, are fire-adapted, and are also host plants for endemic CFR butterflies such as the Orange-banded protea (*Capys alpheus alpheus*) (Mercenero et al., 2013).

The change in vegetation structure and increase in openness immediately following a fire may indirectly benefit butterflies also by providing opportunities for activities such as patrolling and basking (Dennis, 2004; Gillespie & Wratten, 2012). We found that time since fire was significantly negatively associated with vegetation cover, which in turn was negatively associated with butterfly species richness and abundance. Low mobility species were particularly negatively associated with increased vegetation cover. This trend could be due to the lack of gaps for host plants, upon which the abundance of low mobility species and habitat specialists is particularly dependent (Curtis et al., 2015). The removal of shrub and other vegetation through fire creates gaps in renosterveld for the establishment of annuals, including *Poaceae* grasses (Cousins et al., 2017) and *Crassulaceae* spp. (Krug, 2004), which are larval host plants for observed butterfly species including the Tulbagh Sylph (*Tsitana tulbagha tulbagha*) and Cape Black-eye (*Leptomyrina lara*). However, structural heterogeneity in renosterveld fragments may also be beneficial for butterflies, as shrub components including *Elytropappus rhinoceritis* may act as nurse plants for other renosterveld plant species (Simons, 2017). Mature shrubs can also provide high numbers of pollinator-attracting flowers, which may explain why we found no association between fire and flower abundance.

In addition to these indirect associations between fire and butterflies via vegetation, fire may directly affect butterfly populations by loss of individuals at egg and larval stages. Adult butterflies (imago), as mobile taxa, may be able to escape fire and to quickly recolonize, unlike many other pollinators which may be limited in their dispersal ability (Johansson et al., 2020; Steffan-Dewenter et al., 2002). Greater proximity and amount of neighbouring habitat can allow for recolonization of recently burned patches by butterfly species (Moranz et al., 2012). We hypothesized that natural habitat would be positively associated with butterfly diversity in focal fragments. Our study found that natural habitat in the surrounding landscape was positively associated with overall butterfly species richness. We also observed that overall butterfly abundance is negatively associated with time since last fire, and that in large fragments where one part has been burned, butterfly abundance is higher than in the remaining area which remains late-successional. These observations suggest the importance of the availability of good quality habitat within large habitat fragments and also in the landscape for butterfly populations (Kormann et al., 2019; Pocewicz et al., 2009), particularly for highly fragmented Mediterranean-type ecosystems where surrounding land use may be intensive (e.g. Fernández-Chacon et al. 2014; Stefanescu et al., 2004). Renosterveld fragments in the surrounding landscape to the focal fragment are a potential pollinator source for renosterveld plant species, suggesting that landscape context plays an important role for mutualistic species relationships (Donaldson et al., 2002). Therefore, while vegetation structure at the local scale is crucial in providing suitable habitat quality, which affects butterfly diversity, this cannot be considered in isolation to landscape-level attributes (Loos et al., 2014; Öckinger and Smith, 2007; Steffan-Dewenter et al., 2002), particularly when the landscape is fire-prone and successional stage can alter habitat quality.

We also hypothesized disturbance through fire to be more strongly negatively associated with low mobility species than high mobility species. We found that high mobility (as proxy for larger body and wing size and stronger fliers) species richness was positively associated with time since last fire. The highly mobile species observed in our study sites included the Common Meadow White (*Pontia helice*) and the Citrus Swallowtail (*Papilio demodocus*), the larvae of which feed on Brassicaceae and cultivated *Citrus* spp, respectively, and may therefore persist in agricultural landscapes without the need to use renosterveld. As suggested by the results of our NMDS, highly mobile species such as *Melampias huebneri* and the Spring Widow (*Tarsocera cassus*) are able to roam in search for habitat, and therefore may be present in late-successional fragments or more isolated fragments. We found that low mobility (as proxy for decreasing body size and migrational ability) butterfly species were positively associated with increasing natural habitat in the surroundings and, similar to Steffan-Dewenter and Tscharntke (1997), were negatively associated with increasing successional age. However, low mobility species varied from generalist and widespread species to colonial species with limited ranges. Thus, although body and wing size may differ among species, other traits leading to successful dispersal may drive functional butterfly diversity in remaining renosterveld. For example, small weak fliers such as the Cupreous Blue (*Eiochrysops messapus*) and the Fynbos Blue (*Tarucus thespis*) rely on larval host plant species from the genera *Thesium* and *Phylica*, respectively, both of which widely occur in Western Cape fynbos and renosterveld (Mercenero et al., 2013), and are fire-adapted. *Thesium* species are able to reappear following fire due to long-lived seedbanks, and *Phylica* species may be obligate reseeders or ant-dispersed (Kraaij & van Wilgen, 2014). Daily foraging patterns of generalist butterflies with widespread larval host plants, such as the African Grass Blue (*Zizeeria knysna*), which also occur in disturbed agricultural lands, may also support dispersal. Additionally, many low mobility butterfly species we found, such as *Thestor protumnus* and *Aloeides* spp., have obligative or associative associations with ant colonies (Edge & van Hamburg, 2010). Ants may be particularly resilient to fire in the CFR (Pryke & Samways, 2012). Successful ant colony survival or colonization following disturbance through fire may thereby support the favourable conditions for these butterflies' colonization of remaining fragments.

Implications for management

Resilient agricultural landscapes that support biodiversity would ideally consist of a mosaic of well-connected early and late successional habitats, ensuring that recolonization can take place following disturbance (Bengtsson et al., 2003; Tscharntke et al., 2005). However, fire can be viewed as problematic in fragmented agricultural landscapes, where it can pose a threat to crops, livestock and humans (van Wilgen et al., 2010). Current renosterveld conservation management, which includes prescribed burning, is mostly focused on the large remaining fragments. Small fragments are nonetheless important for collective butterfly diversity across the target landscape (Fahrig 2020, Topp and Loos, 2019b), and it is therefore key to ensure a range of successional ages and structural heterogeneity across all fragment sizes, as part of landscape-scale conservation strategies (e.g. von Hase et al., 2003). Some Swartland renosterveld fragments may be designated as nature or biosphere reserves, although this term covers a broad range of management activities of which prescribed burns are not necessarily an integral part. Renosterveld is considered to be of little use by many land managers and largely left unattended, which may be in part due to lack of clarity on the necessity to burn and the associated risks (Cousins et al., 2017; Wilgen, 2013). Farmers in the Swartland annually burn their wheat fields following harvest, a practice which some consider outdated and harmful to soils, but may provide an opportunity for controlled burns to take place in renosterveld patches adjacent to farmland. Conservation practitioners recommend to burn renosterveld every 10-15 years to regenerate plant diversity (Curtis, 2013; Kraaij & van Wilgen, 2014; Esler, Piers & de Villiers, 2014), which our results suggest would also benefit butterflies. Our results suggest that more frequent burns may be particularly positively associated with butterfly abundance, while the range of responses of butterfly richness suggest that some sites older than 16 years may also host diverse butterfly populations. For example, burning areas within fragments every ten years or so could support low mobility butterfly species, while high mobility species may persist in fragments with burns of 15 years or more. Such a mosaic approach to fire regime would increase the diversity of renosterveld structures and may cater for different habitat preferences of various butterfly species, while corresponding to recommendations for plant diversity.

Ideally, butterfly surveys would take place before prescribed burns, in order to assess potential impacts. For example, while widespread species may be able to recolonize following a burn, rare or highly specialized species may struggle to recolonize if there is a lack of metapopulations, such as the case of the Brenton Blue butterfly (*Orachysops niobe*) elsewhere in South Africa (Brenton Blue Trust, 2019). Some lycaenid species that we observed, such as *Thestor protumnus* and *Chysoritis pan*, have strictly colonial population structures of limited area, and may be particularly vulnerable to direct mortality due to fire. In this case, it may be beneficial to burn partially without disturbing the colony, but still providing habitat heterogeneity, as recommended for single species conservation elsewhere (e.g. New et al., 2010). Our study investigated the time since previous burn of all sites. We did not investigate the relationship of butterfly diversity to repeated short-term burns in renosterveld, which would be an important step for future research. Moreover, ecologically appropriate fire regimes must be complemented by supportive grazing regimes so that regeneration of plant diversity is not mitigated by livestock too soon following a burn (Curtis et al., 2013; Esler et al., 2014).

Our data reflect the heterogeneous nature of the agricultural landscape in question; however, to further study the effects of grazing and its interaction with fire on renosterveld vegetation, butterflies and other associated insects, an experimental design of treatment plots including burning and grazing treatments and control plots could be used in further research. This could also address some of the study limitations given that our study design was observational rather than experimental in nature. Similar to previous studies of fire ecology and invertebrates (e.g. Adedoja et al, 2019), the interpretation of our findings may be limited given the potential influence of other environmental factors. For example, the sites of different fire ages were not randomly distributed throughout the landscape and surrounding land use, soil types and microclimate were not controlled for. It is important to note that our findings indicate associations rather than causal relationships.

In summary, landscape context and fire regime are associated with butterfly species richness and abundance in renosterveld fragments, both directly and through changes to vegetation. Conservation activity including prescribed burns, which aim to regenerate plant diversity, may therefore benefit butterfly diversity. Butterflies should be considered within the scope of fire management for fire-adapted renosterveld plant diversity. For example, butterfly surveys for rare, habitat specialists or small colonies could be conducted before burning large patches of renosterveld for plant regeneration. In this intensively farmed landscape, remaining large and small renosterveld fragments must be sensitively managed with fire and livestock in order to support landscape-wide biodiversity.

Conflict of interest

The authors declare that they have no conflict of interest.

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Supplementary Material

Supplementary Material 1: Table of environmental data for each surveyed site used in site-level models.

Fragment ID	Site ID	Natural habitat in 2km (ha)	No patches in 5km	Years since previous fire	Grazing regime (NG – not grazed, HG – heavily grazed, LG – lightly grazed)
1	1	388.98	29	1	NG
2	2	55.9	20	1	HG
3	3	25.91	31	5	NG
4	4	88.65	19	0	NG
5	5	517.49	69	7	NG
6	6	1224.9	11	10	NG
6	7	1145.71	7	6	NG
7	8	76.58	35	7	NG
7	9	77.51	37	1	NG
8	10	46.83	25	16	HG
9	11	228	22	6	NG
10	12	8.98	25	7	LG
11	13	545.81	5	2	NG
12	14	94.03	97	15	NG
12	15	67.74	91	0	NG
13	16	139.42	6	0	NG
14	17	250.54	27	16	NG
15	18	312.24	53	3	NG
16	19	104.05	33	3	NG
17	20	1.41	7	4	NG
18	21	124.63	36	9	LG

Supplementary Material 2: Table of butterfly species observed in 2018-2019 on 50 renosterveld fragments in the Western Cape, South Africa. Conservation status is from Mercenero et al (2013) and based on IUCN Red List categories: LC = Least Concern.

Butterfly species (Latin Name)	Butterfly species (Common Name)	Family	Mobility	Conservation Status	Observed abundance
Aloeides apicalis	Pointed Copper	LYCAENIDAE	Low	LC	68
Aloeides pierus	Dull Copper	LYCAENIDAE	Low	LC	448
Aloeides thyra thyra	Red Copper	LYCAENIDAE	Low	LC	2
Anthene definita definita	Common Hairtail	LYCAENIDAE	High	LC	7
Brephidium metophis	Tinktinkie Blue	LYCAENIDAE	Low	LC	1
Cacyreus dicksoni	Dickson's Geranium Bronze	LYCAENIDAE	Low	LC	4
Cacyreus lingeus	Bush bronze	LYCAENIDAE	Low	LC	18
Cacyreus marshalli	Common Geranium Bronze	LYCAENIDAE	Low	LC	112
Charaxes pelias	Protea Emperor	NYMPHALIDAE	High	LC	6
Chysoritis pan	Pan Opal	LYCAENIDAE	Low	LC	7
Colias electo electo	African Clouded Yellow	PIERIDAE	High	LC	1
Danaus chrysippus orientis	African Monarch	PAPILIONIDAE	High	LC	1
Dira clytus	Cape Autumn Widow	NYMPHALIDAE	High	LC	5
Eicochrysops messapus messapus	Cupreous Blue	LYCAENIDAE	Low	LC	230
Lampides boeticus	Pea Blue	LYCAENIDAE	High	LC	18
Leptomyrina lara	Cape Black-eye	LYCAENIDAE	Low	LC	8
Leptotes pirithous pirithous	Common Zebra Blue	LYCAENIDAE	Low	LC	8
Melampias huebneri	Boland Brown	NYMPHALIDAE	High	LC	556
Papilio demodocus demodocus	Citrus Swallowtail	PAPILIONIDAE	High	LC	19
Phasis thero thero	Silver Arrowhead	LYCAENIDAE	High	LC	20
Pontia helice helice	Common Meadow White	PIERIDAE	High	LC	3886

Spialia diomus ferax	Common sandman	HESPERIIDAE	Low	LC	11
Spialia nanus	Dwarf Sandman	HESPERIIDAE	Low	LC	37
Spialia spio	Mountain sandman	HESPERIIDAE	Low	LC	1
Tarsocera cassus	Spring Widow	NYMPHALIDAE	High	LC	378
Tarucus thespis	Fynbos Blue	LYCAENIDAE	Low	LC	141
Thestor protumnus protumnus	Boland Skolly	LYCAENIDAE	Low	LC	25
Tsitana tulbagha tulbagha	Tulbagh Sylph	HESPERIIDAE	High	LC	85
Vanessa cardui	Painted Lady	NYMPHALIDAE	High	LC	9273
Zizeeria knysna	African Grass Blue	LYCAENIDAE	Low	LC	28

Chapter 5

Decision-making for nature's contributions to people in the Cape Floristic Region: the role of values, rules and knowledge

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The Paardeberg, Western Cape, South Africa, October 2018

Highlights

- Land-use decision-making for remaining renosterveld vegetation in the Cape Floristic Region is characterized by land managers' values, rules and knowledge (*vrk*).
- Three *vrk* decision-making contexts, namely "Bottom-up conservation", "Top-down conservation" and "Utility", are associated with different nature's contributions to people (NCP) derived from renosterveld.
- Regulating NCP were associated with all *vrk* contexts, while more non-material NCP were associated with a Bottom-up conservation context.
- The *vrk* and NCP frameworks complement each other based on the inclusion of shared diversity of values, rules and knowledge.
- Application of the NCP framework demonstrates fluidity between material, non-material and regulating NCP categories as well as between both beneficial and detrimental NCP.

Abstract

Nature conservation on privately owned land depends on land managers' decision-making. Interactions between values, rules and knowledge (vrk) underpin decision-making, thus, it is important to understand these interactions to support conservation intentions. We investigated how different sets of vrk determine the decision-making context regarding the management and conservation of renosterveld, a critically endangered ecosystem in the Cape Floristic Region, and how this relates to land managers' perceptions of nature's contributions to people (NCP). From interviews with thirty land managers, we identified nine value types, four rule types, three knowledge types and 13 different NCP. We found that different vrk combinations can be grouped into three decision-making contexts: Bottom-up conservation, Top-down conservation and Utility. Each context is associated with the perception of different beneficial and detrimental NCP. Regulating NCP are perceived across all contexts, whereas non-material NCP are associated with a Bottom-up conservation context and relational values, such as family ties. Contexts that were comprised by plural value types were also associated with multiple regulating, material and non-material NCP. The prevalence of relational values in Bottom-up and Top-down conservation contexts illustrates the complexity and non-substitutability of the dynamic relationships between renosterveld and people. This indicates the importance of plural valuation in nature conservation to foster diverse NCP provided by renosterveld.

Keywords: ecosystem services, local ecological knowledge, private land conservation, relational values, renosterveld, South Africa

1. Introduction

As is widely demonstrated by the evidence given by the global and regional assessments of biodiversity and ecosystem services in the last two decades, biodiversity and its ability to provide multiple nature's contributions to people (NCP) are increasingly threatened (IPBES 2019, 2018a-d; MA 2005; Diaz et al. 2019). NCP are defined as "all the contributions, both positive and negative, of living nature to people's quality of life" (Díaz et al. 2018, p270) and encompass other conceptualizations of these contributions, such as ecosystem goods, services, benefits or nature's gifts (Díaz et al. 2018; IPBES 2019; Ellis et al. 2019). The recent Global and Regional Assessments of Biodiversity and Ecosystem Services of the Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES) provide evidence on the essential role of both biodiversity and NCP for the good quality of life of human societies, and how both biodiversity and NCP are jeopardized by multiple drivers of change (IPBES 2019, 2018a-d). Among the full array of drivers of change, the transformation of ecosystems to agricultural and urban land is considered the largest driver undermining the capacity of biodiversity to provide NCP (MA 2005; Pereira et al. 2012; Díaz et al. 2019; IPBES 2019; 2018a-d). However, land use changes result from the individual and collective decisions on land planning and management that are underpinned by the complex interactions between individual and societal values, rules and knowledge (IPBES 2019; Colloff et al. 2017b). These interactions form part of the institutions, governance structure and societal dynamics that are increasingly recognised as one of the most relevant knowledge gaps in ecosystem service research (Mastrangelo et al. 2019).

Interactions between values, rules and knowledge (vrk) define the decision-making contexts of individuals and social actors that drive actions either for conserving ecosystems or for transforming them to other land uses, such as agriculture (Martín-López and Montes 2015; Colloff et al. 2017a). The vrk perspective, which has originally been applied in climate change adaptation research (Wise et al. 2014; Gorddard et al. 2016; Prober et al. 2017), emphasizes that a particular actor uses a system of values, knowledge and rules when designing or deciding on ecosystem management actions. Reflection on these decision-making contexts can reveal pertinent aspects of how society and institutions shape decisions and enables identification of new options and strategies for conservation and ecosystem management (Colloff et al. 2018). In this paper, we refer to values (V) as the importance of a particular asset (i.e. biodiversity and ecosystems) for itself or for others (Pascual et al. 2017). Diverse actors value biodiversity and ecosystems in multiple ways, including intrinsic, instrumental and relational values (Díaz et al. 2015; Chan et al. 2016; Pascual et al. 2017; Arias-Arévalo et al. 2018). While intrinsic values refer to the inherent value of nature as an end in itself, regardless of any human experience, instrumental and relational values are human-driven (Díaz et al. 2015). The valuation guidelines developed by IPBES acknowledges that intrinsic values are independent of human experience and therefore human valuation (IPBES 2015); however, humans can express regard for biodiversity and ecosystems independent of human interest, reflecting subjective intrinsic values (O'Connor and Kenter 2019). While instrumental values refer to the value of nature for human utility, including economic benefits, relational values are those concerns related to the meaningfulness of relationships, such as those among people and between nature and people (e.g. people's sense of place, spirituality, social cohesion or responsibility towards biodiversity) (Chan et al. 2016; Pascual et al. 2017). Focusing on relational values among land managers in agricultural landscapes can help to foster stewardship values for conservation (Chapman et al. 2019).

Alongside values, rules and knowledge are important factors influencing decision-making. Rules (R) refer to both 'rules-in-use', which include informal norms, practices, taboos, habits, and 'rules-in-form', which include legislation, treaties and directives (Gorddard et al. 2016). These rule types can be perceived and experienced at both the individual and collective levels (Paavola, 2007; Ostrom, 2009). Institutional diversity, including multiple formal and informal rules, enhances compliance, addresses conflicts and supports adaptive governance for natural resources (Dietz et al. 2008; Kenward et al. 2011; Emerson and Gerlak 2014). Knowledge (K) refers to the information, awareness, understanding and perspectives that have explanatory value for the issues being addressed (Colloff et al. 2018). Actors and institutions create, organize, transfer, share and use this knowledge (Cornell et al. 2013). Relevant knowledge for biodiversity conservation and land planning include formal scientific and technical knowledge, lay knowledge from practitioners, and local ecological knowledge (LEK) (Tengö et al. 2014; Colloff et al. 2018).

Interconnected vrk sets can identify which elements must be employed, retained and used in order to achieve the desired outcome in decision-making (Gorddard et al. 2016). The vrk perspective therefore emphasizes that interactions between the systems of values, rules and knowledge held by a particular stakeholder group (e.g. land owners, environmental managers or national agencies) underpin current decision-making regarding conservation and land planning actions (Colloff et al. 2017a). These systems must be disentangled to better understand why land, particularly in areas of exceptional biodiversity, is often not managed for the intrinsic, instrumental and relational value of its biodiversity, and the related implications for the provision of NCP.

One such area is South Africa's Cape Floristic Region (CFR), a global biodiversity hotspot, which contains more than 9000 vascular plant species and is recognised as a Centre of Plant Diversity (Olson and Dinerstein 2002). More than 70% of natural vegetation in the CFR has been transformed to other land uses, primarily agriculture but also urbanization (Myers et al. 2000). Natural renosterveld vegetation has been particularly susceptible to transformation, due to its rich substrate and relatively accessible topography compared to other habitat types of the CFR (Topp and Loos 2019; Rouget et al. 2014). This transformation began in colonial times, although much occurred throughout the 20th century (Newton and Knight 2005), and has led to major biodiversity losses which threaten the provision of NCP. In this landscape context, we thus aim to understand what interplay of values, knowledge and rules leads to specific land uses that result in certain NCP outcomes. To address this research goal, we specifically aim to: a) unravel values, rules and knowledge that drive land use decision-making contexts by renosterveld land managers, and b) identify which detrimental and beneficial NCP are derived from renosterveld subject to different decision-making contexts of land management.

2. Case study

Our study area is the Swartland municipality in the Cape Floristic Region, South Africa (Figure 1). This winter-rainfall region is situated approximately 60km north of Cape Town and is well known for grain production, primarily wheat. The region's fertile soils and proximity to a major urban centre contributed to widespread transformation of land use from natural vegetation to intensive commercial agriculture (Newton and Knight 2005). The Swartland municipality covers an area of approximately 3707 km^2. Land cover in the municipality is now mostly grain cropland (approximately 58% of total cropland), grazing land (27%), and vineyards (6%) (Western Cape AgriStats, 2019). Urbanization has also increased rapidly in the Swartland over the last 40 years, with a current growth rate of 5.6% (Western Cape Government 2017). This trend is partly due to an influx of migrant workers, as well as the expansion of the greater Cape Town metropolitan area into the southern part of the Swartland, and the expansion of the administrative centre Malmesbury (Halpern and Meadows 2013; Western Cape Government 2017). The endemic natural renosterveld vegetation has therefore been affected by both recent and historical land-use planning.

West-coast renosterveld, as part of the CFR, is globally significant in terms of biodiversity. It is a fire-prone, shrub-scrub, evergreen ecosystem also known as 'Cape transitional small-leaved shrublands'. Renosterveld contains more than 800 plant species, including many endemic geophytes and succulents (Halpern and Meadows 2013; Bergh et al. 2014). Whereas renosterveld formerly covered much of the Swartland, less than 3% natural west-coast renosterveld vegetation now remains, mostly in fragments on steep slopes and hilltops among intensively farmed private land (Moll and Bossi 1984; McDowell and Moll 1992; Newton and Knight 2005; Halpern and Meadows 2013). While agricultural expansion is the major driver of renosterveld loss in the Swartland, other threats include biological invasions and climate change, which can converge with poor land management and further deteriorate renosterveld (Kemper et al. 1999; Topp and Loos 2019). Regional scale conservation planning has taken place across the Cape lowlands (von Hase et al. 2003) and private easements are used as a conservation mechanism in south-coast renosterveld (Overberg Renosterveld Conservation Trust, www.orct.org), but conservation approaches remain piecemeal (Topp and Loos 2019). Some renosterveld fragments are designated municipal reserves on the outskirts of towns such as Malmesbury and Darling, but the majority are on privately owned land (Von Hase et al. 2010).

The Swartland landscape is therefore rich in contrasts, with remaining fragments of high biodiversity-value renosterveld largely surrounded by intensive, monocultural grain and fruit production. Such contrast creates a complex decision-making context for land-use planning, as biodiversity conservation implementation is often not priority for farmers and those responsible for agricultural land-use decision-making (Topp and Loos 2019; Winter et al. 2007). In terms of values, previous studies have found farmers to perceive renosterveld as largely unprofitable and associate its retention with problem plants and animals, as well as lack of financial reward (McDowell et al. 1989; Von Hase et al. 2010; Winter et al. 2005, 2007). Meanwhile, formal rules including legislation exist to prevent ploughing of virgin soil (National Environmental Management Biodiversity Act of 2004), and renosterveld fragments are nationally designated as critical biodiversity areas. However, multiple barriers inhibit conservation action by land managers, including the lack of knowledge and awareness of importance of biodiversity, high cost of conservation measures and lack of institutional collaboration (Winter et al. 2007; Cowling et al. 2003; Musil et al. 2005; Topp and Loos 2019). The transformation of land management towards conservation management requires changes in values and aspirations, which may facilitate shifts in industry practice and rules such as government regulations (Pelling 2011; Prober et al. 2017). These barriers and values may differ among land managers with different farming systems (Darnhofer et al. 2005). With the application of the *vrk* and NCP perspectives, we seek to unravel the complex social decision-making contexts and implications for related NCP.

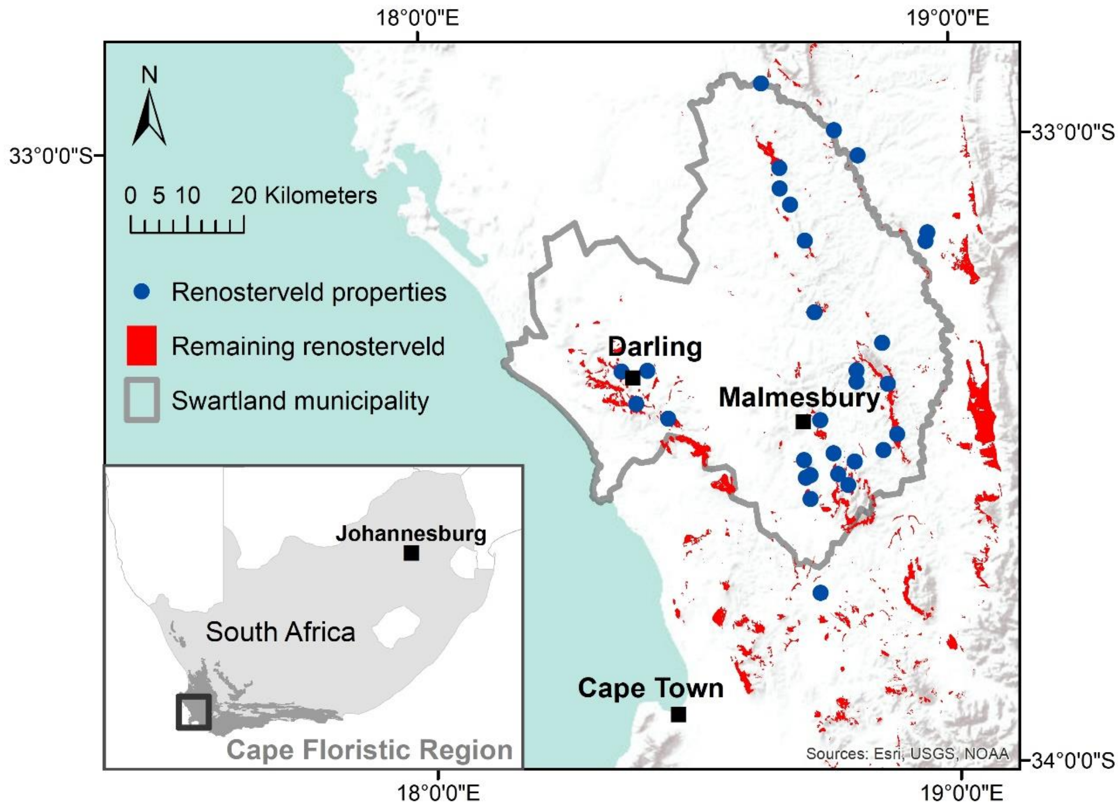

Figure 1. Map of study area and location of the Cape Floristic Region (CFR) in south-western South Africa (inset, CFR indicated in light grey). The Swartland municipality is outlined in grey. Remaining renosterveld fragments are visible in red. Major urban centres are represented by black squares. Properties under management by sampled land managers with remaining renosterveld fragments (n=30) are located within the Swartland municipality plus a 10km buffer and are indicated by blue circles.

3. Materials and methods

3.1 Sampling strategy

Two fieldworkers conducted interviews with 30 land managers across the Swartland municipality with renosterveld remnants on their land (Figure 1). As we wanted to explore differences between farming systems, interviewees were selected to account for both wheat (*Wh*) and wine grape (*Wi*) production as well as for differently-sized renosterveld fragments in the landscape. Fieldworkers conducted face-to-face semi-structured interviews in both English and Afrikaans between September 2017 and December 2018. A draft of the questions was piloted with colleagues and land managers and revised before fieldwork. We structured the interviews in three sections, including questions concerning: 1) General history and factual information on farming and land management; 2) Experiences with biodiversity and ecosystems, including wildlife encountered in renosterveld; 3) Perceptions of the benefits and detriments renosterveld provides. In this last section, we designed open-ended questions to capture information on beneficial and detrimental NCP (e.g. "What are the benefits from nature on your farm?"; "What threats do you perceive?"), values related to renosterveld (e.g. "What is the renosterveld good for, for you and for society?"; "Why do you appreciate this place?"), the formal and informal rules underpinning land use (e.g. "How do you manage the renosterveld?"; "Do you get any help from external sources for farming or land management?") and land manager's knowledge (e.g. "What can you tell me about the renosterveld on your farm?"; "Why did you leave a patch of renosterveld on your farm?"). We used open-ended questions since they capture the perceptions of beneficial and detrimental NCP and plural values of biodiversity, ecosystems and NCP (Klain et al. 2014; Arias-Arévalo et al. 2017; Masterson et al. 2017; Tadaki et al. 2017; Jacobs et al. 2018). Socio-demographic data such as age, gender and land ownership type were collected in writing before the interview commenced. The duration of the interview varied between 17 and 50 minutes (see Appendix 1 for the interview details).

Interviews were recorded, transcribed and translated from Afrikaans to English in full. Before the interview, respondents were given information on the purpose and background of the research and gave written consent to their participation. Ethical clearance for the study was obtained through the University of Göttingen Ethics Commission on 15.11.2017.

3.2 Content analysis

We loaded interview transcripts into the text analysis software MaxQDA (Version 2020) and coded each interview according to two different frameworks: the *vrk* perspective (Colloff et al., 2017b;

Gorddard et al., 2016) and the NCP paradigm (Díaz et al., 2018). The content analysis includes a reiterated review of the corpus made up by the transcripts of the 30 interviews. Through the content analysis, we identified the main categories of values, rules, knowledge and NCP types, and also captured newly emerging NCP categories.

To address the first specific objective, we applied the *vrk* perspective (Colloff et al., 2017b; Gorddard et al., 2016) and coded for values, rules and knowledge. We coded for values by distinguishing between subjective intrinsic, instrumental and relational values (Chan et al. 2016; Pascual et al. 2017; Arias-Arévalo et al. 2018). Reference to the worth of nature for its own sake and the right of nature to exist was placed under the code of subjective intrinsic value, while reference to monetary benefits was coded as instrumental values (see Arias-Arévalo et al. 2017). We further identified multiple relational values, such as the meaningful relationships between people and nature that derive from sense of place, aesthetic enjoyment, leisure, interdependency with nature, family ties or moral duty to biodiversity (Table 1). We coded rules by classifying both 1) formal rules, including legislation, market arrangements and conservation agreements, and 2) informal rules, such as community practices, relations and habits (Table 2) (Abson et al. 2017; Prober et al. 2017). We coded the systems of knowledge by considering how land managers acquire knowledge. We considered three different types of knowledge acquisition: 1) LEK, including both local knowledge transmitted through cultural settings and regional history, and experiential knowledge relating to the acquisition of understanding through daily experiences and observation; 2) scientific knowledge, stemming from research sources and institutions; and 3) technical knowledge, related to farming practices and technologies (Table 3). In addition, we also noted when land managers expressed a lack of value of renosterveld, lack of rule enforcement and a lack of knowledge related to renosterveld.

To address the second research objective, we operationalized the classification of NCP (Díaz et al. 2018) by coding both detrimental and beneficial contributions of remaining renosterveld fragments to people. When coding, we distinguished between beneficial and detrimental NCP, as well as between material, non-material and regulating NCP (Table 4). As stated by Díaz et al. (2018), a particular NCP may be framed as beneficial or detrimental, depending on the social actors' cultural and socio-economic contexts (Saunders and Luck 2016; Díaz et al. 2018). In our study, we considered NCP to be detrimental when the interviewee framed the NCP has having a negative impact either to people or to ecological integrity of renosterveld. Thus, the same NCP can appear as beneficial and detrimental contribution throughout the content analysis. Likewise, a particular NCP does not necessarily fit squarely into the categories of material, non-material and regulating and, therefore, in such cases, we classified the NCP in multiple categories. Additionally, the operationalization of NCP contains a mixture of general and context specific perspectives (see Díaz et al. 2018). We applied this by first following the generalizing perspective through assigning expressed NCP to general categories from the framework, and second, by using the information from farmers to identify new NCP which do not fit in the existing generalizing perspective, but are region and context-specific (Díaz et al. 2018). We included family ties as an NCP as well as a relational value, because family activity in renosterveld may be a tangible NCP, whereas the importance of preserving renosterveld for future generations is a relational value.

The results present the qualitative content analysis with example verbatims (the words of the interviewees, lightly edited for ease of reading without altering meaning) and descriptive analysis that shows differences between wheat and wine farmers. We explored whether the expressed *vrk* and perceived NCP differed between wheat and wine farmers. We then pooled the coded *vrk* from all land manager interviews and checked for associations among *vrk* components. In an exploratory first step, we created a pairwise matrix of *vrk* based on proximity of codes within the interview text and mapped these *vrk* into a multidimensional ordination (see Appendix 2) to see if groupings of *vrk* elements emerged from the data. The ordination is based on Principle Co-ordinates Analysis and is part of the Code Maps function provided in the text analysis software MaxQDA (Version 2020). In a second qualitative step, we used pairwise matrices to manually check for associations among *vrk*. In a third step, we generated frequency tables for *vrk* and NCP to see which NCP occurred with each *vrk* component (see Appendix 3). From this analysis we distinguished three separate decision-making contexts that are underpinned by a particular *vrk* interplay and are related to different NCP. It is important to note that one NCP could be associated with more than one decision-making context.

The resulting contexts are not definitive, so each combination of elements does not automatically lead to the associated land management decision; rather, the decision may result from the associated combination of *vrk* elements, based on our interpretations of the interviews with land managers.

4. Results

4.1 Sample characteristics

While most interviewees (n=27) were actively farming their renosterveld-adjacent land, three were responsible for the renosterveld fragments, but not adjacent farming activities and were characterized as "Other management practices (O)". Of active farmers, 13 were primarily farming wheat and 14 were primarily farming wine grapes, although many farms (n=24) contained a mix of these crop systems, plus other fruit, vegetables and livestock (sheep and cattle; see Appendix 1 for full interviewee data). The majority of interviewees were aged between 30 and 50 (62%) and the majority identified as male (90%). The main spoken language on sampled farms was Afrikaans, except for one farm where English and Xhosa were the main spoken languages. Farms ranged from 46 hectares to 1800 hectares in size. The median farm size was 477 hectares. Renosterveld fragments ranged from 0.3 to 1401 hectares in size and the median fragment size was 13.9 hectares. The majority of land managers owned the farm in a family trust (57%), while 23% were sole owners and 13% were employed by landowners.

4.2 Values

Relational values, including seven different articulated sub-types, were expressed by land managers more frequently than intrinsic and instrumental values (Table 1). Of relational values, the most frequently articulated value type were sensing wildlife and nature, moral concerns for nature and family ties to the landscape (Table 1). We found little difference between the articulated values of wine and wheat farmers, particularly for subjective intrinsic and relational values (Fig. 2). However, we found that wheat farmers expressed more instrumental values than wine farmers (Fig. 2).

As well as expressing different value types related to nature and renosterveld, almost all land managers expressed that renosterveld lacks value (n=27). This perception often related to the perceived lack of instrumental values and monetary benefits, for example:

> *"Up to now, I didn't think about anything about it, it's just wasted land. I had to pay for 470 hectares and it's 70 hectares I can't plant on so that is… for me it's a total loss."* (Wh2); and *"They don't bother with it, so they don't make any effort to know what's going on in there, because they can't make any money out of it." (Wh10).*

Some land managers expressed a widespread lack of valuing of renosterveld while simultaneously acknowledging that this was regrettable, as illustrated by:

> "*Yes it's so heartbroken [sic] that in South Africa nobody is interested in fynbos. If this fynbos is vanish, then nobody will notice. Believe me. Nobody will notice it."* (Wh6).

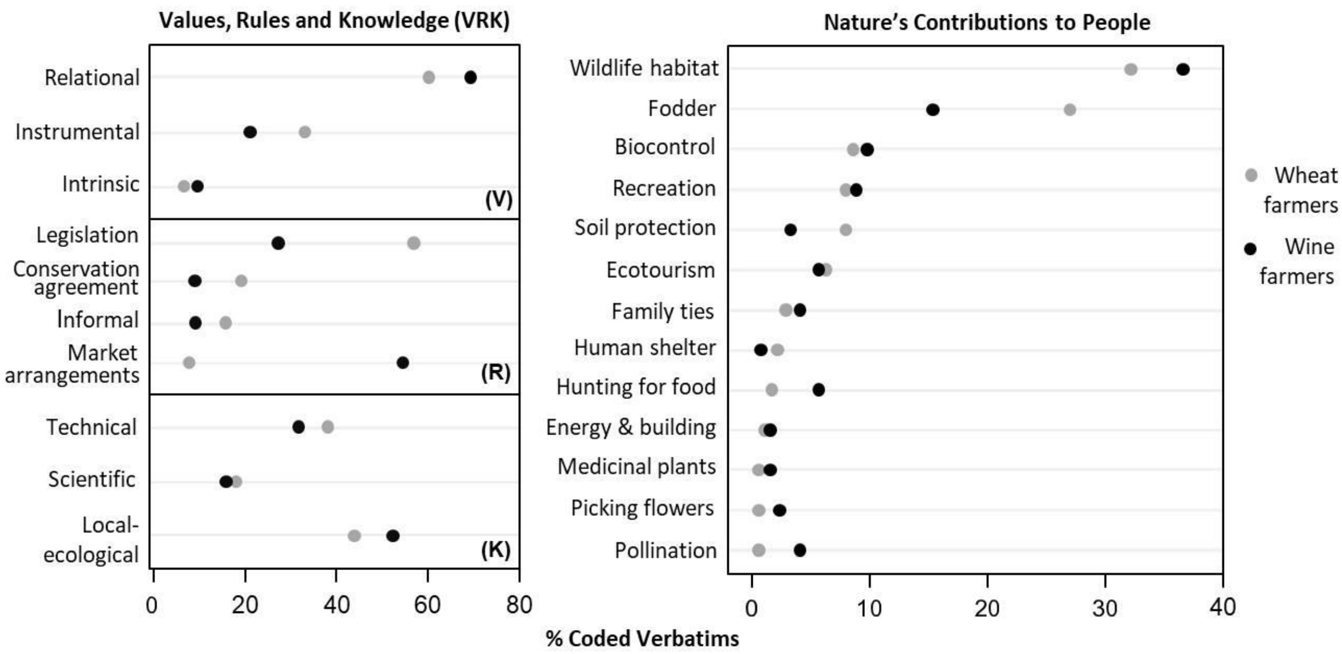

Figure 2. Differences in the % of coded verbatims between wine and wheat farmers (n=13, n=14 respectively) for the expressed values, rules, knowledge and nature's contributions to people in the Swartland of South Africa's Western Cape. The x-axis represents the proportion of coded verbatims.

Table 1. Values articulated by renosterveld land managers. N = number of interviews. * Verbatim segments that relate to values (i.e., not rules, knowledge or NCP).

Value type	Articulated value	n	% of all verbatim segments*	Example verbatim
Instrumental	Direct or indirect monetary benefit; utility	23	26.3	*"If we want to make the renosterveld economical beneficially, it will be ecotourism." (Wh1)* *"At the moment I only make money from the paragliders and the Wifi towers on the mountain." (Wh5)*
Subjective intrinsic	Nature's right to exist	15	9.0	*"I think it must be a part of the farm. Because it is there, it is growing there and it must be there. I think we must leave it there because it's there for a reason." (Wi8)*
Relational	Sensing wildlife & nature	22	14.3	*"For us, the benefit of having a piece of veld is we go walking there throughout the year, and there's always something to see." (O1)*
	Moral duty & concern for nature	21	15.5	*"It is our duty to protect the nature as a farmer. Because it is an ongoing relationship between nature and farming."(Wi7)* *"I just feel that nature as it was made should be protected, we can't just let everything go."(O2)*
	Family ties & future generations	15	9.5	*"I grew up with it… we used to go and pick the bulbs there and give them little names...we picked it with my grandmother….It's just a generation thing…I don't want it to become extinct." (Wi1)* *"To preserve your land for the future generations or future farmers, you have to be careful with what you're doing." (Wh1)*
	Interdependency of nature and farming	21	9.5	*"Farming is close to nature. So if you do not care about nature I don't think you will be successful in farming." (Wi10)*
	Recreation & leisure	15	7.2	*"These days there's a Funduro with quad bikes and stuff, so there's more of a relationship with recreation than farming. We don't use the mountain or the renosterveld for farming, but only to enjoy it." (Wh8)* *"I think it is so nice for me to go for a walk there on Sundays. You can sit and drink your coffee or tea and the dogs play about in the veld… and have this peaceful experience there." (Wh13)*
	Aesthetics	9	5.4	*"In a different kind of way, it's beautiful. It's another beautiful than farming, you can sit up there and have a beer. It's really nice. Looking over the renosterveld." (Wi9)* *"It makes quite a difference to go and walk in the veld than just to drive around in the car or tractor. There's millions of species and different plants and stuff. It's beautiful. I love it."(Wh11)*
	Sense of place	7	3.3	*"Everybody knows that if you are situated in Malmesbury or the Swartland, it is recognizable by the renosterbos." (Wi4)* *"It's what the society hinges on, it's really what it is, I mean the renosterveld is Darling." (O3)*

4.3 Rules

Formal legislation was the most frequently expressed rule type (n=24) whereas informal rules were the least frequently expressed (n=13) (Table 2). Community conservation agreements differ from other formal conservation agreements in that they are more contingent upon community goodwill, compared to, for example, municipally owned and managed nature reserves or biodiversity conservation legislation. Biodiversity conservation legislation was not explicitly named by land managers, although many were aware of such rules (n=24). Conservation formal rules were characterized with problems related to enforcement, for example, regarding national legislation:

> *"I could take the renosterveld out and plant wheat, if it was possible, I can assume no one in South Africa would stop me. I don't think there is any... it's can't... I don't think it can be controlled."* (Wh2); and *"No reprimand or repercussions, nothing. It's rather everyone keeps to his own business."* (Wi3).

This could also result in conflict over renosterveld management, as illustrated by the next verbatim:

> "*Most people think that the renosterveld is public property. Whereas this specific [piece] is part of four farms. Even the local tourism board, they made three hiking trails with no control."* (Wh5).

Land managers also mentioned informal rules as underpinning their decision-making (n=13). In some cases, neighbour relations or family traditions influenced the way land managers chose to use their land. For example, one land manager explained the informal rules for keeping renosterveld flowers on a small hilly outcrop of renosterveld (known as a 'koppie'):

> *"In this case…the farmers' mother was very much into flowers, the flower shows and she said to him, you don't do anything to this koppie! I mean he's come up close, but he's leaving the koppie because his mother said to him – Leave the koppie."* (O1)

There were differences in the way wheat and wine farmers perceived the role of rules (Fig. 2). While formal legislation was expressed more frequently by wheat farmers (59.2% of verbatim segments) than wine farmers (26.9%), market rules related to environmental issues were mentioned more frequently by wine farmers (53.8%) than wheat farmers (6.1%) (Figure 2).

Table 2. Rule types articulated by renosterveld land managers. * Verbatim segments that relate to rules (i.e., not values, knowledge, or NCP)

Rules	Description	n	% of all verbatim segments*	Example verbatims
Legislation	Relating to laws and regulations on land use at local, regional, national or international levels	24	33.3	*"I was just waiting for permission to build a dam." (Wh12)* *"You cannot make land anywhere. There are [regulations for] soil protection. If you really clear land, you cannot prevent erosion, and then they [authorities] will come and stop you." (Wh10)*
Market arrangements	Relating to economic incentives and market-based mechanisms, such as product certifications	12	29.0	*"They [certification body] have something about biodiversity which I filled in one year … the natural veld, the pockets of veld, they actually want it you to cordon them off to, put up a fence and that sort of thing, which obviously just costs you money and you get nothing in return.." (Wi5)*
Conservation agreements	Conservation agreements among multiple stakeholders, either state or community-driven, also known as a conservancy	12	19.1	*"We hope that it can be proclaimed under the stewardship agreement. Then at least it is formally set aside." (O3)* *"There are parts that we cannot expand further as it is part of the Greater Paardeberg Conservancy, although it is on private land." (Wh4)*
Informal rules	Customs and habits, neighbour and family relations	13	18.5	*"Well I used to go up on the motorbike quite a bit, and the neighbours started saying no motorbikes." (Wi5)* *"I don't shoot [pest wildlife] at all, and my children are not allowed to shoot them at all." (Wh5)*

4.4 Knowledge

Land managers articulated diverse forms of knowledge. The most commonly expressed knowledge type was local-ecological knowledge (48% of verbatim segments), followed by technical knowledge (31%) and scientific knowledge (21%; Table 3). Scientific knowledge was often identified as belonging to other sources, such as scientists or researchers, whereas technical knowledge and LEK were more frequently expressed as belonging to the land managers themselves. LEK included substantial awareness of renosterveld-associated fauna derived from land manager observations, often mammals, for example:

> "*Well there are lots of jackals, and rooikat [caracal]. I've seen some rabbits through [the renosterveld]. Guinea fowl, lots of snakes, tortoises, lots of them. And then game, a few game species. Duikers, there's a few bush boks, and quite a bit of deer, I've seen." (Wh11)*

However, many land managers (n=24) expressed a perceived lack of knowledge on renosterveld ecology, and a corresponding lack of understanding of the ecological significance of renosterveld, as illustrated by the next verbatim:

> *"But you want to ask me about the renosterveld, you are asking the wrong guy. I'm not a plant guy at all."* And: *"For me it was just bushes, but for them [visiting botanists] it was something like gold." (Wh5)*

This lack of knowledge of renosterveld ecology was related to a lack of renosterveld conservation rule enforcement. For example, one land manager described the difficulty with prevention of unregulated harvesting of medicinal plants:

> *"Our law enforcement guys, they don't know the plants, so it's difficult to identify them if you just have the bulb. If you don't catch them red-handed, you can't do anything about it." (O3)*

Knowledge types articulated by wheat and wine farmers were similar. Wine farmers expressed marginally more local-ecological knowledge (52.4%) than wheat farmers (43.9%), and wheat farmers marginally more technical knowledge (38.1%) than wine farmers (31.7%; Figure 2).

Table 3. Types of knowledge articulated by renosterveld land managers. *n* = number of interviews. * Verbatim segments that relate to knowledge (i.e., not values, rules or NCP)

Knowledge type	**Description**	**n**	**% of all verbatim segments***	**Example verbatims**
Local-ecological	Knowledge derived through daily experiences in nature and farmland, local history, cultural beliefs, practices and traditions	30	48	*"I like it to walk sometimes in the veld when I was younger. I'm too busy now. But yeah, we saw butterflies." (Wh6)* *"If the ants are making a road, wherever you're walking on the farm, then it's going to rain. The insects give an indication of farming. So then we can know by watching nature." (Wi4)* *"I actually spoke to another woman the other day that goes walking in the mountain, and they said that they've found a cactus that grows under moss, under rocks, and it's only found here, and Paarl mountain" (Wi2)* *"The whole Swartland used to be renosterveld. And the name Swartland came from the colour of the renosterveld in the summer. All [of] it looks dark."(Wh1)*
Technical	Knowledge derived through farming experiences resulting from technology use and training	25	31	*"He had the soil analysed, and he thought it would be quite sour, but it's actually good soil. But still very little grows there, except for the natural vegetation." (Wi7)* *"We attend a lot of courses about it and we want to get our soils in the same state as before anyone planted here." (Wh2)*
Scientific	Knowledge derived from scientific sources, exchange with specialists, nature authorities	22	21	*"The people who are cleverer than I, they told us years ago that the renosterveld must be grazed a little bit so the animals can break the branches. It's good for the renosterveld." (Wh2)* *"My father-in-law is actually quite big in botany as well. He's an agronomist and he actually introduced me to - I know there's quite a few scarce plants on the property as well, through him." (Wi13)*

4.5 Nature's Contributions to People

Land managers articulated a range of NCP from both renosterveld and nature within the wider farming landscape (Table 4). The most frequently articulated NCP derived from renosterveld and nature in general was the maintenance of habitat for wildlife (n=28). The verbatims show that a particular NCP can be simultaneously articulated by interviewees as material and non-material (Table 4). For example, renosterveld flowers are a material NCP, and picking them for display at regional flower and agricultural shows is also non-material in the sense that it is tied to local identity and family traditions:

> *"My grandmother used to do the agricultural show, where they had a big flower display area. We used to go and pick the bulbs there and give them little names. I can still remember it because we had to help her."(Wi1)*

In addition, interviewees articulated particular NCP as both beneficial and detrimental (Table 4). For example, ecotourism is considered as beneficial by creating positive experiences and for added farm income, but detrimental when it becomes difficult to manage, as illustrated by the next verbatim:

> *"When you develop it, then it is open to humans, and then you have got other challenges, like litter. They've got their demands, they want to have fire places and whatever." (Wh1)*

While human shelter may be considered beneficial for the humans using the renosterveld as refuge, land managers considered it as detrimental due to fears of crime and damage to their land (n=2). The contribution of renosterveld as human shelter led one land manager to consider removing remaining renosterveld:

> *"If you look at the bossieveld [renosterveld], one can easily hide there for a week or two and nobody will know about it. That is the biggest reason for me to change the renosterveld." (Wh13).*

Wildlife habitat was often identified as a detrimental NCP by land managers (n=18) due to the presence of pest wildlife, such as steenbok (*Raphicerus campestris*), caracal (*Caracal caracal*) and baboons (*Papio ursinus*). Alongside particular dominant shrubs (such as *Galenia africana*), which degrade productive farmland, these mammalian species were reported to threaten crops, livestock and people:

> *"Six years ago when we started planting very many grapes, we had big problems with the steenbok and the duikers, because they were eating up all our young grapes."(Wi9).*

However, wildlife habitat was more often expressed as a beneficial NCP (n=28), as illustrated by the next verbatims:

> *"It's good for boks and for rabbits and everything." (Wi6)* and: "*You get the wildlife in there, the tortoises, the antelope, the boks, steenbokkies and the duikers…obviously for the caracal as well, it's their habitat, where they thrive. You also find a load of flowers up there, especially in Springtime." (Wi2).*

Some NCP were identified as beneficial to certain stakeholders, yet associated with negative impacts through potential for over-extraction. Thus, while the NCP itself is not detrimental, it may be regarded as incompatible with biodiversity conservation. For example, three interviewees reported medicinal plants as beneficial NCP for people's quality of life because of their contribution to health and cultural significance, but harmful for renosterveld integrity due to potential over-harvesting of plant species:

> *"The other thing that's a problem are the people harvesting medicinal plants. People have been seen going in there with spades coming back with bags of stuff, there's a whole lot of plants just taken out." (02).*

Similarly, fodder was described by interviewees as beneficial, due to the economic benefits of saving feed costs for livestock, but also detrimental for renosterveld through potential overgrazing by hardy native livestock breeds:

> *"The tough breed of sheep and the Gunny cattle are going to destroy these patches, definitely." (Wh6)*

Perceptions of NCP provided by renosterveld were relatively similar between wheat and wine farmers (Figure 2). We found the greatest difference between wheat and wine farmers for the NCP of fodder, which was expressed more by wheat farmers (27% of verbatim segments) than by wine farmers (15.4%) (Figure 2).

Table 4. Nature's contributions to people (NCP) derived from the interviews with farmers in the Swartland renosterveld. We present the correspondence with the particular NCP and NCP categories (material, non-material and regulating) of the generalizing perspective developed by Diaz et al. (2018). We also present how many verbatim segments refer to detrimental and beneficial NCP. n = number of interviews; Wh = wheat farmers, Wi = wine farmers; O = other management practices

NCP derived from this study	**Example verbatim**	**Correspondence with the NCP derived from the generalizing perspective by Diaz et al (2018)**	**NCP category**			**Beneficial (% verbatim segments)**	**Detrimental (% verbatim segments)**	**n**	**% all NCP verbatim segments**
			Material	**Non-Material**	**Regulating**				
Maintenance of habitat for wildlife	*"It's good for boks and for rabbits and everything." (Wi6)* *"It's a little ecosystem running on its own. You don't see the birds that are there on the rest of the farm"(Wi13)* *"And we've got the rooikat, the caracal, which takes the lambs." (Wh5)*	1. Habitat creation and maintenance			X	64%	36%	28	29.9
Fodder	*"The cattle would come down to the medicago pastures but they want to go to the veld, because they are in need of the high fibre grazing." (Wh1)*	12. Food and feed	X			92%	8%	21	19.5
Recreation	*"We have the privilege that we can go when the wind is still and it's a hot day, just go for an hour or two, so we can go and walk around there." (Wh8)*	16. Physical and psychological experiences	X	X		100%	0%	16	11.2
Ecotourism	*"The people said they'd love to come and see it for the birds and for the flowers." (01)* *"The new generation use it for more agritourism than we are many years ago." (Wh12)*	15. Learning and inspiration, 16. Physical and psychological experiences	X	X		90%	10%	14	7.9
Pest removal & biocontrol	*"After the fire, I saw a lot of anthills, and I am glad that the anteaters are there, otherwise there would be many more." (Wh5)*	10. Regulation of detrimental organisms and biological processes			X	100%	0%	14	7.9
Soil protection	*"So the renosterveld is actually good too. For erosion. It helps definitely for erosion." (Wh10)*	8. Formation, protection and decontamination of soils and sediments			X	100%	0%	9	6.0
Family ties & memories	*"When me and my wife got engaged, it was up there and we put a little message in a champagne bottle and buried it there, so some day the children can go and dig it up." (Wh9)*	17. Supporting identities	X	X		100%	0%	10	3.8

Hunting for food	*"The labourers may capture porcupines. It's kind of delicacy to have a porcupine." (Wi11)* *"Sometimes we find snares and that we don't like because there are not so many {Cape spur fowl]" (O1)*	12. Food and feed, 17. Supporting identities	X	X		54%	46%	11	3.6
Pollination	*"We need nature. I just spoke about bees. We need nature for farming"(Wi1)*	2. Pollination and dispersal of seeds and other propagules			X	100%	0%	5	2.7
Flowers for shows	*"We go and pick the flowers for the agricultural show." (O1)*	13. Material, companionship and labour; 17. Supporting identities	X	X		100%	0%	5	2.2
Medicinal plants	*"There are a lot of medicinal plants in there that have not yet been discovered." (02)*	14. Medicinal, biochemical and genetic resources	X	X		60%	40%	3	1.4
Energy & building	*"This big wall is renosterbos and clay in between"(Wi12)* *"The renosterveld was also used for firewood before electricity." (Wh1)*	13. Material, companionship and labour	X			100%	0%	5	1.4
Human shelter	*"Vagrants living there in hiding for 2 days. We found the place he was staying. He was eating there, sleeping there."(Wh13)*	-	X			0%	100%	2	0.8

4.6 VRK-NCP decision-making narratives

Our qualitative analysis identified three different groups of *vrk* associations. We considered each group as a distinct decision-making context for renosterveld land management and termed them: 1) Bottom-up conservation; 2) Top-down conservation and 3) Utility (Fig. 3). Each context consists of a combination of specific values, rules and knowledge, which is associated in turn with different bundles of NCP. The first decision-making context 'Bottom-up conservation' comprises of specific relational values (such as aesthetics and family ties), informal rules and LEK. The renosterveld-derived NCP associated with this context included regulating, material and non-material NCP, such as maintenance of habitat for wildlife, fodder, hunting for food, flowers and family ties and memories. We termed this context "Bottom-up conservation" with recognition that bottom-up conservation strategies are underpinned by community structures, local identities and cultural relations between people and ecosystems (Abrams et al. 2009).

The second decision-making context 'Top-down conservation' is comprised of intrinsic, instrumental and relational values (such as moral duty and concern for nature), formal conservation agreements, and scientific knowledge. We found that the outcome in terms of NCP, as perceived by interviewees, was similar to 'Bottom-up conservation', but lacks non-material NCP, such as preservation of family ties and memories and hunting for food. We termed this context 'Top-down conservation' in recognition that top-down approaches are driven by national and international government, large-scale NGOs and policy intervention (Abrams et al. 2009), and are rooted in scientific evidence (Lochner et al. 2003).

The third decision-making context 'Utility' focused on use of renosterveld as part of farming practices, primarily for grazing purposes. This context is underpinned by the interplay of instrumental values, formal rules, and technical knowledge. The outcomes perceived in terms of NCP included material, non-material and regulating NCP, such as fodder, soil protection, recreation and ecotourism. The Utility and Top-down conservation contexts included the regulating NCP pollination, and therefore contained more regulating NCP (n=4) than the other two contexts (n=3).

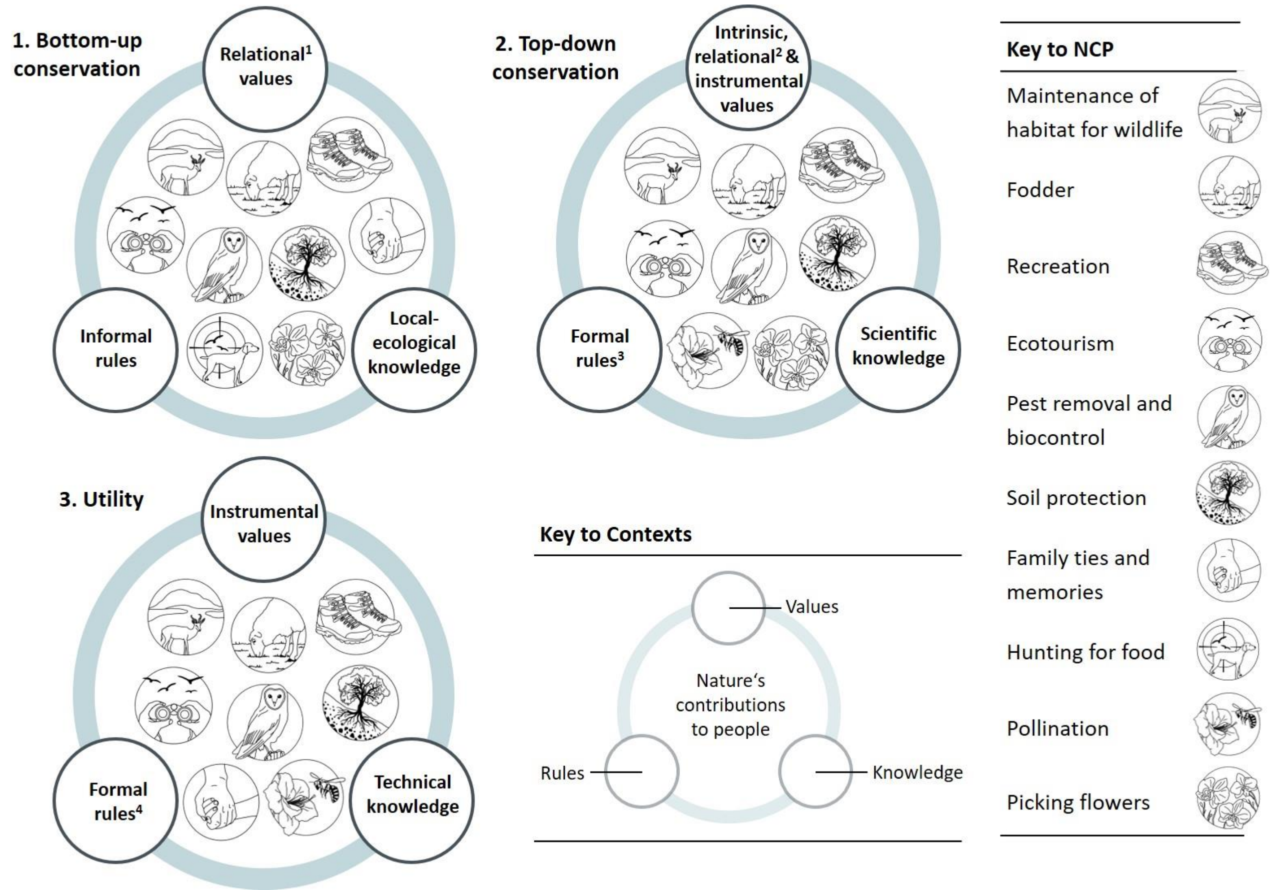

Figure 3. *vrk* decision-making contexts: 1. Bottom-up conservation, 2. Top-down conservation and 3. Utility, showing combinations of values, rules and knowledge and associated NCP (illustrated in Key to Contexts). Icons representing different types of NCP are based on those from The Economics of Ecosystems and Biodiversity (TEEB) project (Sukhdev et al. 2010). [1]Relational values include sensing wildlife and nature, family ties, recreation and aesthetics. [2]Relational values include moral duty and concern for nature and interdependency with nature. [3]Specifically conservation agreements. [4]Including market arrangements and legislation. For NCP categories see Table 4. For the statistical associations that led to *vrk* decision-making contexts, see Appendices 2 and 3.

5. Discussion

Our analysis found that, in the context of renosterveld, certain *vrk* types were more likely to occur together, creating unique decision-making contexts that were associated with different sets of NCP. We discuss here first, the identified *vrk* types and their interplays leading to different decision-making contexts; second, the findings and prospects for linking *vrk* and NCP; third, the limitations of our study and acknowledging dual perceptions of beneficial and detrimental NCP; and fourth, implications for future NCP assessments.

5.1 VRK types and their interplay

The unique combinations of *vrk* illustrate the aspects of societal decision-making, which can constrain or enable behavioural change (Colloff et al. 2017b). In our study, land managers articulated value statements that contained multiple, sometimes contrasting or conflicting values, often relating to production and conservation, as found elsewhere (e.g. Prober et al. 2017). For example, *Wh4* expressed relational values including interdependency with nature for farming and aesthetic appreciation of renosterveld, while also expressing a lack of instrumental value of natural areas. The fact that relational values were expressed more frequently than instrumental and subjective intrinsic values illustrates the complexity, specificity and non-substitutability of relationships between renosterveld and people (Arias-Arévalo et al. 2017; Himes and Muraca 2018). Relational values are "demonstrated and solidified through behaviours associated with biodiversity conservation" (Allen et al., 2018, p1). It is therefore important to speak to all values to promote native vegetation management by farmers (Gosling and Williams, 2010; Chapman et al 2019). We found that in the Bottom-up conservation and Top-down conservation contexts, relational values were associated with LEK and scientific knowledge, combinations which can contribute to conservation mindsets and pro-environmental behaviour (Gosling and Williams 2010; Keniger et al. 2013; Soga and Gaston 2016; Ives et al. 2018). The overall prevalence of relational values, particularly sense of place and interdependency with nature, indicates the rich ongoing interactions between people and biodiversity in the CFR and the potential for care and stewardship action to result (Masterson et al. 2017; Jax et al. 2018; West et al. 2018).

Farming land managers expressed the contrasting belief that responsibility for conservation falls on state government, while land managers themselves preserve autonomy on land management decisions. In South Africa, state legislation relevant to renosterveld conservation includes the National Environmental Management Act and the Conservation of Agricultural Resources Act, which control the conversion of natural land, specifying virgin soil as land which has not been cultivated in the previous ten years (Conservation of Agricultural Resources Act 43 of 1983, 1983, National Environmental Management: Biodiversity Act 10 of 2004, 2013). However, land managers frequently expressed a lack of legislation enforcement, suggesting that other rule types play a role for renosterveld management. Indeed, we found that in the Utility context, market-based arrangements also provide limited incentive for renosterveld conservation activities. These arrangements consist of international audited production standards which require environmentally-friendly farming practices. However, these standards are applicable only to wine and table grape farmers, who export internationally, and not for wheat farmers who supply mainly to the domestic market. Such arrangements were reported to also lack strict enforcement and are not tailored to specific renosterveld conservation needs. Gorddard et al. (2017) note that the efficacy of formal or 'in-form' rules may be constrained or enhanced by informal or 'in-use' rules. For example, a plurality of rule types may limit rule avoidance (Dietz et al. 2008). Despite the plurality of rule types present in the Utility context, some land managers suggested that increasing reliance on this context could pose a threat to renosterveld integrity. For example, choosing to utilize renosterveld for livestock grazing could result in damage to renosterveld plant diversity. The Bottom-up conservation context contained only informal rules deriving from neighbourly and family relations, which combined with relational and intrinsic values. Such informal arrangements have been found to be more efficient conservation strategies than formal agreements in the Cape Lowlands (Von Hase et al. 2010).

The lack of formal rule enforcement expressed by land managers was also linked to a lack of knowledge pertaining to renosterveld ecology and management and perceived lack of value, a result consistent with those found in an Australian land-use decision-making context (Prober et al 2017). Here, as in other applications of *vrk* to endangered species conservation, the *vrk* perspective can help to identify limitations for decision-making options resulting from interactions among knowledge and rules (Colloff et al. 2018). For example, detailed scientific knowledge of renosterveld ecology is highly specialized and relatively difficult to acquire. Enforcing conservation legislation to regulate activities such as medicinal plant harvesting is hindered by the lack of scientific knowledge of law enforcers, who may not be able to identify plants. Additionally, land managers expressed a lack of scientific knowledge. These land managers may refrain from implementing conservation practices with the expectation that other actors with access to scientific knowledge, such as the state or nature conservation bodies, take responsibility for renosterveld conservation. For successful integration into decision-making, such knowledge must be perceived as legitimate, meaning it has been produced with respect to stakeholders' values, and with fair treatment of opposing interests (Cash et al. 2003). However, land managers were found to have extensive LEK, which is particularly important as a means to foster NCP (Hill et al. 2019). The promotion of diverse knowledge types, for example, by combining LEK with scientific knowledge, is known to support effective land management and conservation of natural landscapes and NCP (Tengö et al. 2014, 2017; Morales-Reyes et al. 2019).

5.2 Linking *vrk* and NCP

We show that it is possible to link the *vrk* perspective to NCP. The congruence of these frameworks rests on the inclusion of plural valuation, a fundamental part of the IPBES approach, as well as the importance of involving different knowledge types (Pascual et al. 2017). We concretize these concepts in our application of the two frameworks to the study region. We find that renosterveld fragments are multifunctional sources of NCP within the Swartland agricultural landscape and unique NCP bundles are associated with different decision-making contexts. The Bottom-up conservation context was associated with the NCP family ties and memories, flowers for shows and hunting for food, which link to local cultural traditions. These NCP can thus be viewed as non-material NCP and according to the IPBES framework, categorized as 'Supporting identities' (IPBES framework generalizing category #17, Diaz et al 2018). The multiple non-material NCP identified in our study may exemplify the relational value sense of place, which while not exclusive to a specific context, is a value known to strengthen protective norms and support environmental stewardship (Masterson et al. 2017). Regulating NCP (habitat for wildlife, soil protection and biocontrol) was associated with every context, contributing to recent evidence that stakeholders frequently identify not only tangible but intangible NCP in rural landscapes (Martín-López et al. 2012; Iniesta-Arandia et al. 2014). Renosterveld has been shown to be important for the regulating NCP hydrological function and soil protection (O'Farrell et al. 2009), and is here shown to be subjectively valued for additional regulating NCP, such as pollination and habitat for wildlife.

The identification of the different *vrk* contexts may reveal how and why existing land management decisions might be perpetuated or constrained throughout the decision process (Gorddard et al, 2016). The *vrk*-NCP associations imply that should certain *vrk* components be excluded from the decision-making context, renosterveld may not be managed optimally for certain NCP. For example, in the case that LEK and informal rules are excluded, NCP such as hunting for food and picking flowers for agricultural shows may be overlooked. Similarly, a reliance on a Top-down conservation context may miss the benefit of family ties and memories, which is associated with both a Utility context and a Bottom-up conservation context. Renosterveld conservation activities, such as invasive species removal, appropriate burn regimes, livestock control, fencing of particularly rare or endangered species and awareness-raising of biodiversity, require multiple actors for implementation and diverse knowledge types. The implementation of these activities can be informed by reframing the decision-making context and supported by shifting societal values (Prober et al, 2017). Our study suggests that the multiple underlying relational values may be emphasised in such a reframing. Supporting bottom-up conservation approaches in particular diversifies management options, in which public agencies can remain pivotal enablers within a collaborative approach to conservation (Enqvist et al. 2019). Such work requires collective decision-making on behalf of land managers at the regional scale, particularly for larger fragments, which border multiple farms or constitute municipal reserves and may play important roles for ecological and social connectivity (De Vos and Cumming 2019). Thus, to foster widespread renosterveld conservation on privately owned land, recognition of all *vrk* components will be necessary in future decision-making.

5.3 Study limitations and acknowledging dual perceptions

Effective land planning is required to integrate not only agricultural land use with biodiversity conservation, but also social justice (Crane, 2006; Hornby et al., 2018). Our study focused on land-use decision-makers and therefore does not represent every member of the Swartland society, including farm labourers, who are among those affected most by structural inequality. Given the land manager demographics, our study partially represents the voices of women. Considering Baker et al. (2019), we recognise that the positions of both researchers and subjects in our study contain implicit biases and power imbalances, stemming from the legacies of colonialism and apartheid and exacerbated by modern economic conditions. Our findings are thus only a part of a much wider narrative. This bias is inherent in the recognition of the NCP human shelter, which demonstrates the role that ecological systems play in regional societal complexity. Viewed from the perspective of the land manager, use of natural areas for human shelter is a detrimental NCP, whereas from the perspective of those requiring shelter, it may be viewed as beneficial. These divergent perspectives are echoed in other identified NCP, such as habitat for renosterveld wildlife. Acknowledging dual perceptions helps to address social-ecological complexity, to recognise that as the same NCP may be viewed differently by different stakeholders, landscape management may include trade-offs (Saunders and Luck 2016; Saunders et al. 2016; Morales-Reyes et al. 2019; Pascual-Rico et al. 2020).

Acknowledging nuance in perception of wildlife is another key part of embracing value and knowledge diversity into land management decision-making. While plant species diversity and endemism form the principal scientific basis for renosterveld conservation, we found, similar to Winter et al (2007), that a major relation between renosterveld and land managers is often mammalian wildlife (Section 4.5). The perception of this wildlife as pests leads to negative perceptions of renosterveld, although these fragments act as species refuges in the agricultural landscape and are vital for conserving the mammal assemblage of the CFR (Clements et al. 2019). Mammals are also hunted for food by farm labourers, an NCP which can be seen as beneficial from the perspective of the hunters but it was also perceived as a detrimental NCP by land managers (see Table 4). Such nuance must be taken into account when anticipating actions from land managers for control of wildlife on farmland (Morales-Reyes et al. 2018) and may help anticipate challenges to progress towards biodiversity-friendly farming landscapes in the CFR (Giliomee 2006).

5.4 Implications for future vrk and NCP assessments

Our study highlights that decision-making of agroecosystem management is characterized by interlinked configurations of values, rules and knowledge. We posit that future applications of the *vrk* framework would find similar associations and interplays among *vrk* components, as we found (e.g. Prober et al. 2017). Regarding NCP assessment, the context-specific approach we employed widens the scope of what constitutes NCP and illustrates the fluidity between material and non-material categories for NCP. For example, we found that picking flowers for shows can be regarded in the general categories from Diaz et al. (2018) as both material and non-material, since it contributes to supporting identities (Table 4). This result echoes previous findings that mushroom harvesting is both a material and non-material NCP (García-Nieto et al 2013). Of particular interest for further research would be in-depth assessment of perceptions of beneficial and detrimental renosterveld wildlife to unpick perceptions of different taxonomic groups and their specific functions (e.g. Morales-Reyes et al. 2018; Pascual-Rico et al. 2020). Further quantifying relational values held by CFR land managers may also help to test the causation of certain NCP outcomes, and to support political legitimacy of conservation decision-making (Schulz and Martin-Ortega 2018), as well as effectively motivate landowner participation in conservation programs (Chapman et al 2019). Additionally, scenario planning to further understand the constraints of these different contexts to changing land management would help to concretize these concepts further. These approaches could help to scale up pluralistic valuation of the CFR biodiversity hotspot in the future.

Concluding remarks

Our application of the vrk and NCP frameworks to renosterveld land management in the CFR identify three different land-use decision-making contexts. Bottom-up and Top-down conservation contexts contain relational values, but differing knowledge and rule types, while a Utility context is principally determined by instrumental values, formal rule types and technical knowledge. Remaining renosterveld fragments are associated with multiple NCP, demonstrating the contribution of these fragments to the multifunctional agricultural landscape, but material, non-material and regulating NCP types vary among the decision-making contexts. As important as understanding where these contexts diverge is recognizing their overlap, in order to foster decision-making for integrated renosterveld management. Hence, it is crucial to note that land managers express multiple and at times conflicting values, rules and knowledge and thereby occupy multiple decision-making contexts. Relational values are also key to understanding how land-managers perceive and therefore make decisions for renosterveld use. The success of integration of conservation and utility approaches dictates the survival of an irreplaceable ecosystem which, despite extensive fragmentation, continues to provide a diverse range of contributions to people.

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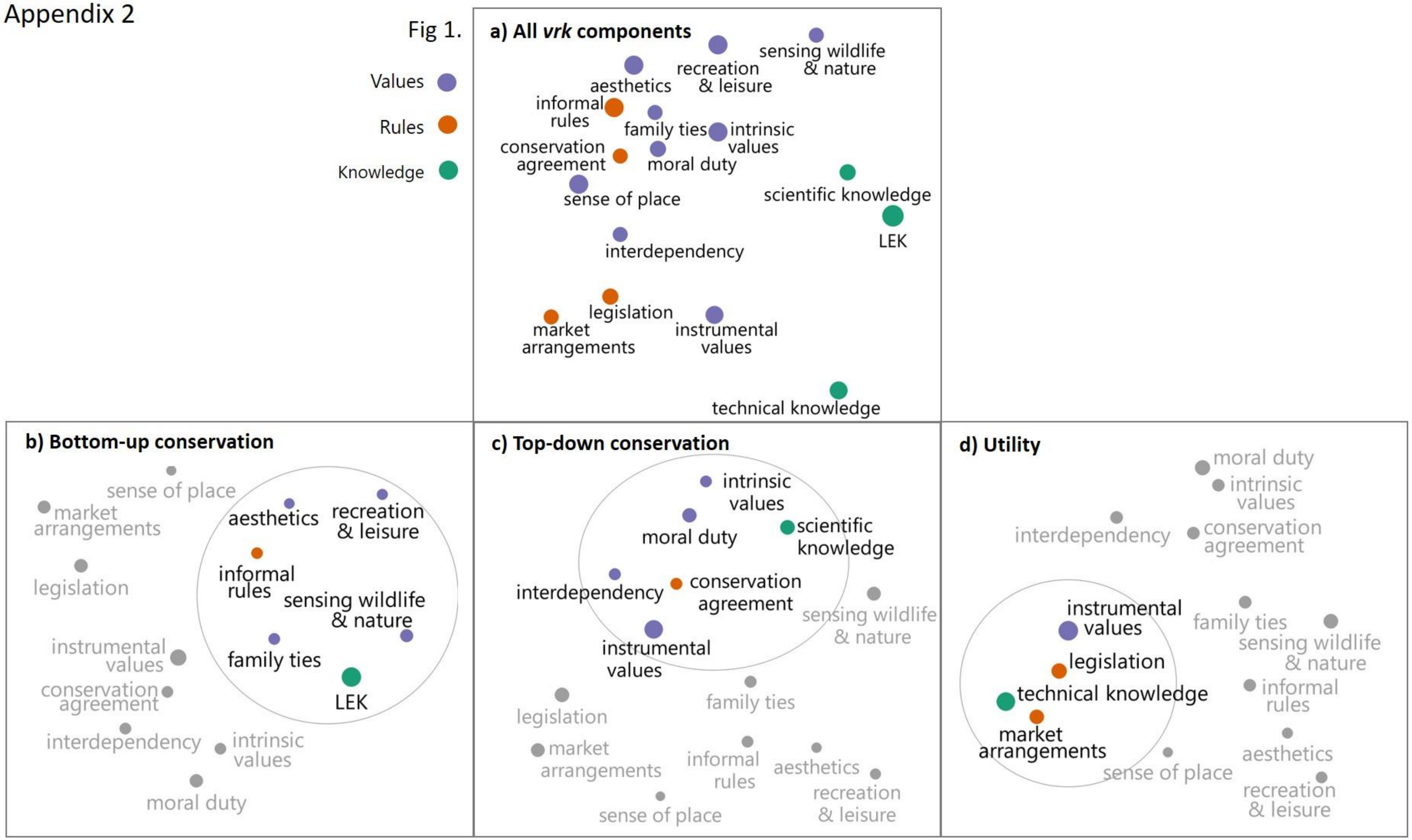
Appendix 1: Interviewee data.

Code	Gender	Age	Primary crop	Farm size (ha)	Renosterveld fragment size* (ha)	Duration of interview (mins)
Wh1	M	30-50	Wheat	163	51.2	41
Wh2	M	30-50	Wheat	450	0.7	43
Wh3	M	30-50	Wheat	380	9.8	26
Wh4	M	>50	Wheat	1080	13.0	19
Wh5	M	>50	Wheat	470	1036.5	50
Wh6	M	30-50	Wheat	471	1.5	37
Wh7	M	>50	Wheat	46	38.7	48
Wh8	M	30-50	Wheat	1800	60.8	46
Wh9	M	30-50	Wheat	1000	464.9	35
Wh10	M	30-50	Wheat	450	112.8	38
Wh11	M	30-50	Wheat	720	446.1	38
Wh12	M	>50	Wheat	620	1.4	37
Wh13	M	<30	Wheat	300	9.3	33
Wi1	F	30-50	Wine grape	520	3.3	31
Wi2	M	30-50	Wine grape	350	485.0	17
Wi3	M	>50	Wine grape	550	9.2	42
Wi4	M	<30	Wine grape	460	11.9	35
Wi5	M	30-50	Wine grape	180	1401.1	25
Wi6	M	>50	Wine grape	315	633.8	34
Wi7	M	>50	Wine grape	483	9.0	23
Wi8	M	30-50	Wine grape	729	27.0	31
Wi9	M	30-50	Wine grape	560	96.3	45
Wi10	M	30-50	Wine grape	1300	14.7	35
Wi11	M	30-50	Wine grape	755	3.4	23
Wi12	M	>50	Wine grape	1000	1.4	25
Wi13	M	30-50	Wine grape	180	0.9	25
Wi14	M	30-50	Wine grape	321	7.1	18
O1	F	>50	Other	NA	22.6	50
O2	F	30-50	Other	NA	31.0	39
O3	F	30-50	Other	NA	17.8	29

*Renosterveld patch size refers to entire size of patch which could also border neighbouring farms, hence the size in ha can be larger than farm size.

Appendix 2



Appendix 2. Fig 1. Ordination of values-rules-knowledge (*vrk*) based on Principle Co-ordinates Analysis (PCoA), performed in MaxQDA (Version 2020) with the 'Code Maps' function. Closeness of points suggests associations among coded components. In Fig 1a, all *vrk* components including the three knowledge types are included. Knowledge types do not show clear dissimilarity, so we chose to separate the ordination by knowledge type and their respective closest associations. Fig 1b-d: Ordination for *vrk* separated by knowledge type. Grouped *vrk* components are shown in colours according to legend and were more associated with each other than remaining *vrk* components (shown in grey). These associations provide the basis for the different decision-making context

Chapter 6

Farmers' perceptions of climate change and adaptation strategies in South Africa's Western Cape

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L-R Cattle in dry land near Malmesbury; a dried up farm waterhole near Darling, 2018

Abstract

Climate change poses a serious threat to South Africa's agricultural sector. Implementing adaptation strategies is thus crucial to secure future agricultural production and rural livelihoods. To support effective adaptation, it is necessary to understand how farmers, as primary land-use decision-makers, perceive and respond to climate change. We conducted semi-structured interviews to examine climate change adaptation behaviour by commercial wine grape and cereal farmers in a water-scarce, recently drought-stricken agricultural region of South Africa's Western Cape. Specifically, we investigated (1) how farmers perceive climate change, (2) which factors influence their adaptive behaviour and (3) which adaptation strategies they apply in their farming practices, and whether these are medium to long-term or short-term coping strategies. Through the resulting discourses, we found that most farmers have observed long-term regional changes in climate, such as changes in rainfall patterns, increasing temperatures and extreme climatic events. Farmers' adaptive behaviour is influenced by previous experience of climatic stresses and internal factors, including risk perception, perceived adaptive capacity and cognitive biases. Institutional and biophysical constraints including perceived lack of government support and soil composition are external barriers to adaptation. Most farmers have implemented adaptive strategies on their farms, including alterations to soil and crop management, such as changes of harvest and planting time, crop rotations and water conservation techniques. However, farmers have planned fewer adaptive strategies to future impacts of climate change than current implemented strategies. Current strategies are mostly technological and address direct impacts of climate stressors, although climate change impacts go beyond the farm scale into society. These findings may have important implications for future policy making and climate change adaptation in this region, given the place-specific institutional and biophysical barriers identified by farmers, and the strategic importance of the Western Cape in South African agriculture.

Key words: adaptive behaviour, Cape Floristic Region, drought, risk perception, South Africa.

1. Introduction

Climate change is one of the biggest challenges facing humankind to date. The severity of the future impacts of climate change is largely determined by peoples' present ability and action to adapt (Wolf and Moser 2011). Adaptation is particularly important in agriculture, given the climate sensitivity of the sector (Smit and Skinner 2002; Haden et al. 2012; Niang et al. 2014). To secure agricultural productivity and rural livelihoods, farmers need to adapt their farming practices to present and future impacts of climate change. However, the relationship between perception of and adaptation to climate change is not straightforward (Wiid and Ziervogel, 2012). Understanding the motivating factors leading to adaptive behaviour is key to promoting climate change adaptation to secure food production and farmers' livelihoods.

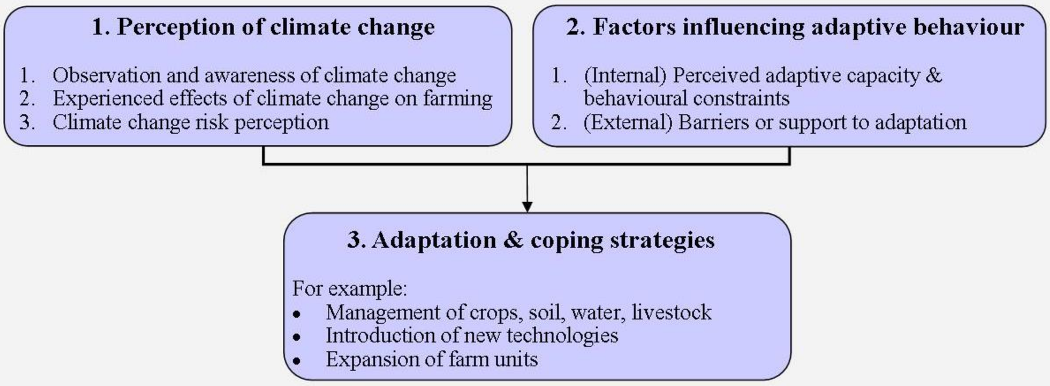
An important precondition to understand individual climate adaptive behaviour is to reveal farmers' cognitive processes (Bryant et al., 2000), which are shaped by experiences and perceptions to climatic changes (Wiid and Ziervogel, 2012). Individual adaptive behaviour is strongly influenced by the perception of climate change, the appraisal of associated risks (Hyland et al., 2015), and the perception of one's own capacity to adapt (Grothmann and Patt, 2005; Woods et al., 2017). Furthermore, the perception of risks and adaptive capacity are affected by cognitive biases, such as the optimism bias, whereby people perceive their personal risk as lower than average (Grothmann and Patt, 2005) and which commonly appear under conditions of uncertainty (Woods et al., 2017).

While the perception of climate change and its impacts can motivate adaptive behaviour (Hyland et al., 2015), farmers' behaviours are also influenced by multiple external factors (Chiotti and Johnston, 1995; Smit et al., 2000; Smit and Skinner, 2002). These factors can either act as a barrier or support adaptation behaviour, and include the access to or lack of resources and capital, such as financial means, technology, information, societal and systemic support (Smit and Pilifosova, 2003; Grothmann and Patt, 2005; Darnhofer et al., 2010; Tessema et al., 2019). Farmers' behaviours are also strongly shaped by personal, environmental and socioeconomic contexts (Findlater et al., 2018, Takahashi et al., 2016). To better understand farmers' adaptation behaviour to climate change, it is necessary to investigate both internal (e.g., cognitive) and external (e.g. institutional and biophysical) influencing factors. This adaptation behaviour can be further differentiated between coping, which consists of immediate or short-term responses to impacts and hazards, and adaptation itself, seen as transformative medium and long-term change (Birkmann, 2011; Fischer, 2019). Determining whether farmers adapt or cope is important for developing policies that foster not only short-term, temporary adjustments but also enduring adaptation in the face of environmental change (Fischer, 2019).

South Africa is especially vulnerable to climate change and its impacts, as a semi-arid and water-stressed country (Botai et al., 2018). Mean annual temperatures have increased by at least 1.5 times the observed global average of 0.65°C, a trend which is projected to increase, along with reduced rainfall, increased rainfall variability, drier winters and high risks of severe droughts and extreme weather events in the southwestern regions of Africa (Niang et al., 2014; Nhemachena et al., 2014; Ziervogel et al., 2014; Davis-Reddy and Vincent, 2017). These projected changes and associated water scarcity will exacerbate existing stresses (Midgley et al., 2005; Dennis and Dennis, 2012; Niang et al., 2014; Botai et al., 2018), leading to negative effects on agriculture, water and food security, ecosystem services and the South African economy (Hannah et al, 2013; Nhemachena et al,. 2014; Ziervogel et al., 2014, Archer et al., 2019). Indeed, climate change-induced increasing water scarcity and insufficient irrigation are expected to lead to severe declines in agricultural productivity of up to 50% in South Africa, as well as other countries in the Southern African Development Community (SADC) region (Davis-Reddy and Vincent, 2017). Next to South Africa, Namibia and southwestern parts of Botswana are already facing high risks of water scarcity and are vulnerable to further climatic changes, especially in climate-sensitive sectors such as agriculture (Davis-Reddy and Vincent, 2017). The highly developed South African commercial farming sector contributes significantly to food security of the southern African region (Tibesigwa et al., 2017), while the spectrum of South African farmers also contains approximately two million subsistence-oriented, smallholder farmers and approximately 20,000 small- to medium-scale commercial farmers (WWF, 2018). South Africa's commercial farming sector has been largely deregulated since the end of apartheid and the transformation of South Africa's political system, meaning that commercial farmers had to respond to free global market conditions without subsidies, credit or trade protections (Hornby et al. 2018; Kheswa, 2013; Mapfumo et al., 2014; Schulze 2016). South African commercial farmers therefore operate under different conditions to other highly mechanized agricultural sectors in higher-income countries, potentially rendering them less resilient to climate change impacts (Findlater et al. 2019). This may be particularly pivotal in the wine industry, where South African farmers compete against developed regions with subsidies such as Europe, North America and Australia (Ashtenfelter and Storchmann, 2016).

In the years 2015-2018, South Africa's Western Cape province was subject to a rare and severe drought attributable to anthropogenic climate change (Wolski, 2018; Otto et al., 2018). The Swartland agricultural region in the Western Cape is the most productive agricultural region in the province, and the recent drought resulted in crop losses and associated economic impacts (Moseley, 2006; Archer et al., 2019). The region is dominated by large-scale commercial agriculture, with associated environmental and socio-political problems, including significant loss of native vegetation and economic inequality (Crane, 2006; Halpern and Meadows, 2013). Many grain farmers in the Swartland have adopted 'conservation agriculture' (CA) principles, such as practicing minimum tillage, introducing crop rotations with legumes and increasing permanent soil cover (Findlater, 2017; FAO, 2017; Western Cape Department of Agriculture, 2019). These principles are promoted in part to combat climate change impacts and diversify risk to farm operations, and are linked to climate change adaptation in the region (Findlater, 2017; WWF, 2018). Considering the region's distinctive climatic variability and the dominance of commercialized agriculture, the Swartland constitutes a unique area to investigate farmers' perceptions of climate change and factors influencing climate change adaptation, particularly in light of recent severe water stress.

In this context, we aim to answer the following research questions: (I) How do Swartland farmers perceive climate change? (II) Which cognitive and external factors influence their risk perception and adaptive behaviour? (III) Which adaptation strategies do they apply in their farming practices and which do they envision to apply in the future? To answer our research questions, we adapted the conceptual framework Model of Private Proactive Adaptation to Climate Change (MPPACC) created by Grothmann and Patt (2005) to study the individual response to climate change. The MPPACC-framework categorizes the variety of cognitive and external factors that determine a person's adaptation intention and resulting adaptive behaviour. We adapted the framework into three components, whereby (1) perception of climate change and (2) factors influencing adaptive behaviour lead to (3) strategies for current or planned adaptation. These three components are further described in Box 1. We also sought to distinguish between adaptation strategies and coping behaviour by interpreting the stated adaptation strategies according to approaches taken by Fischer (2018, 2019), and to identify the overlaps of these stated adaptation strategies with CA principles.



Perception of climate change
1. Observation and awareness indicates whether, and to what extent, farmers evaluate observed changes in climatic parameters as a sign of ongoing, global climate change (Hyland et al. 2015). 2. *Experienced effects of climate related events on farming* refers to the impacts on farming that farmers ascribe to climatic stresses. 3. *Climate change risk perception* indicates farmers' individual appraisals of the probability of exposure to, and the level or harm of, climate-related risks (Grothmann and Patt, 2005).

Factors influencing adaptive behaviour (Internal and External)
1. Internal perceived adaptive capacity and behavioural constraints relates to the farmer's perceived own ability to take effective adaptive responses (Woods 2017; Grothmann and Patt 2005). *2. External barriers or support to adaptation* address the availability or lack of external resources, such as knowledge, money, and institutional support, as objective determinants of adaptive behaviour (Smit and Pilifosova 2003; Grothmann and Patt 2005; Darnhofer et al. 2010; Nhemachena et al. 2014).

Adaptation and coping strategies
We considered agricultural adaptation strategies as all measures, activities and changes in the agricultural system, at farm level, related to reducing the system's vulnerability to climatic stresses (Esham and Garforth 2013, Smit and Skinner 2002). We distinguished between long and medium-term adaptation strategies and short-term coping strategies according to Fischer (2018, 2019).

Box 1. Conceptual framework of adaptive response to climate change in agriculture, adapted from Grothmann and Patt (2005).

2. Methods

2.1 Study area

Our research area is the Swartland municipality and its close surrounding in the Western Cape province, South Africa (Fig. 1). The Western Cape accounts for 12% of South Africa's total agricultural area and provides 20% of the nation's total agricultural production output (Meterlekamp, 2011; Directorate Statistics and Economic Analysis, 2013), mostly in large-scale commercial enterprises (Findlater, 2013). Commodities include rain-fed winter grains including wheat, oats and barley, plus viticulture, horticulture and livestock (Midgley et al., 2005; Meterlekamp, 2011; Department of Agriculture, Forestry and Fisheries, 2017). The province is a Mediterranean-type, winter rainfall region with Atlantic ocean influence and fertile soils, rendering it especially favourable for cereal farming, including wheat, oats and barley, and viticulture (Midgley et al., 2005; Western Cape Government (WCG), 2015; Araujo et al., 2016). Additional farming types include fruit and vegetable production and livestock (Midgley et al., 2005; Meterlekamp, 2011; Department of Agriculture, Forestry and Fisheries, 2017). The region has experienced a mean annual temperature rise of approximately 1.0°C over the last 50 years, as well as increased flooding, droughts and heat waves (WCG, 2015). Climate models project continued warming and a general drying trend in the next decades (WCG, 2014), increasing number of hot days and more frequent heat waves in the Western Cape (WCG, 2015). The western parts of the region in particular are projected to experience drier winters and high risk of droughts (Midgley et al., 2005; Niang et al., 2014; WCG, 2015).

Grain production covers approximately 58% of all cropland in the Swartland, while vineyards cover 6% (Western Cape Agristats, 2019). While wheat is the major grain under cultivation, crop rotations include medics (clover) and lucerne (alfalfa). Grain production in the Swartland is sensitive to higher temperatures and heat waves, reduced rainfall, longer dry spells and higher frequencies of intense rainfall events. The majority of wheat farmers in the Swartland grow rainfed wheat during the winter wet season and do not use irrigation (Findlater, 2017; Western Cape Agristats, 2019). Grape production is sensitive to climate variability, temperature changes and droughts (Hannah et al., 2013; Araujo et al., 2016). Wine grape farmers often have irrigation systems, and are hence less sensitive to changes in rainfall (Araujo et al., 2016), although some Swartland farmers also have dryland vines. The limited supply of water leaves little scope for expansion of irrigation (Archer et al., 2019). The projected climatic changes are thus likely to have negative effects on both grain and wine grape production in the region (Hannah et al., 2013; Araujo et al., 2016).

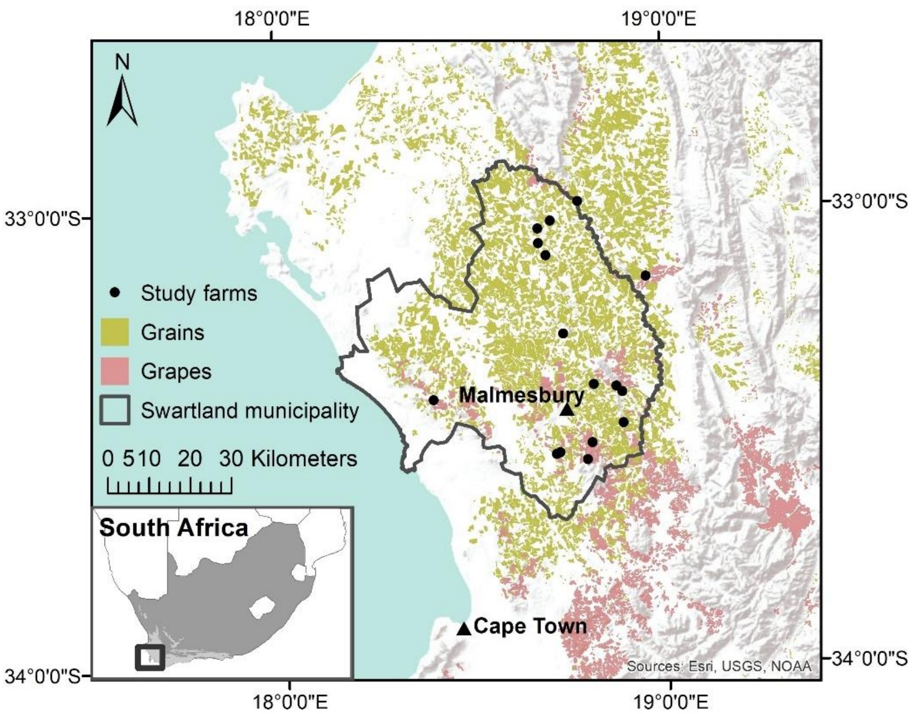


Figure 1: Location of study farms in or within 5km of the Swartland of South Africa's Western Cape province. The Swartland municipality is outlined in grey and the 16 farms represented in the study are identified with black circles. Spatial information on crop cover from Western Cape Department of Agriculture Crop Census 2017 (https://gis.elsenburg.com/apps/cfm/) Rainfed annual crop also includes planted pastures.

2.2 Data collection and analysis

We collected qualitative data by conducting face-to-face semi-structured interviews with 16 commercial farmers, of which eleven concentrated on wheat farming and five on wine farming in the Swartland. Farmers from a pool of participants of a previous study in the region (Topp and Loos, 2018) were contacted and asked if they would be willing and available to participate. From this pool, 16 farmers signalled their willingness and availability. Interviews were conducted between September and October 2018. Prior to each interview, we informed all participants about the purpose of the study and the interview process and obtained their written consent to participate in the research. All interviews were conducted in English, audio-recorded using voice recorders and later transcribed in full. The average length of the interviews was 40 minutes, ranging between 25 minutes and 1.5 hours. The interview questions were designed to address each of our research questions, and informed by a scoping of literature on climate change adaptation in Southern Africa (Nhemachena et al., 2014; Elum et al., 2017; Filho et al., 2017; Callo-Concha, 2018). The full interview guide is provided in Appendix 1. We differentiated wheat (WH) and wine (WI) farmers in order to relate potential differences in farmers' perceptions of climate change and differences in the implementation of adaptation to farming systems. Such contextual information may help to improve understanding of farmers' observations and "ground" knowledge in place (Soubry et al., 2019). The transcribed interviews were coded and analysed with the software MaxQDA Version 2018. We applied qualitative content analysis (Mayring, 2002; Kuckartz et al., 2008) to uncover the components of the conceptual framework outlined in Box 1. In order to code for climate change risk perception, we coded statements into three categories; low, moderate or high. We coded for low risk perception where farmers expressed little concern for climate change and low perceived exposure to its impacts, whereas we coded for high risk perception when farmers expressed high concern and high perceived exposure to its impacts. Low risk perception also encompassed cognitive biases such as optimism and avoidance of dealing with climate change. Moderate risk perception encompassed more measured statements which relativized the severity and urgency of climate change, and high risk perception encompassed statements of anxiousness and resignation towards the effects of climate change. Perceived adaptive capacity was not explored by direct questioning but identified from farmers' responses to other questions, such as those regarding problems caused by climatic changes, the availability of information and support towards climate change or the application of adaptation strategies. We identified strategies and interpreted whether they were short-term coping strategies or more medium and long-term adaptation strategies, evaluating the stated benefits of each strategy in order to better understand the purpose behind its implementation and assess if the practice may be considered adaptation (Fischer, 2018). We also categorized whether an adaptation strategy overlapped with CA principles based on recommendations for CA in a South African context (WWF, 2018). The CA principles are primarily for grain farming and therefore less overlap of CA principles with stated adaptation strategies in wine farming was expected. While our sample size was relatively small, our in-depth conversations with farmers allowed for expression and contextualization of perceptions and responses to climate change, with the potential for a rich dataset. The entire coding system, including a detailed description of all categories and codes, is available in Appendix 2.

3. Results

All interviewees were white, predominantly male (n=15), and spoke Afrikaans as their first language, although the interviews were conducted in English (see Appendix 3 for full interviewee data). The average time spent farming was 24 years, ranging from 6 to 43 years. The area of arable farmland belonging to farmers ranged from 180 to 1800 hectares, and the median average was 550 hectares. The majority of wheat farmers (n=10 out of 11) practiced dryland agriculture, whilst all wine farmers irrigated their vines (n=5). Three farmers were hired managers, whereas the remaining thirteen were the owners of the land they farmed. We present our results according to the three components of the conceptual framework presented in Box 1.

3.1 Perception of climate change

3.1.1 Observation and awareness of climate change

The majority of interviewees (n=12) were aware of climate change and ascribed the local climatic events they experienced within the last two decades to global climate change, for example: *"There is a climate change definitely happening. And the seasons have moved along with that as well."(F8_WI)*. Four interviewees expressed scepticism for anthropogenic climate change and whether natural weather variability and climatic cycles could be distinguished from long-term regional climate change, for example: *"It's very difficult to say that global warming has an effect on our farming, because last year was dry, it was a dry year, but this year it's more normal. And now the harvest is really good! So what can you say now? Is it now global warming, what is it? I don't know." (F10_WH).* All interviewees reported that they had observed changes in climate throughout the last 20 years (Table 1). Whilst the majority (n=12) related these changes to climate change, interviewees that were uncertain or sceptical about climate change considered them a natural phenomenon (n=4). Reported changes included rainfall variability (n=13), increased drought (n=11), reduced precipitation (n=8), shorter rainy seasons and increased intensity of single rainfall events (n=3), and extreme weather events including floods (n=2). Many interviewees (n=9) stated they had observed a change of seasons, for example: "*It feels like it's getting later and later… the seasons probably moved on almost three weeks*" (F16_WH). Wheat farmers in particular evaluated the change and unpredictability of rainfall patterns as critical for the germination and grain filling period of the wheat, as illustrated by the next quotes: "S*ometimes we start early to plant and the seeds won't come up [or] they will come up but they only get 4.5 mm of water and come up and then die. So the next rain is taking too long to come*" (F14_WH) and "(…) *we plant in a dry season, the soil is very dry, we can't wait for the moisture because the timing [of rain] is of the essence."* (F15_WH).

3.1.2 Experienced effects of climate related events on farming

Twelve interviewees reported that they experienced climate-related problems on their farms, including reduced yields (n=11), crop failure (n=7), soil erosion (n=2), and lower crop quality (n=1). These effects were often considered to be interlinked, for example, reduced yields were linked to financial losses (n=5). Crop failure and damage was associated with above-average heat events or extreme weather events such as hailstorms. One interviewee reported increasing pests in relation to climate change and two interviewees reported a shorter growing season. Four interviewees reported few or no problems due to climate related events.

3.1.3 Climate change risk perception

Of interviewees that expressed concern for climate change-related risk (n=9), three demonstrated high risk perception. Concerns included the impacts of climate change on farmers' livelihoods and on those dependent on them, including family and employees, for example: "*Some of the farmers nearly lost their farms because it was so dry. Because you get so scared because it's not just [affecting] you and your family, it's the farm workers that work for 20, 30, 40 years for you"* (F1_WH). One interviewee expressed strong concern for the impacts of climate change on his ability to farm: *"But the climate change make it more difficult and more and more difficult [to farm]. So where does it stop?"* (F14_WH) and another respondent showed resignation towards the global consequences of a changing climate: "*I don't know what we can do, because I think it will be too late for the people in the world to do something"* (F13_WI).

Five interviewees expressed moderate risk perception and stressed the long-term, gradual occurrence of severe climatic impacts, for example: *"Climate in our region wouldn't turn over night into a dry area. It will be 50 or 100 years. Or 300 years for that matter."* (F4_WH). Interviewees that expressed moderate risk perception were confident that there was sufficient time to adapt, or that addressing a fluctuating climate required a year-by-year approach. For example, interviewee F7_WI reported recent extreme weather events that had severe impacts on her farm but considered climate change to be too unpredictable to implement long-term adaptation strategies: "*Last year was a difficult year and this year it was normal again. So you don't know… you can maybe try to prevent stuff and then it's not necessary… so we basically just take it as it comes.*" (F7_WI). Four interviewees, while expressing awareness of climate change, hesitated to adapt as they did not feel affected to a degree that justified the economic cost of implementation of adaptation measures, for example: *"The changes are too small to make any… huge strategies."* (F14_WH).

Four interviewees expressed low risk perception. Interviewees were either optimistic about not being affected by climate change in their lifetime, expressed hope that climate change would not happen, or that the extent of its impacts would be less severe than projections estimate. Three farmers attributed hope, optimism and confidence that climate change is a natural phenomenon to their religious beliefs and convictions, for example: *"I believe in God and I believe God won't let us down*" (F10_WH). In contrast, other farmers expressed an avoidant attitude, stating that although they were aware of climate change and did experience climate related yield losses, they did not want to know about the topic for example: *"I just put a blanket over my head and don't worry about it."* (F9_WI). In three cases, interviewees presented inconsistent statements relating to risk perception, by assessing current risks as marginal but future risks as threatening (i.e. F14_WH) or by expressing belief in and anxiousness towards climate change but optimism towards its impacts and their own ability to adapt (see 3.2.1) (F10_WH; F13_WI).

3.2 Factors influencing adaptive behaviour

3.2.1 Perception of adaptive capacity

In total, 13 interviewees expressed perceptions of their own capacity to adapt to climate change and different attitudes towards change and adaptation. Five interviewees revealed a low perceived adaptive capacity, referring to perceived superior forces of nature, for example: *"You can't fight against nature. So you can only do what you can do. If there is no water you can do nothing."* (F1_WH) and stating a lack of possibilities: *"All that I can think of, that we did already. We're out of options."* (F6_WH). This low perceived adaptive capacity was considered an internal barrier to adaptation (Table 1). Other interviewees characterized climate change as an antagonistic force they could not oppose, alongside a passive attitude towards their own action, for example: *"So somewhere you going to have to stop [farming]… Because climate change pushing you and that's a direction you can't farm."* (F14_WH). Adaptation was simultaneously framed as a necessity to survive: *"It's actually adapt or die. We need to adapt always. Thinking of new methods, new ways."* (F6_WH).

In contrast, nine interviewees expressed a high perceived adaptive capacity, presenting statements that revealed a proactive attitude towards change and adaptation. The ability to adapt was designated as an essential characteristic of a good farmer: "*But to be a good farmer you must change. So if the world changes, so you must change. If you don't change you lose your farm."* (F2_WH). One interviewee specifically attributed the capacity to solve problems as a distinctive characteristic of all South African farmers (F10_WH). Younger interviewees contrasted their own ability to adapt to the older generation of farmers, who were not willing to change their way of farming any more, and emphasized the necessity of being open-minded in order to have personal adaptive capacity: "*It isn't a challenge to change, you just have to make a mindset and be adaptable. My dad wasn't very [adaptable], but they are the older generation. So for us it's easier, we can adapt like that [snaps fingers]"* (F16_WH). Three farmers likewise expressed that the recent drought experience had caused an increased consciousness and behaviour change in their personal water usage and named this as beneficial for their future adaptive behaviour, for example: *"These dry seasons challenge [us] very much economically. We learn to save more in these years. But I think it makes us better farmers moving forward. We learn out of this dryness what we can be capable of. I think we didn't have such dry years in a long long time. So you learn how to work with what you have" (*F8_WI).

A similar yet more combative attitude towards climate change was expressed by two interviewees. This attitude contained statements of self-confidence and framed climate change as a challenge to be defeated, for example: *"I'm an extrovert and I will challenge everything. So I like challenges"* and: *"I will win. And I believe I will win. And I believe in myself and I hope that the climate will change."* (F13_WI). Likewise, one interviewee demonstrated a highly proactive stance: *"I can't sit and wait till the world [to] change, I want to change it myself."* (F11_WH). He perceived a high capacity to deal with climate change, not through climate-specific measures but by maintaining his current farming practice: *"I think we will… outperform maybe climate change; that is my aim. In 20 years' time, I want to sit back and say 'but climate change hasn't affected me'"* (F11_WH).

3.2.2 Barriers or support to adaptation

Farmers named few organizations which provided help or support to adapt to climate change, but identified institutional and political constraints as the major external barriers to adaptation (n=16), followed by biophysical and economic constraints (n=10) (Table 1). Interviewees expressed a negative and frustrated attitude to lack of governmental support (n=14), and reported displeasure with water management by the municipalities during drought years (n=5), stating: *"Government doesn't help us at all… They help pull us down. Not bring us up."* (F14_WH) and "*[water] you don't use they are going to take from you."* (F7_WI). Three wheat farmers felt insecure about future land rights and perceived land tenure insecurity as a political barrier to adaptation, for example: "*We have bigger problems on this moment in South Africa than climate change… That's a big concern for us. Land… reconciliation … that means they can take your land without compensation.*" (F3_WH). This high perceived uncertainty was linked to behavioural constraints such as lack of motivation to plan for the future. One interviewee reported he felt insecure about changing land rights and the prospect of losing his farm in the future: *"It's a bit demotivating to build your soil and one day in a month you maybe go and say to yourself: Is this really worth it? Because are you going to have your farm? If I am building up my soil and they are taking the land, what I've been working for my whole life."* (F11_WH). Although three farmers were hired as land managers and were not landowners, this was not mentioned as a factor in choosing whether to implement adaptation strategies.

Biophysical and economic constraints were also identified as external barriers to adaptation. For example, two farmers identified the regional soil composition as a barrier to successfully reducing tillage and moving toward CA principles (Table 1). One farmer expressed his general willingness to adapt but named the unfavourable topography of his farm as a biophysical barrier to implement actual adaptation: "*In a perfect world, I would love to keep the stubble and prepare my soil better for when the big and quick rains come … and I have a very hilly farm, so it's a problem. If I had a flat farm, it would be much easier*" (F15_WH). Farmers also saw little potential in natural vegetation on their farms to contribute to climate risk mitigation. One farmer noted that the remaining natural vegetation on his farm may be a good location for a borehole to find more water: "*I have a good feeling about that spot in the renosterveld between the rocks. I think maybe there is some water down there*" (F12_WI). Undertaking climate change adaptation measures was seen as a challenge to remaining financially profitable. Identified economic constraints included the lack of government subsidies, price pressure due to subsidized grain imports, decreasing crop market values and increasing input costs for fertilizers and pesticides (Table 1).

Available information supported farmers to learn about climate change (n=15) and adaptation strategies (n=13), but a lack of reliable and long-term information was identified as an additional constraint to adaptation (n=4). The most commonly stated source for climate change information was media, including the internet and weather forecasts (n=11), followed by exchange with other people, such as self-organized farmer unions, other farmers and agricultural consultants (n=7). The most commonly stated sources for information on adaptation strategies were institutions and agricultural companies, such as research farms, agrochemical companies and regional or national agricultural research boards (n=9). Information constraints led to a reported lack of awareness of climate change (n=4) and the need of accurate predictions for future decision-making: "*All that we saw about the long term predictions is that…you can't work with that, it's not dependable enough*." (F5_WH).

Table 1: External and internal barriers to climate change adaptation as identified by all interviewed farmers (n=16).

Barriers to adaptation		**All farmers (n = 16)**
External	**Institutional and political constraints**	**16**
	Lack of governmental support	14
	Inadequate municipal water management	5
	Insecurity of land rights	3
	Restrictions on building dams	2
	Lack of capacity of government institutions	2
	Biophysical constraints	**10**
	Dependency on nature and climate	4
	Local soil composition	2
	Farm topography	1
	Economic constraints	**9**
	Maintaining profitability	8
	Lack of financial means	2
	Increasing input costs	2

Internal	**Information constraints**	**4**
	Technological constraints	**1**
	Low perceived adaptive capacity	**5**
	Behavioural constraints	**5**
	Perceived exhaustion of adaptation possibilities	3
	Lack of motivation to plan for the future	1
	Lack of open-mindedness for change	1

3.3 Adaptation strategies

3.3.1 Implemented adaptation strategies

We found that all farmers (n=16) adapted their farming practices in response to experienced climatic stresses. In total, 22 strategies were identified in five different adaptation groups: crop management, soil management, water management, livestock management and other (Table 2). Wheat farmers generally stated more soil management strategies than any other adaptation group, whilst wine farmers stated more water management techniques. Of these 22 strategies, 11 could arguably be identified as coping while 15 could arguably be identified as more long-term adaptation strategies, and these groups were not mutually exclusive (Table 2). For example, the change of harvest and planting time may be a short-term response in that a farmer can implement this change from one farming cycle to the next, but is also a long-term strategy in that this reflects gradual climatic changes and requires ongoing flexibility at farm level. Stated adaptation strategies such as minimum tillage, legume cover crops and extended crop rotations overlapped with CA principles (Table 2). These changes were also stated by farmers as beneficial for experienced climatic stresses, as illustrated here: "*I think the best precaution we did here for the drought is the no-till*." (F5_WH). While 11 interviewees stated to have implemented adaptation strategies as a direct response to climate change, two farmers applied changes primarily for economic or agricultural reasons (F3_WH; F4_WH) and stated to have experienced fewer or no climatic stresses effecting their farms. These farmers also expressed uncertainty about the reality of climate change or the imminence of its impacts (see for example section 3.1.3, quote from F4_WH).

Table 3: Climate change adaptation and coping strategies implemented by interviewed farmers (n=16).

Implemented adaptation strategy	Stated benefits	All farmers (n=16)	Coping strategy (short-term)	Adaptation strategy (medium to long-term)	Conservation Agriculture principles
Crop management		14			
Change of harvest and planting time	Match plant growth stages to rainfall variability	4	X	X	
Introduction of legume cover crops	Reduced loss of soil moisture; less application of chemical fertilizers thereby reducing production costs	3		X	X
Crop rotation	Improved soil moisture and structure	3		X	X
Crop diversification	Spread of financial risks and improved cash flow	3		X	X
Removal of unproductive crops	Water saving	2	X		
Reduction of fertilizer input	Lower production costs, leading to greater financial stability in drought years	2	X	X	X
Increase of fertilizer input	Increased yield despite climatic stress	2	X		
Introduction of cultivars with shorter growing seasons	Better adapted to changing seasons	1		X	
Crop protection with netting	Protection against weather extremes and decreased soil moisture loss through shade	1	X	X	
Introduction of drought-tolerant cultivars	More adapted to drought conditions	1		X	
Soil management		11			
Minimum tillage	Increase in yields, soil moisture and organic carbon; reduced energy input	7		X	X
Increased soil cover	Reduced water evaporation	5		X	X
Building topsoil	Improved fertility, organic carbon and water holding capacity	3		X	X
Composting	Soil improvement	1		X	X
Water management		6			
Water conservation techniques e.g. drip irrigation	Maximise water use efficiency	4	X	X	
Technological advancements e.g. computerized soil moisture meters and solar water pumps	Maximise water use efficiency	2	X	X	
Increase of water usage	Crops can be more frequently watered with available water	1	X		
Livestock management		3			
Abandonment of livestock	Reduced feed costs, leading to greater financial stability	2	X		
Change of grazing patterns	Prevention of overgrazing and soil protection	1		X	
Change of fodder	Increased likelihood of livestock survival through times of climatic stress	1	X		
Other		3			

Table 3: Climate change adaptation and coping strategies implemented by interviewed farmers (n=16).

Introduction of new technologies e.g. computerized soil mappings and GPS control systems	Reduced cost of agrochemical use, leading to greater financial stability	2				X
Expansion of farm units	Additional income from additional farmed land	1	X			

3.3.2 Future adaptation strategies

As well as identifying already implemented strategies, twelve interviewees identified adaptation strategies they may implement in future. The most commonly mentioned strategy was the introduction of cultivars with shorter growing seasons or better drought-tolerance (n=11). Additional future strategies included crop diversification (n=2), shifting to livestock husbandry if future wheat or wine grape profitability declined (n=2), and netting for crop protection and shade (n=1). Three interviewees stated no intention to adapt, as they perceived the range of adaptation possibilities to be exhausted (see 3.2.2). Two interviewees (F13_WI; F11_WH) who showed a high perceived adaptive capacity and combative attitude towards climate change listed fewer or no concrete future adaptation strategies (see 3.2.1).

4. Discussion

We found a range of perceptions and adaptations to climate change among Swartland commercial farmers. We discuss our findings according to the three components of the applied framework: perceptions of climate change, factors influencing adaptation behaviour, and adaptation strategies.

4.1 Perceptions of climate change

The majority of interviewed farmers were aware of climate change and reported experienced climate changes consistent with long-term regional trends, including increasing mean annual temperatures, and short-term climatic events, such as severe drought (Davis-Reddy and Vincent, 2017; Otto et al., 2018). Farmers' perceptions are often affected by recent years' experiences (Bryant et al., 2000; Takahashi et al., 2016). Recent drought exacerbated some interviewees' anxiety about climate change, while interestingly, rather than seeing the 2015-2018 drought as evidence of the increasing need to adapt, some interviewees partly downplayed the reality or severity of climate change by ascribing the recent drought to natural climate fluctuations. Specific farming context also plays a role in farmers' perceptions (Wiid and Ziervogel, 2012), with wheat and wine farmers respectively emphasizing different impacts of climate change. Water stress can conversely improve wheat quality by concentrating proteins in the grain, potentially leading to satisfaction with 2017 and 2018 harvests for some wheat farmers, despite water scarcity (Archer et al., 2019). While only one wheat farmer we interviewed stated this potential benefit to wheat quality (F4_WH), the majority of wheat farmers mentioned the overall hardiness of wheat in drought conditions and their commitment to its cultivation. Drought conditions can increase pest, disease and physiological stress on grapevines, as well as yield reduction (Araujo et al., 2016), all of which were reported by wine grape farmers in our study. These stressors have been reported in other wine-producing regions such as California and southern Europe (Ashenfelter and Storchmann, 2016) and while at a district scale, impacts on the sector may be managed, the effects on grape yields may be critical for the individual farmer (Araujo et al. 2016).

We found a diverse mix of low, moderate and high risk perceptions among farmers. Farmers with low or moderate risk perception relativized climate change risks by pointing to the long-term uncertainty of climate change, which is in line with Woods et al (2017), who state that risks with longer time horizons are perceived as smaller than those in the short-term. The dominance of perceived short-term risks to farm survival over long-term risks from climate can impede adaptation or uptake of other best practices, such as CA principles (Findlater et al., 2018). Many of the farmers we interviewed acknowledged the risk of climate change but used 'survival' or 'emotional' language, as found by Findlater et al. (2018), including optimism bias, avoidance, and ideologies to describe their perception of risk. These cognitive processes were prevalent among farmers with low risk perception. Previous research found that this low risk perception can hinder adaptation behaviour (Grothmann and Patt, 2005; Gifford et al., 2011; Wolf and Moser, 2011). Overall, farmers expressed multiple forms of uncertainty for the future, in which climate change risk was framed as part of the day-to-day challenges of farming rather than a concern requiring special or targeted consideration (Takahashi et al., 2016). Adaptation is therefore more incremental than transformative (Fischer, 2019). Concern for short-term farm survival can also hinder long-term adaptation behaviour (Findlater et al. 2018), but we found that some farmers named some strategies specifically for bridging low-income periods, such as crop diversification, which could sustain the farm into the longer term and potentially through more challenging climate conditions.

4.2 Factors influencing adaptive behaviour

Woods et al (2017) found that farmers' perception of their adaptive capacity, along with external factors, can hinder or support an individual's adaptation intention. We found that perceived adaptive capacity varied among respondents. Interviewees with low perceived adaptive capacity referred to an exhaustion of adaptation possibilities or to their high dependency on climate and nature, whereas those with high perceived adaptive capacity had a positive attitude towards change and their ability to solve problems. Arbuckle et al (2015) suggested that this problem-solving attitude means farmers are more open to adaptation than mitigation. We also identified an extreme version of this attitude to climate change adaptation, where climate change was viewed not only as a problem to solve, but as an opponent to defeat. While this combative approach shares some aspects with perceived high adaptive capacity, such as confidence in current farming practices, its proponents listed fewer future adaptation strategies and expressed a less adaptive mindset. We also found evidence that the interplay of external and internal factors can support adaptation intention, as some farmers identified that restricted water usage taught them that it was possible to work in highly challenging conditions, increasing their perceived adaptive capacity. Although the variables we considered in this study comprise a basic conceptualization of perception, the underlying processes of human cognition are deeply complex (Gifford et al., 2011), and these links between perceptions, adaptation intention and actual adaptation implementation in the Swartland context would benefit from further investigation.

Farmers consistently reported barriers to adaptation. We found that, similar to Findlater et al. (2018), perceived external barriers to adaptation were mostly institutional and political, although they often intersect with economic constraints; for example, a lack of government subsidies is related to a lack of financial means at farm level. These barriers also point to shared responsibilities at a regional scale for adequate water management. The commercial farmers we interviewed in the Western Cape did not list socio-economic constraints felt in other South African regions, such as poverty, lack of credit and gender issues, which were found to be important in previous research (e.g. Crane, 2006; Nhemachena and Hassan, 2007; Gbetibouo et al., 2008; Bryan et al., 2009). However, the farmers in our study expressed concern for potential changes to land ownership, which was named as a demotivating influence for farm investment, including implementation of costly strategies to deal with climate change. This perceived uncertainty demonstrates how external factors may override internal factors such as perceived adaptive capacity and limit adaptation behaviour. Farmers also acknowledged that this perceived uncertainty, along with related economic insecurity, affects future farm employment. Climate change adaptation at farm-level should also include risk assessment and mitigation to farm employees and dwellers (Hornby et al., 2018). It must be noted that our interviews reflect perceptions from farming decision-makers but do not reflect perceptions of the full spectrum of the Swartland agricultural society, including farm employees and dwellers. Further investigation into social interactions and the potential impact of land ownership changes on adaptation could also shed light on Swartland farmers' uncertainty and related implications for rural livelihoods.

Biophysical constraints, including dependency on nature and farm topography, were noted as additional barriers to adaptation. Here we found evidence that rather than supporting intention to adapt, external factors can limit internal perceived adaptive capacity. For example, hilly farm landscapes were identified as a physical constraint to effective soil management despite the farmer's willingness to implement soil conservation measures. Interestingly, natural vegetation was not identified by farmers to support climate risk mitigation. Notwithstanding, natural vegetation provides valuable grazing during drought conditions, when planted pasture is insufficient to provide enough fodder for cattle (Winter et al., 2007), and has been shown to reduce soil erosion (O'Farrell et al., 2009), which was attributed to climate change by farmers in our study. Farm locations with remaining natural vegetation were identified by farmers as areas which may provide extra water sources, which when coupled with increased grazing, potentially increases pressure on remaining fragments of natural vegetation. The combination of perceived uncertainty, barriers, and the related uptake of specific implementation strategies among Swartland farmers, illustrates the knock-on effects that farmers' responses to climate change have, not only on farming operations, but on the surrounding landscape and society. This underlines the need to embed the perception and adaptive behaviour of farmers in their specific social-ecological context (Soubry et al. 2019).

4.3 Farmers' adaptation strategies

Our interviews revealed that farmers with experience of climatic stresses were more likely to implement adaptation strategies, upholding the theory that risk experience influences response behaviour (Grothmann and Patt, 2005; Clayton et al., 2015). A wide range of adaptation strategies were implemented by farmers, but the most commonly mentioned strategies aimed to maintain crop productivity and soil quality, with reduced climate vulnerability a secondary benefit. For example, farmers mentioned the increased use of fertilizer as a response to climatic stress, although Tessema et al. (2019) found that farmers may attribute this strategy to climate change due to social desirability bias: the desire of the interviewee to tell the interviewer what they want to hear. However, some of these strategies are also implemented by farmers elsewhere in Africa to adapt specifically to climate change (Nhemachena and Hassan, 2007; Gbetibouo, 2008; Findlater, 2017; Archer et al., 2019).

The identification of strategies which may be termed short-term coping in contrast to long-term adaptation enables the differentiation of actions related to immediate impacts compared to those related to change (Birkmann, 2011). While many strategies named by farmers in our study may be termed short-term coping, proactive, long-term adaptation measures, such as diversification of crops, the introduction of drought-tolerant cultivars or technology and infrastructure investments were implemented less often and cited as potential future adaptive strategies. These future ideas differed little from current practices, suggesting that farmers do not consider approaches beyond their usual methods, an inclination which may be attributable to other influences such as farmer information networks (Wiid and Ziervogel, 2012), or a lack of external innovation influx. Indeed, the fact that some of our interviewees belonged to the same local community or farmed neighbouring parcels of land suggests that their perceptions of possible farming practices are likely to be similar, although we found suggested differences in attitudes between generations. However, some of these practices, such as experimentation with different wine grape varieties, are key parts of multi-faceted adaptive approaches to climate change risk in comparable wine grape-producing regions, such as South Australia (Bardsley et al. 2018).

Although wheat farmers perceived a wider range of barriers to adaptation than wine farmers, they identified more future adaptation strategies (Table 2). This may be in part due to the recognition of benefits of adopting CA principles in commercial grain production, and the development of an associated long-term outlook (Findlater et al., 2018). In addition, specific farming system context was found to be important for adaptation, since wheat farmers responded to ongoing water scarcity principally through soil management, whereas wine grape farmers noted adjustments to water management as a present and future response. We found confirmation that wine grape farmers apply recommended mitigation strategies, such as adjusting irrigation timing to grapevines' early growth periods (Araujo et al., 2016). Both wheat and wine farmers may also be aware of a wider range of future adaptation strategies due to regional promotion of climate-smart farming practices (WWF South Africa, 2018; Western Cape Department of Agriculture, 2019). However, all strategies listed were primarily technological in nature, although climate change was cognitively linked to wider societal concerns, and therefore technological adjustments alone do not address the full spectrum of impacts of climate change (Hornby et al., 2018). Tibesigwa et al. (2017) observed that the commercial South African farming sector may be as vulnerable as smallholder farming systems to climate impacts, particularly for highly specialised commercial production. Nonetheless, our findings on perceptions and barriers for commercial farmers also highlights the challenges for non-commercial, low-input, subsistence and smallholder agriculture elsewhere in southern Africa. These regions are among the world's most vulnerable and limited access to relevant information and technologies pose many challenges for future climate adaptation (Mapfumo et al. 2014).

5. Concluding remarks

Our study echoes Wolf and Moser (2011) in recognizing that no single theory can explain the variation in human perception and response to climate change. We found a mix of low to high climate risk perception and perceived adaptive capacity among Swartland commercial grain and wine grape farmers. All farmers perceived climate change impacts and acknowledged accessible sources of information about climate change, while noting institutional, political and biophysical barriers to adaptation, which are shared and place-specific. The combination of particular internal cognitive factors, including optimism bias, avoidance and ideologies, with these external barriers, can limit Swartland farmers' perceived adaptive capacity and influence their adaptation behaviour. Our conversations with farmers illustrated how climate change transcends environmental issues and how this is often contextualized in other socio-political issues (Wolf and Moser, 2011). Farmers' strong perceptions of uncertainty regarding climate change impacts, and related implemented strategies, have knock-on effects for rural livelihoods and the Swartland landscape. By recognizing enabling and limiting factors for climate-adaptive behaviour, as well as alternative attitudes held by decision-makers, we can understand dynamics at play in agricultural systems contributing to food production. The effects of climate change are already being felt in the Western Cape and are likely to be exacerbated in future (Archer et al., 2019; Otto et al., 2018; Midgley et al., 2005). Climate resilience in the province is important not only for South Africa but for southern Africa more widely due to the region's strategic importance for export and its contribution to regional food security. By assessing both grape and grain farmers, our study reveals how neighbouring producers may experience and respond differently to climate change impacts in the climate-vulnerable Western Cape. We found farmers tended to list strategies which were in keeping with widespread farming practices and which overlapped with conservation agriculture principles. This tendency reflects the capacity, both perceived and external, of farmers to respond to incremental changes in climate with the set of approaches they use day to day. While these approaches are largely technological, they do not address the aforementioned broader socio-economic impacts of climate change, which highlights the cognitive challenges of land management in the face of uncertainty. In differentiating between coping and adaptation strategies we enhance the understanding of farmer responses to climate impacts and identify which strategies are more likely to support farm resilience. Our findings may help to assess policy objectives for climate change adaptation, including technical recommendations, with asserted experiences of commercial farmers in South Africa.

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Appendices

A1: Interview guideline

A2: Socio-demographic and agricultural data of interviewees

A3: Coding system

A1: Interview guideline

Main Category	Variable	Questions
Personal Context and Farming Practices	1. Length of time spent farming	1. For how long have you been farming the land?
	2. Cultivation of crops	2. Which crops do you grow on your land?
	3. Change of farming practices	3. Have you changed your farming practices over the years? (If yes, how?)
Perception of Climate Change	1. Observation and awareness of climate change	4. Have you perceived a change in climate and the environment throughout the last 20 years? Which changes have you experienced in the climate and environment over the last 20 years?
	2. Effects of climate related events on farming	5. Which problems arise on your farm because of these changes in climate?
Factors influencing adaptive behaviour	1. Perceived adaptive capacity	(inferred from responses, see article section 2.2)
	2. Barriers to adaptation	6. What are the major challenges for you in order to deal with climate change?
	3. Availability of knowledge and information (sources)	7. From where or whom have you gotten your knowledge about climate change? Do you get any information about adaptation strategies towards climate change? From whom do you get knowledge about adaptation strategies?
	4. Accessibility to information, external help or resources	8. Do you receive any other external help to adapt to climate change? Can you name specific people or organizations that inform you about the impact of climate change?
Response and adaptation strategies	1. Implemented adaptation strategies	9. Have you taken any strategies to adapt to these climate effects in your farming practice? (y/n) Which strategies have you taken to respond to climate change?
	2. Influence of natural vegetation	10. Does the natural vegetation on your land, such as the renosterveld, influence your ability to adapt to climate change?
	3. Future adaptation strategies	11. Are you planning to take further adaptation strategies in the future? If yes, which ones?

Future	1. Challenges and Opportunities in the future	12. Which challenges and opportunities do you see in the future of your farm in terms of climate change?
	2. Future Coping Mechanisms	13. What would you need in the future to better cope with the current situation of climate change?

A2: Coding system

Coding system: 1. Perception of climate change

Major category encompassing (1) Observation and awareness of climate change, (2) experienced effects of climate change on farming and (3) climate change risk perception.

Minor category	Code	Description of code	Representative quote
Awareness of climate change	Awareness of climate change	Statements of awareness of climate change that indicate that farmers understand observed changes in climate as an indication of on-going climate change	*"There is a climate change definitely happening. And the seasons have moved along with that as well." (F8_WI)*
	Scepticism towards climate change	Statements of scepticism or uncertainty about climate change that indicate that farmers do not understand changes in climate as an indication of on-going climate change	*"I'm not a what you call it, a climatologist, but (…) in my 35 years that I can say it's a long term climate change I would more say it's like cycles, like cycles, it's like you get wetter periods and drier periods. (…) so the climate is changing all the time. But I can't confirm that it's going in a certain direction." (F3_WH)*
Observation of long-term changes of climate	**Changes of rainfall**		
	Change of rainfall patterns and variability	Observed changes of rainfall patterns and rainfall variability	*"When I was a little boy we would have rain for 7 to 10 days on end, light rains. But that have changed totally. It's at the most we get 3 to 4 days of that kind of rain but it's shorter bursts and more at a time." (F15_WH)*
	Lack of rainfall	Observed decrease of amounts of mean annual or seasonal rainfall	*"Yeah the winters are more drier[sic]. The last three years we didn't have a lot of rain. Like last year was very bad". (F12_WI)*
	Rainfall intensity	Observed changes of rainfall intensity such as changes in quantity of rainfall on single rainfall events	*"In recent years I think the raining season got shorter and the quantity of rain was more intense at a time." (F15_WH)*

	Drought events	Observed changes of amounts, intensity or duration of drought events	*"But the intensity of the drought is increasing." (F6_WH)*
	Changes in temperature		
	Increasing temperature	Observed increase of mean annual or seasonal temperatures	*"I as a child was born up here, 35 degrees was quite hot. Now we're getting 40 degrees. 40 degrees I want to run out into the dam and I want to swim. So it's getting really really hot, so that scares me." (F13_WI)*
	Increasing number of hot days	Observed increase of number of hot days during summer months	*"Because when I was younger it was very very rare and I'm speaking about much summer that the temperatures was above 40 degrees. These days you can get like a week or two weeks that the temperatures is 44, 45, 46." (F3_WH)*
	Seasonal extremes (hot summers, cold winters)	Observed changes in seasonal temperature extremes, i.e. warmer summers and colder winters	*"Or I am seeing on my farm is that it's getting colder in the winter and also hotter in the summer." (F13_WI)*
	Change of seasons	Observed changes in onset, duration and /or length of (agricultural) seasons	*"It's just the seasons I think it's a bit… summer starts month later and winter starts a month later." (F7_WI)*
	Extreme weather events	Observed extreme weather events such as hail storms, floods	*"It (hail storm) was two or three times this year (…)it's just like thunder and five minutes hail and gone (…) we didn't see that often here. Like… this size balls (laughs) falling out of the sky." (F8_WI)*
Experienced effects of climate related events on farming	Reduced yields	Experienced climate-related yield losses or reductions of yield	*"The wheat that's… that harvest was not so good. The tons were about 500 instead of 1000, maybe. So… so… that is one thing that definitely was bad." (F10_WH)*
	Crop failure and damage	Experienced climate-related crop failure and damage	*"Young vines might die, I lost about, what's it about 30% of my new plantation, that had to be replanted this year." (F9_WI)*

	Financial losses	Experienced climate-related financial losses and decrease in profitability	*"Well we're not profitable anymore. I think that's the biggest problem. That's because production is related to irrigation." (F9_WI)*
	Damage to seeds and shoots	Experienced climate-related damages on seeds and shoots of crops	*"Sometimes we start early to plant and the seeds won't come up because they… they will come up but they only get like 4,5 mm of water and come up and then die. So the next rain is taking too long to come." (F14_WH)*
	Erosion and runoff	Experienced climate-related erosion and runoff	*"Because it's very hilly you get a lot of erosion, because you're breaking up the soil, it's a lot of loose soil. And if it (the rain) comes so quickly in 24 or 48 hours there isn't really time for the soil to absorb the moisture, it's a lot of running water." (F15_WH)*
	Shorter growing season	Experienced climate-related shortening of agricultural season	*"Some of the seasons are like last year shorter and then it's a big problem for us because you don't get the… tonnage that you must have." (F3_WH)*
	Increasing pests	Experienced climate-related increase of pests on crops	*"Yeah more ants. And the ants are the carrier of the mealybug. So yeah we, I think we had a good fight with the mealybug with the biological ways we use. So the ants weren't a problem for us but you can see there is more ants." (F12_WI)*
	Lower crop quality	Experienced climate-related decrease of crop quality	*"So with the temperatures rising there was a real problem with the quality of wheat." (F15_WH)*
Climate change risk perception	High risk perception	Strong concern for climate change and high perceived probability of being exposed to its impacts. Encompasses statements of anxiousness and resignation towards climate change and its impacts.	*"So it's getting really really hot, so that scares me. Really. So I have spoken to my one son, the oldest one and we are very concerned about this. About the climate change. I don't know what we can do, because I think, I think what going to be late, too late for the people in the world to do something." (F13_WI)*
	Moderate risk perception	Moderate concern for climate change and moderate perceived probability of being exposed to its impacts. Encompasses statements of composure and relativization of the severity and urgency of	*"So this is actually a very good spot for farming wheat. So we are lucky in that regard. So when the full rough of climate change is going to come to us I think we will be the last influenced by it… hopefully." (F15_WH)*

		climate change and its impacts.	*"Last year was a difficult year and this year it was normal again. So you don't know… you can maybe (…) try to prevent stuff and then it's not necessary (...) So we basically just take it as it comes." (F7_WI)*
	Low risk perception	Low concern for climate change and low perceived probability of being exposed to its impacts. Encompasses statements of optimism, hope, wishful thinking and avoidance of climate change and its impacts.	*"But I'm not afraid of global warming. There is something that tells me, it's there. But I'm not afraid of it. I think we will overcome the problem." (F10_WH)* *"I think with climate change I rather just put my head in the… put a blanket on my head and don't worry about it." (F9_WI)* *"We believe in the God. And we believe that we will [be] here for the next, how many years. Maybe. I don't know… That's why I say, isn't it a phase that we go in, warmer climate and is there after this warmer climate is there another colder time for us? Maybe?"* (F10_WH)

Coding system: 2. Factors influencing adaptive behaviour

2.1 Perceived adaptive capacity
Major category encompassing farmers different perceptions of their own adaptive capacity and attitude towards adaptation and change.

Minor category	Code	Description of code	Representative quote
Low perceived adaptive capacity	Perceived exhaustion of adaptation possibilities	Statements expressing a low perceived ability to undertake adaptation actions due to a perceived exhaustion of adaptation possibilities	*"All that I can think of that we did already. We're out of... options." (F6_WH)*
	Superiority of nature and climate	Statements expressing a low perceived ability to undertake adaptation actions due to a perceived superiority of nature and climate	*"But I don't know how to adapt… at the moment we don't know what will happen if the climate turns against us." (F5_WH)*
High perceived	Positive or proactive attitude towards adaptation and change	Statements expressing a high perceived ability to undertake adaptation actions. Encompasses statements that reveal a positive or proactive	*"But to be a good farmer you must change. So if the world changes, so you must change. If you don't change you lose your farm." (F2_WH)*

adaptive capacity		attitude towards adaptation and change	*"It isn't a challenge to change, you just have to make a mindset and be adaptable. My dad wasn't very, but they are the older generation. So for us it's easier, we can adapt like that [snaps fingers]." (F16_WH)*
	Combative attitude towards adaptation and change	Statements expressing a high perceived ability to undertake adaptation actions. Encompasses statements that reveal a combative attitude towards adaptation and change	*"I think we will… outperform maybe climate change, that is my aim. I intend… of 20 years' time I want to sit back and say 'but climate change haven't affected me'." (F11_WH)*

2.2 Barriers or support to adaptation

Major category encompassing barriers or support to climate change adaptation, which address the availability or lack of resources such as knowledge, money, and institutional support.

Minor category	Code	Description of code	Representative quote
Institutional and political constraints	Lack of governmental support for farmers	Lack of or insufficient governmental support for farmers and agriculture (e.g. lack of subsidies) is perceived to be an institutional barrier to adaptation	*"Our government is not looking after our farmers. We don't subsidize, we don't get subsidies, nothing. You must do all the stuff on our own." (F8_WI)*
	Inadequate water management of municipalities	Adverse or inadequate water management by government and municipalities	*"Because the government, (…) they already said they all going to take the farmers' water. Like we have the water that's registered on our farm, on our farm we don't have enough space in the dam to get that. So they… everything you don't use they gonna take from you." (F7_WI)*
	Insecurity of land rights	Statements expressing fear, concern or perceived insecurity on land rights due to on-going debates	*"The future is not so clear for us in South Africa, so that is the one thing but that is not what you want the answer for so… it's a bit demotivating to build your soil and one day in a month you maybe*

		on land reforms and restitution programs	*go and say to yourself: Is this really worth it? Because are you going to have your farm? If I am building up my soil and they are taking the land, what if I've been working for my whole life." (F11_WH)*
	Restrictions on building dams	Institutional restrictions to build dams that complicate access to and availability of water sources are perceived to be an institutional barrier to adaptation	*"And you can't build dams because the… you're not allowed to do it. (…) that's a big problem. " (F10_WH)*
	Lack of capacity of government institutions	General incapacity of government institutions (e.g. lacking financial resources) is perceived as an institutional barrier to adaptation	*"The problem is, there is a very very great incompetency in every state control department of them. They appoint people that does not have the ability or the qualities to do the job for their appointment. And that's a pity. And a lot of money is going into that, so there is money for their salaries, but not for research, there is nothing left anymore." (F6_WH)*
Biophysical constraints	Water scarcity	Increasing water scarcity is perceived as a biophysical constraint to adapt to climate change	*"So if our rainfall in the winter will get less, then we've got a big problem. Because we are on the rim of like last year, we can't grow crops with less rainfall that is our average now." (F3_WH)*
	Dependency on nature and climate	Dependency on nature and climate is perceived as a biophysical constraint to adapt to climate change	*"You can't fight against nature. So you can only do what you can do. If there is no water you can do nothing " (F1_WH)*
	Farm topography	Unfavorable topography of farm as a biophysical constraint to adapt to climate change	*"So in a perfect world I would love to keep the stubble and prepare my soil better to when the big and quick rains come that the impact of the rain isn't that big and that it absorbs the water better and running away of water is stopped. And I have a very hilly farm, so it's a problem. If I had a flat farm, it's much easier." (F15_WH)*
	Local soil compositions	Diverse soil compositions of the Western Cape as a biophysical constraint to identify common adaptation strategies	*"I think with the diverse different soils that we have in the Swartland area, you know it's challenging. You know there is not one formula fits all type of thing. You know the cover crop which works for me doesn't work for my neighbour on the*

			other side of Malmesbury or on the other side in Koringberg." (F9_WI)
Economic constraints	Maintaining profitability	Maintaining profitability is perceived to be an economic barrier to adapt to climate change	*"I think we… the challenges is… these dry season challenges very much economically wise. We learn to save more in these years." (F8_WI)*
	Lack of financial means	Lack of financial means is perceived to be an economic barrier to adapt to climate change e.g. by not being able to invest in new technologies	*"I think probably capital is going to be our biggest challenges because… it's most of these changes will involve new implements and new strategies how to do stuff and (…) everything is just getting so much more expensive. So if you don't have capital behind you that's probably going to be your biggest challenge." (F16_WH)*
	Increasing input costs	Increasing input costs (e.g. fertilizers, fuel) are perceived as an economic barrier to adaptation	*"The chemical companies can make the prices they want and when you sell, it's the other way around you have to take the price they give you. (…)There is no bargaining, you just have to take the price. But our inputs versus outputs from the farm, they don't have anything, any power or bargaining that we can do with that. We just have to accept that." (F6_WH)*
Behavioural constraints	Perceived exhaustion of adaptation possibilities	Statements expressing a perceived or experienced exhaustion of adaptation possibilities	*"But if the rain gets less, there is not much we can do if the rain gets less and less… I don't know, how we're going to adapt any further, I don't…" (F5_WH)*
	Lack of motivation to plan for the future	Statements expressing a lack of motivation to plan for the future and to implement future adaptation strategies	*"The future is not so clear for us in South Africa, so that is the one thing (…) it's a bit demotivating to build your soil and one day in a month you maybe go and say to yourself: Is this really worth it?" (F11_WH)*
	Lack of awareness towards climate change	Lack of awareness or ignorance towards climate change as a perceived behavioural constraint to adaptation	*"The first thing is you have to be open-minded for (climate change), that you mustn't ignore the fact that it will or may affect us." (F4_WH)*
Information constraints	Lack of reliable information and weather forecasts	Lack of information on climate change and / or reliable weather forecasts	*"Like in the beginning with this year, three meteo that we use weather predictions, they predicted no rain for the whole year. (…) And we had quite a lot of rain this year. So it's good to have predictions but you can't… I can't say threemeteo says there is no rain this year*

			so I won't be planting this year. Because it's not dependable enough. Any weather prediction that's in the long term… you can really predict a week or 10 days maybe, but long term… All that we saw about the long term predictions is that it's not, you can't work with that, it's not dependable enough." (F5_WH)
Practical and technological constraints		Practical or technological challenges in farm practices as a perceived barrier to adaptation	*"I would love to farm in soils that is rich in earth worms and you can just see the microbial activities there. We've tried it for few years on the one field but as the organic stuff increases the flow becomes a problem in the planter. So you win on the one hand but the practical stuff gets more difficult on the other hand. So we have very stony soils, so it's difficult to move away from the tine implements." (F15_WH)*
Information on climate change from technology	Media	Information on climate change or adaptation strategies that is derived from media such as newspapers, TV and radio	*"You hear it on TV, global warming and all that stuff." (F8_WI)*
	Internet	Information on climate change and / or adaptation strategies that are derived from the internet	*"These days you know that everything is on internet and google and something." (F3_WH)*
	Weather forecasts	Information on climate change and / or adaptation strategies that are derived from weather forecasts such as weather stations, programs or mobile apps	*"We've got weather stations in Moorreesburg and Langebaan so we've got all that information." (F3_WH)*
Information on climate change from people	Farmers' unions (Afrikaans: Landbouverenigeng)	Information on climate change and / or adaptation strategies that are derived from local, monthly self-organized farmers unions	*"We are on (...) an agricultural organization in town. We call it the Landbouverenigeng in Afrikaans. (...) So if there is any climate changing that will be happening and then like there will be… it's harvesting time and there will be lot of big rain they will tell the guys, you know." (F8_WI)*
	Other farmers and people	Information on climate change and / or adaptation strategies that is derived from other farmers or other people	*"It's on everybody's tongue. Everybody is worried about it and everybody talk about it." (F10_WH)*

Information from institutions and companies	Agricultural consultants	Information on climate change and / or adaptation strategies that is derived from or offered by agricultural consultants	*"I just have this wonderful friend of mine (...) she is practicing on old vines and she, she really looking about the whole industry, about wines, about climate and everything." (F13_WI)*
	Department of agriculture	Information on climate change and / or adaptation strategies that is derived from or offered by the Department of agriculture	*"I get emails sometime from (...) the department of agriculture, they now and then have an article about climate change and predictions and stuff." (F11_WH)*
	Research farms and science institutions	Information on climate change and / or adaptation strategies that is derived from research farms (e.g. Langgewens) and science institutions (e.g. Agricultural research council)	*"There is a farm Langgeweens and that's a farm, I think it's owned by the (...) Agricultural research council they call it. The other farm… people come and (...) plant new cultivars there. (...) At the end of the year when everything is harvested we get the results. So you can see okay this cultivar did good." (F5_WH)*
	Non-profit agricultural companies	Information on climate change and / or adaptation strategies that is derived from non-profit agricultural companies such as GrainSA, Vinpro, Infrutec	*"No except for the research they are doing on the different varieties of wheat and barley and even canola. So they are trying to get varieties that are growing with less water and especially the growing season, they try to shorten it. Like if the drought is coming at the end, that the growing season is not like 130 days but 110 days so (...) they are working on that and we are getting the information all the time from Sensako and Grain South Africa." (F3_WH)*
	Agrochemical companies	Information on climate change and / or adaptation strategies that is derived from agrochemical companies such as fertilizer companies	*"Some of the fertilizer companies, the chemical companies they do a lot of research. (...) And they give us information. (...) Yeah because they develop stuff that they can sell. So if they can develop something that they can sell, then we get the info." (F5_WH)*
	Academia	Information on climate change and / or adaptation strategies that is derived from academic institutions	*"The university of Cape Town they've got a department of studying of climate change. There is one often, not regularly, I hear it on*

		the radio or if I can read something I will read it." (F4_WH)
Information on climate change from own experiences and observation	Information on climate change and / or adaptation strategies that is based on own observations of nature and local surroundings	*"And you live it, you can see it around you. It's happening."(F12_WI)* *"I took more time to notice the changes. If you are aware of something then you're much more susceptible to look at it and to see if there is something changing or what." (F6_WH)* *"I have to look self at nature, I have to be in the field the whole day to felt it, to see it." (F14_WH)*
Information on climate change from magazines	Information on climate change and / or adaptation strategies that is derived from agricultural magazines (e.g. Landbouweekblad)	*"Only thing is the Landbouweekblad. You can read it, you can maybe get an article or something like that." (F14_WH)*
Information on climate change from seminars and vocational trainings	Information on climate change and / or adaptation strategies that is derived from agricultural seminars and vocational trainings	*"There is a seminar that I visited last year. It's bewaringslandbou (Afrikaans) (…) Conservation farming basically. It's not very well attended but very informative. They would advise you to… keep… to increase carbon in the soil." (F1_WH)*
Information on climate change from overseas farming systems	Information on climate change and / or adaptation strategies that is derived from farming systems or agricultural practices in other countries	*"So we constantly looking at whatever Canada or Australia are doing with canola, because they are the leaders. So just in terms of that and I think they're also far ahead of us in terms of using it effectively in conjunction of climate change." (F16_WH)*

Coding system: 3. Adaptation strategies

3.1 Implemented adaptation strategies

Major category encompassing different farm-level adaptation strategies that farmers have applied as a response to climate change and the experienced climatic stresses in their (1) crop management (2) soil management (3) water management (4) livestock management (5) introduction of new technologies and (6) expansion of farm units.

Minor category	Code	Description of code	Representative quote
Crop management	Change of harvest and planting time	Implemented changes in harvest and planting time of crops as a response to climate change	*"So just by maybe planting a bit later we always start first of March, maybe we start 10th March or 20th March." (F14_WH)*
	Introduction of legume cover crops	Introduction of legumes (medics, clover etc.) as cover crops in farming system as a response to climate change	*"(Medics) is a natural way to put nitrogen into your soil. And if you get drought natural nitrogen is much better for the plant than chemical nitrogen." (F2_WH)*
	Crop rotation	Use of multi-year crop rotations (such as wheat-medics systems) as a response to climate change	*"We must help the soil with the material to absorb more moisture and that kind of stuff. And that is our aim with our crop rotation and the part of on the wheat side." (F4_WH)*
	Diversification of crops	Diversification and extension of cultivated crops on the farm	*"We're just feeling that we love to have another branch to divide the risk. (…) So if we do have a drought, a dry year like last year and the wheat is not doing good then maybe the cattle is doing better or the wool is very good and then maybe the tea can help. It's just to not to have all your eggs in one basket." (F3_WH)"*
	Removal of unproductive crops	Removal of unproductive crops to reduce water stress	*"And to remove some older orchards that are not productive, to remove them. And there we had a lot of problem with water." (F10_WH)*
	Reduction of fertilizer input	Reduction of fertilizer application on crops	*"And we lowered it (the fertilizer input) with the medic-clover system to 60, 50 kilograms of nitrogen. We're half… did the half. And now we're on 9 kg of N with this." (F11_WH)*

	Increase of fertilizer input	Increase of fertilizer application on crops as response to climatic stresses	*"We are under pressure with the size (of fruits) (...) So we've… more water, more fertilizer especially phosphate, more phosphate, the nitrogen for the fruit size to get better but you can do anything but if the temperatures is not right then you can do nothing." (F10_WH)*
	Introduction of cultivars with shorter growing season	Introduction of crops and cultivars with shorter growth time / growing season	*"We plant the wheat cultivars that grow shorter." (F5_WH)*
	Crop protection with netting	Application of nets to protect crops from climatic stresses such as sun, storms and winds	*"We have put some nets on, nets. And the nets… we're using 50% less water than we had using in the past." (F13_WI)*
	Introduction of drought-tolerant cultivars	Introduction of drought-tolerant or resistant cultivars to reduce water stress	*"Barley (...) can grow with less water than wheat. (...) So we bring that in for rotation with wheat and the canola and the medics. So there is definitely one thing we're looking to extend our barley branch, especially for the dry years." (F3_WH)*
Soil management	Minimum tillage	Usage of minimum tillage or no-till practices to reduce mechanical disturbance of the soil	*"I think the best precaution we did here for the drought is the no-till. Because if you take where the ground is heavy worked (...) there your moisture in the ground gets less, so you get… your tons per hectare on your wheat on the no-till and your tons per hectare on conventional it's much better." (F5_WH)*
	Increased soil cover	Increase of soil cover by leaving stubble or other organic material on the ground to reduce evaporation and improve soil	*"So we try and leave as much stubble or material on the soils to keep it cooler." (F15_WH)*
	Building top soil	Soil management practices that facilitate the buildup of top soil / organic carbon content of the soil	*"Because the way we are farming now with the less disturbance of the soil and we try to build up the organic material in the top that will absorb more moisture." (F4_WH)*

	Composting	Application of compost	*"We're using some compost and everything and put better… they can use less water I think." (F13_WI)*
Water management	Water conservation techniques	Water management techniques that conserve water / reduce water usage, such as introduction of drip irrigation	*"We went from sprinklers to drip irrigation (…). And you save a lot of water. And you give the water only where it's needed on the roots and… so that's one of them." (F12_WI)*
	Technological advancements / moisture meters	Technological innovations that support a general reduction of water usage	*"We had working with moisture meters, we… not giving … not only water. We moisture it by computers, we all… it's all computerized." (F13_WI)*
	Increase of water usage	Higher water consumption or usage	*"So we've (used) more water, more fertilizer especially phosphate, more phosphate, the nitrogen for the fruit size to get better but you can do anything but if the temperatures is not right then you can do nothing." (F10_WH)*
Livestock management	Abandonment of livestock	Temporary or long-term abandonment of livestock as a response to climatic stresses (such as drought)	*"Firstly we had sheep on the farm but the droughts impact on the sheep farming and the cattle farming is so overwhelming… to feed them and to prepare feed for them you need land that you can cultivate wheat on to feed the animals. You see and in the end your profit is diminishing." (F6_WH)*
	Change of grazing patterns	Change of grazing patterns to improve soil health and increase SOC (soil organic carbon)	*"To increase carbon in the soil by not let your sheep overgraze the land, to keep the carbon content of your soil high so you can keep your moisture (…) would be better." (F1_WH)*
	Change of fodder	Change or adjustment of fodder to increase resilience of livestock towards climatic stresses	*"You kill a living animal, you take the stomach, the grass in the animal stomach (…) and you mix it with sugar and yeast and you give it in (…) for the small sheep so the stomach can start working. (…) So the animal can get quicker in to the state to generate its energy from the food that's available." (F1_WH)*

Introduction of new technologies	Utilization of new technologies (such as GPS, solar pumps etc.) to reduce financial, mechanical, fertilizer inputs	*"But all the things that the new technology of implements, soil mapping, so that helps. So that you don't put something in the ground that costs you money that is not necessary." (F2_WH)*
Expansion of farm units	Expansion of farm and cultivated land to compensate decreasing profitability	*"We rent now more land than we actually have, that we own. If we didn't do that, we wouldn't be here anymore. You need to go bigger as (…) your profit, your profit is diminishing very very fast." (F6_WH)*

3.2 Future adaptation strategies

Major category encompassing different farm-level adaptation strategies that farmers intend or consider to apply as a response to future climatic stresses in their (1) crop management (2) water management (3) livestock management, (4) extensive farming practices, (5) soil management (6) expansion of farm units and (7) introduction of new technologies.

Minor category	Code	Description of code	Representative quote
Crop management	Introduction of cultivars with shorter growing season	Considered or planned introduction of crops and cultivars with shorter growing season as a response to shorter vegetation periods and seasons	*"And then we need cultivars that ripen earlier in the season and that have shorter ripening period. You know to get your harvest in earlier. You know that you don't have the long term effect of the dryness." (F9_WI)*
	Introduction of drought-tolerant cultivars	Considered or planned introduction of drought-tolerant cultivars as a response to future changes in precipitation, heat stresses and droughts	*"We will have to minimize the risk of drought, then we have to plant cultivars that is more dry resistant" (F4_WH)*
	Extension of crop rotation	Considered or planned extension of crop rotation	*"But the one thing I do know is I can make my rotation longer to survive easier. That I can do." (F11_WH)*
	Introduction of new cover crops	Considered or planned introduction of new and adjusted cover crops	*"Now we have drier winters, you know we're not having those wet soils, so the oats doesn't work anymore. So we've got to find something that grows in the shorter period of time, that will still give me the same amount of mass, of green mass, that I can still mow, that*

			will give me a good cover to protect my soil." (F9_WI)
	Crop diversification	Considered or planned diversification of cultivated crops to respond to shorter growing seasons, to minimize financial risks or to reduce future water stress	*"The other option is to grow crops that is more… (…) say you produce for three or four months, the grain season of the wheat is six months, so if I go into either vegetables or other stuff that takes a shorter period, that has less water use, we can go in that, on that route." (F15_WH)*
	Crop protection with netting	Considered or planned introduction of nets as physical crop protection from climatic stresses like sun, heat stresses and storms	*"I think the only thing that we can change (…) something that we will look at is netting for the vegetables." (F7_WI)*
	Change of harvest time	Considered or planned adjustments of harvest time to respond to future shift of seasons	*"It's the weather and the rain and we will just have to adapt and move everything two weeks a month. That's… I think that's the only thing that we can do." (F7_WI)*
Water management	Water conservation techniques	Considered or planned introduction of water conservation techniques to respond to future water stresses	*"it's like bucket you put around your vines like this bucket plastic thing and you just put it around the vines and it collects the dew, the morning dew. So it collects the dew and the dew just goes down into the soil." (F12_WI)*
	Additional installation of water sources	Considered or planned installation of additional water sources such as drilling boreholes or building dams	*"The one thing is I'm going to the borehole for the water and I have a good feeling about that spot in the renosterveld between the rocks. I think maybe there is some water down there." (F12_WI)*
	Improvement of irrigation	Considered or planned improvements of irrigation	*"If our water resources are not enough then we have to make a plan with the irrigation." (F10_WH)*
Livestock management	Shift to livestock husbandry	Considered or planned shift to or expansion of livestock husbandry as a risk equalization to other farm branches	*"And in my view if the wheat is not profitable we will easily lean more over to the livestock sector." (F4_WH)*
	Change of grazing patterns	Considered or planned adjustment of grazing patterns	*"Like in my business go more natural (…) Different grazing patterns which*

			you see for your cattle or something like that." (F14_WH)
Extensive farming practices	Reduction of machinery	Considered or planned reduction of machinery usage	*"Like in my business go more natural (…) (with) less machinery." (F14_WH)*
	Lower fertilizer input	Considered or planned reduction of fertilizer application	*"You have to bring in crops that put nitrogen into the ground to less input of your fertilizers and then that is what you have to do." (F4_WH)*
	Extensive livestock husbandry	Considered or planned shift to extensive livestock husbandry	*"You have to farm more extensive with livestock" (F4_WH)*
Soil management	Increased soil cover	Considered or planned increase of soil cover by leaving stubble or organic material on the ground	*"The big thing is to keep more stubble on your fields." (F15_WH)*
	Introduction of legume crops	Considered introduction of legume crops to improve soil structure and water holding capacity	*"Next year I want to plant something like (…) beetroot (…) with roots under the ground. Just for the worms. (…) To make the ground more productive and more absorbing to any water or… to stabilize the ground more." (F14_WH)*
Expansion of farm units		Considered expansion of farm units to enable more extensive farm practices	*"I think what is needed in the future is you have to have a bigger farm, so for that either your neighbour farm needs to be bought and then you rest more fields because we don't get any support, subsidies or anything, you have to plant as much as possible to survive. But if you have a bigger farm, if your hectares are bigger, then you can afford to say a third of your farm just lay barren for a year or two for the soils to rest and for the rotting process to take longer and to build up the organic material in the soils." (F15_WH)*
Introduction of new technologies		Considered introduction of new technologies	*"I think it's important to just keep up with technology whatever they offer." (F16_WH)*

A3: Socio-demographic and agricultural data of interviewees

f = female, m = male, n.a. = no answer

Farmer	Gender (m/f)	Years farming	Farm size (ha)	Major Crops	Additional Crops	Livestock
F1_WH	m	33	1600	wheat	medicago	sheep
F2_WH	m	40	1200	wheat	oats	
F3_WH	m	35	1800	wheat	canola	cattle
F4_WH	m	26	n.a.	wheat		sheep
F5_WH	m	22	380	wheat	oats	sheep
F6_WH	m	43	550	wheat, barley	canola, lupins	
F7_WI	f	9	520	vegetables	wine grapes	
F8_WI	m	13	560	wine grapes	wheat	cattle
F9_WI	m	20	180	wine grapes	buchu	
F10_WH	m	40	1600	wheat	nectarines	cattle
F11_WH	m	25	450	wheat	medicago	
F12_WI	m	20	180	wine grapes		
F13_WI	m	30	315	table grapes	wine grapes	
F14_WH	m	6	300	wheat	hay	sheep
F15_WH	m	15	1000	wheat	canola	
F16_WH	m	10	720	wheat	barley	

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Fire history and fragment size influence butterfly diversity in critically endangered renosterveld

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Introduction

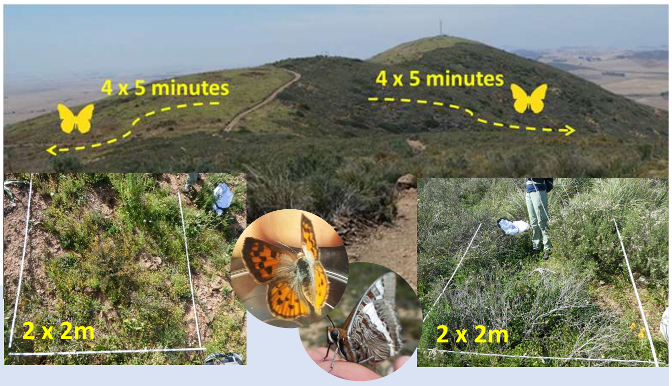
Renosterveld fragments exist mostly on private lands and are subject to fire suppression, accidental fires and occasional controlled burns. We investigated the effect of fire history on butterfly diversity in remaining renosterveld fragments. We hypothesized that butterfly diversity increases with increased plant diversity following fire, and decreases as renosterveld fragments age and become dominated by bushes such as renosterbos (*Elytropappus rhinoceritis*).

In A Nutshell

- Burns benefit plant diversity and floral resources in remaining renosterveld fragments, thereby benefiting butterflies. Conservation practitioners recommend burning every 7-12 years for optimal plant diversity.
- Multiple small as well as several large fragments contribute to landscape scale butterfly species richness. It is important to consider not only large fragments but also small fragments for conservation.
- Burning wheat stubble is common practice during autumn in the Swartland. There is the opportunity to integrate appropriate fire management of privately owned renosterveld fragments alongside existing farming activities.

Methods

- Surveyed 59 patches of varying fire age, across 52 renosterveld fragments of varying size, for butterflies
- Conducted 5 butterfly survey rounds in spring-summer 2018 and autumn 2019
- Collected site level information (burn age, fragment size , protected area status) and transect level information (plant diversity, floral abundance, shrub height) in 2x2m plots



Preliminary Results

- 30 species found across all fragments. Most abundant was the Painted Lady (*Vanessa cardui*) (>12000 individuals)
- Plant species richness and floral abundance decrease with time since last burn. Butterfly species richness increases with plant species richness and floral abundance (Fig. 1)
- At the landscape scale, multiple small fragments contain more butterfly species than few large fragments (Fig. 2). Small fragments are less likely to be protected (t-test, p=0.009).

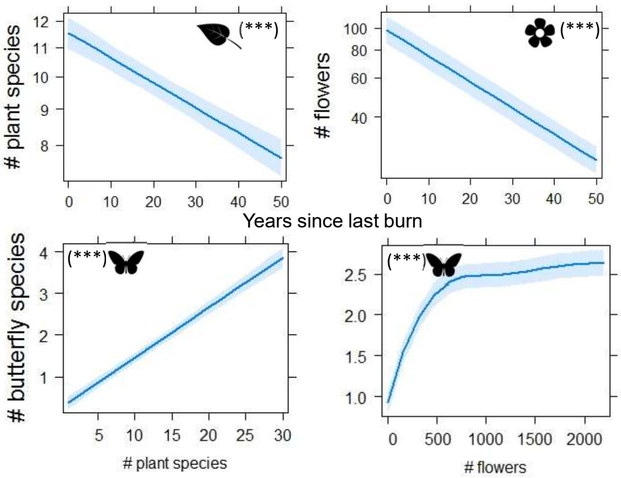


Fig. 1 Transect level linear mixed models indicate that plant species richness and floral abundance decrease with increasing burn age. Butterfly species richness increases with plant species richness and floral abundance.

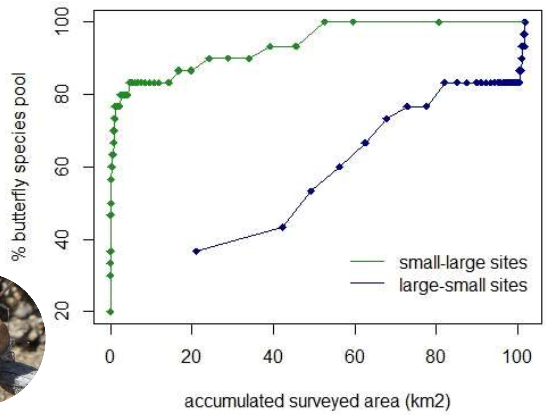


Fig. 2 Species-area accumulation curve of species richness in relation to accumulated surveyed renosterveld area. Species are summed from small to large (green) and large to small (blue), indicating that many small fragments can cumulatively contain more butterfly species than fewer large fragments.

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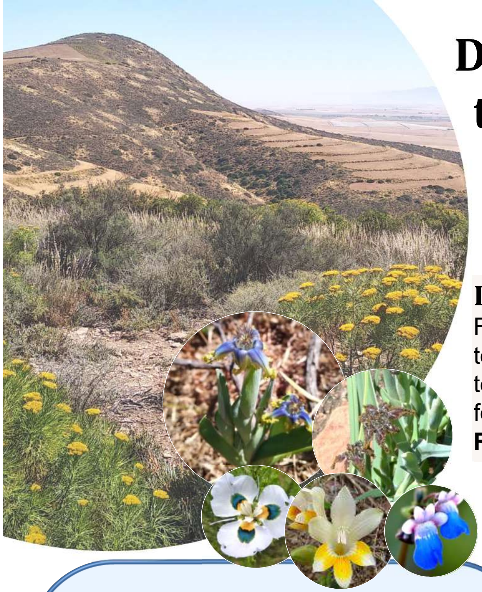

Decision-making for nature's contributions to people in the Cape Floristic Region: the role of values, knowledge and rules

Emmeline Topp [1,2], Jacqueline Loos[2] and Berta Martin-Lopez[2]
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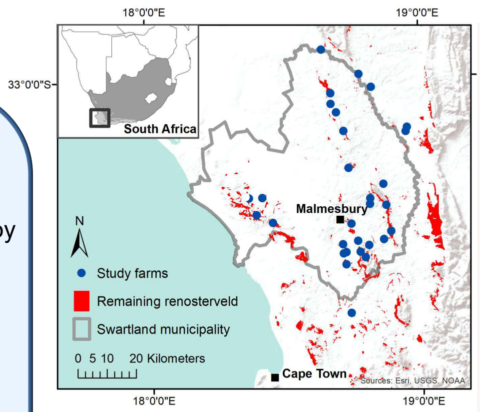
Introduction

Renosterveld is a critically endangered ecosystem in the Cape Floristic Region, home to exceptional biodiversity. In order to conserve remaining renosterveld, it is necessary to understand land manager decision making, and the implications of land management for nature's contributions to people (NCP).

Research question: What drives decision-making for renosterveld management?

In a nutshell…

- Land-use decision-making for remaining renosterveld vegetation in the Cape Floristic Region (CFR) is characterized by land managers' values, rules and knowledge (VRK).
- CFR land managers expressed different value types related to renosterveld, including relational, intrinsic and instrumental values
- Three VRK narratives, *Bottom-up conservation*, *Top-down conservation* and *Utility*, are associated with different nature's contributions to people (NCP) derived from renosterveld.

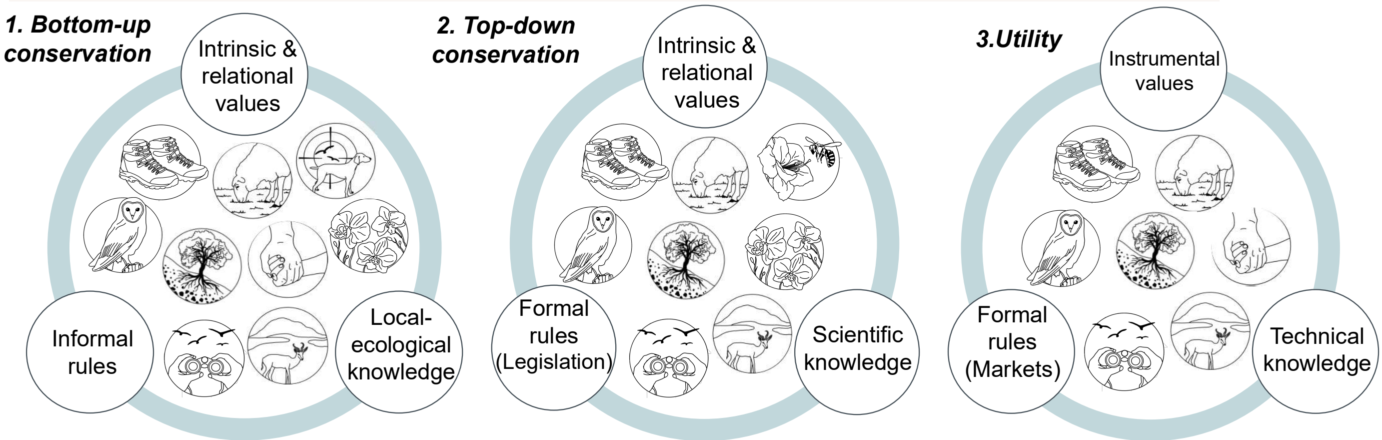


Methods and Study Area

- Semi-structured interviews with 30 land managers during 2017-18 in the Swartland, Western Cape, South Africa.
- Questions included "*What is the renosterveld good for?*" and "*What is the relationship between farming and nature?*"
- Analysis of interviews for associations between different value, rules and knowledge types and different NCP.

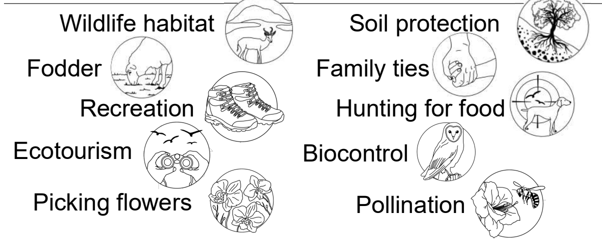
Results

Three decision-making narratives for renosterveld management with associated nature's contributions to people:



- Each narrative corresponds to a specific set of VRK, e.g. bottom-up conservation was associated with intrinsic and relational values, informal rules and local-ecological knowledge.
- Each narrative was associated with a unique set of NCP, which could be *regulating*, such as pollination, *material*, such as fodder, or *non-material*, such as family ties.
- Some NCP could be both material and non-material, such as picking flowers, which is an important material good and cultural activity in the Cape Floristic Region.

Key to nature's contributions to people



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Thanks to Annabelle Braasch for graphic design of NCP icons based on those of the Economics of Ecosystems & Biodiversity (teebweb.org)
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