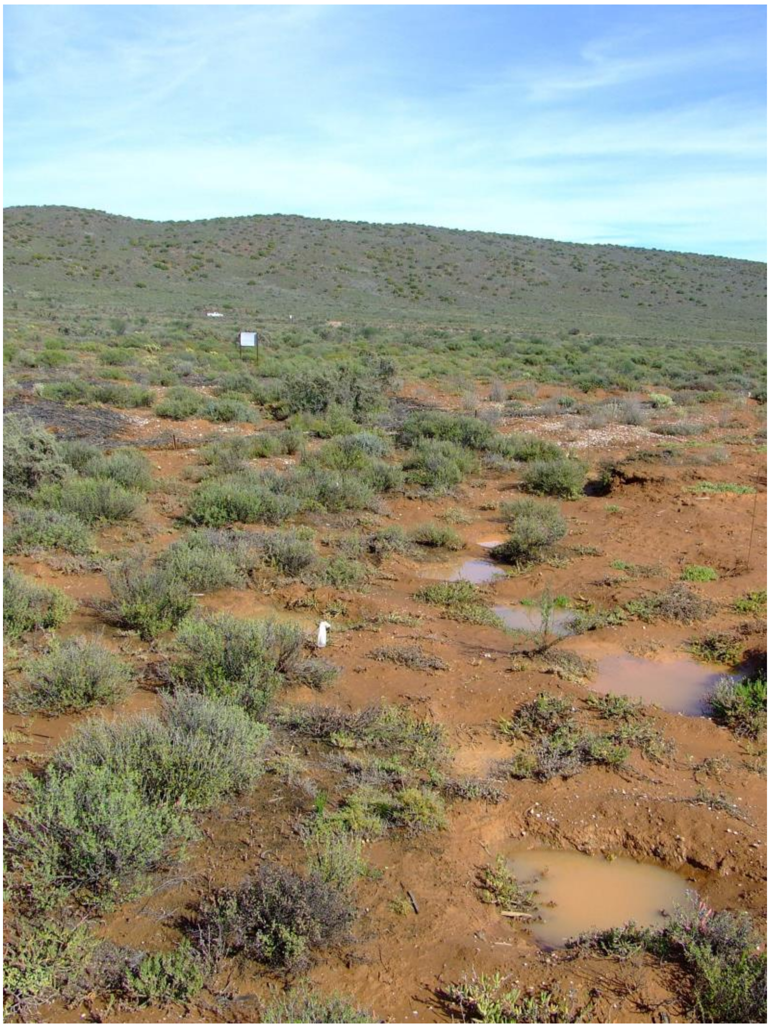
Factors Affecting the Success of Reseeding Rehabilitation in the Semi-Arid Karoo, South Africa

By

Willem Matthee



Submitted in fulfilment of the requirements for the degree *Magister Scientae* in the Faculty of Science at the Nelson Mandela Metropolitan University

April 2015

Supervisor: Dr C. Coetsee

Co-supervisor: Prof. S.J. Milton-Dean

DEPARTMENT OF ACADEMIC ADMINISTRATION
EXAMINATION SECTION
SUMMERSTRAND NORTH CAMPUS
PO Box 77000
Nelson Mandela Metropolitan University
Port Elizabeth
6013
Enquiries: Postgraduate Examination Officer

DECLARATION BY CANDIDATE

NAME: Willem Matthee

STUDENT NUMBER: s208015071

QUALIFICATION: *Magister Scientae* (Botany)

TITLE OF PROJECT: Factors Affecting the Success of Reseeding Rehabilitation in the Semi-Arid Karoo, South Africa

DECLARATION:
In accordance with Rule G4.6.3, I hereby declare that the above-mentioned treatise/ dissertation/ thesis is my own work and that it has not previously been submitted for assessment to another University or for another qualification.

SIGNATURE: ____

DATE: ____

ACKNOWLEDGEMENTS

Firstly, I thank my supervisors, Dr Corli Coetsee and Prof. Sue Milton, for their continued support and valuable input on chapter drafts, for their enthusiasm, motivation and endless patience. I thank Sue for initiating the research, and for instilling an appreciation for the Karoo and rehabilitation in me, and Corli for her open door policy and occasional botanising around the admin building.

Special thanks also go to my family for their continued support and motivation, especially during dark times. To my father for instilling an appreciation for nature, all things great and small, and for logistical assistance in the project. To my mother, for teaching me the value of working diligently and always seeing the positive in life. To Johannes and Frieda, for their continued support, and for always believing in me. I also thank Frieda for her help in clearing lucerne at Lategansvlei, even though the site was never used, and to Johannes for his help with the construction of the research plots at De Denne.

I also thank the staff of NMMU Saasveld for their valuable advice and support, and for constantly checking whether I was still on track to finish on time. I thank Christiaan and Brenda Viljoen for their help in the construction of the experimental plots on Wolwekraal. To those poor souls willing to work in the Karoo sun for extended periods of time in order to collect data (Gareth, Armin, Stefan and Kenny), thank you. A special thanks to Gareth Williams for his willingness to go on data collection trips to relatively remote locations, and his companionship and intellectually stimulating conversations during those long drives. Also, a special thanks to Stefan Goets for collecting data of the germination trials when I was away from campus, for assistance with R Commander, for much-needed LAN-session during break-times, for keeping me relatively sane as the thesis neared completion, for editing early drafts of some chapters, and for providing valuable input on interpretations. I also thank Aneri Roos for her valued friendship and support throughout the years and for constantly listening to my complaints, and Damien Coulson for his input regarding possible future research to be undertaken. I also thank Jama Mashele and Marco Gouws, for collecting data of the germination trials when I was away. Jama is also thanked for putting up with my loud typing two rooms from her in the middle of the night.

All the landowners and managers that took part in this study (Appendix 5) are also thanked, particularly those who provided Gareth and I with accommodation and food during our visits. The Worcester Seed Reserve, in particular Hannes Botha, is also thanked for supplying seeds of *O. sinuatum* for the experimental sites. I thank Anita Wheeler for her help in locating an appropriate site for experimental trials in the Oudtshoorn area, Sue and Richard for allowing me to construct my experimental plots on Wolwekraal, and Johan Keller for allowing me to construct the experimental plots at De Denne. I also acknowledge the South African Weather Service for supplying the rainfall data used in Chapter 4.

Jeanette Pauw from NMMU Saasveld and Tony Booth from Rhodes University are thanked for statistical help. Tony is thanked in particular for helping me understand R, and commenting on the first GLM's used in chapter 4. I also thank Toby Keswick for editing the final draft of the thesis, and commenting on the overall writing style employed, and Stefan for reading through the final product. To anyone else who has made a contribution to my life the past few years: thank you very much.

Lastly, I thank my Creator and constant companion, for the guidance and wisdom I needed to complete this study.

Christiaan Viljoen, a Nature Conservation experiential training student of NMMU, creating a hollow at the Wolwekraal experimental plots.

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ABSTRACT

Due to overgrazing, mining and other anthropogenic disturbances, large sections of the Karoo region have been degraded, resulting in areas with low vegetation cover, where erosion rates are high and vegetation is dominated by unpalatable species. These areas have low and unpredictable rainfall, with slow to non-existent autogenic recovery, and this often forces landowners to implement reseeding rehabilitation in an attempt to increase both overall vegetation cover and the relative abundance of palatable plants. Landowners use soil preparation treatments, which include creating micro-catchments, ripping, mulching and brush packing, to supplement land rehabilitation. This study investigated the significance of initial rainfall, mean monthly rainfall, soil preparation techniques, slope, existing vegetation cover, litter, mulch and stone cover in determining the success of reseeding rehabilitation. Rainfall had the most significant influence, where long-lived shrubs established best under low initial rainfall and high mean monthly rainfall, and grasses established best after receiving high initial rainfall. Micro-catchments proved the most successful soil preparation technique for the establishment of long-lived shrubs, while ripping and mulching impacted negatively on grass establishment. A combination of mulch and micro-catchments aided *Osteospermum sinuatum* establishment in soils where soil shrinkage cracks occurred. Temperature influenced seed germination and drought tolerance of *Lessertia annularis*, *Fingerhuthia africana* and *O. sinuatum*, with higher germination success of *O. sinuatum* under temperatures simulating summer, and of *F. africana* under temperatures simulating winter. *L. annularis* germination had a faster growth rate and higher survival when germinated under autumn/spring temperatures. Landowners are advised to sow seeds of more than one species during rehabilitation, to include micro-catchments as soil preparation treatment, and to sow seeds during a time when rainfall is predicted to be high.

Keywords: reseeding; rehabilitation success; *Osteospermum sinuatum*; rainfall; temperature; drought tolerance; micro-catchments

A severely degraded area near Loxton that has recently received soil preparation and reseeding treatments.

CHAPTER 1 – GENERAL INTRODUCTION

1.1 INTRODUCTION

An increase in the global human population has increased pressure on the environment through agricultural intensification, mining expansion and increased development, which has, in turn, increased environmental degradation (Ehrlich & Holdren 1971; Laurance *et al*. 2001; Teague & Dowhower 2003; Kitula 2006; Laurance *et al*. 2009). The rehabilitation of these degraded areas is an expensive and time-consuming undertaking (Spurgeon 1999), which provides a barrier for many landowners and companies, as high costs may outweigh any gains received once the rangeland has been restored (Schiappacasse *et al*. 2012; Blignaut *et al*. 2013). Jellinek *et al*. (2013) found that landowners that belonged to a landcare group, had an off-farm income, or had experience with rehabilitation were more willing to perform rehabilitation.

Replanting and reseeding, the most frequently-used methods for initiating veld rehabilitation, differ in costs and benefits. Reseeding is less time consuming than replanting of seedlings or mature plants (Palmerlee & Young 2010), but there is less certainty that the rehabilitation will be successful, even in areas of high rainfall (Bainbridge *et al*. 1995; Young & Evans 2001). In arid and semi-arid environments, where rainfall is unpredictable, recruitment levels are low (Cohn *et al*. 2013), and many species recruit mainly after major rainfall events (O'Connor & Roux 1995; Del Cacho *et al*. 2013). If rehabilitation fails to re-establish vegetation cover, particularly of reseeded or replanted species, the economic costs to landowners can be tremendous (Schiappacasse *et al*. 2012), mainly due to the high erosion rates on degraded land and failed monetary investment in seed or plants (Oldeman 1994).

Many methods of rehabilitating degraded rangelands have been proposed to increase the likelihood of successful vegetation re-establishment, including the use of mulch, ripping, brush packing, and creation of micro-catchments (Snyman 2003; Van den Berg & Kellner 2005; Kinyua *et al*. 2010). Reseeding has been instigated in conjunction with these methods, in order to increase vegetation cover of denuded areas and, subsequently, to reduce erosion and invasion by non-native species (Pyke *et al*. 2013). Studies evaluating the success of the various rehabilitation methods have mostly been confined to a specific site (e.g. Snyman 2003 and Kinyua *et al*. 2010), and few studies have assessed the success of these methods across a variety of environmental conditions such as rainfall, soil type, and slope.

This chapter provides background to the study by establishing the causes and effects of Karoo rangeland degradation. It also investigates commonly-implemented rehabilitation methods, and relates this study to existing literature on restoration ecology. It will illustrate the context and importance of this study in increasing our knowledge of factors that influence the success of rehabilitation projects in arid and semi-arid rangelands. It will also delineate the study, and provide the study's aims and objectives. Taxonomy used in this study follows Vlok & Schutte-Vlok (2010).

1.2 INTRODUCTION TO KAROO ECOLOGY

The Karoo is situated in the interior of South Africa, falling within the area below the 500 mm rainfall isohyet (Desmet & Cowling 1999). The mean precipitation ranges between 100 and 500 mm annually, classifying it as an arid to semi-arid region (Lovegrove 1993; Esler *et al*. 2006).

The Karoo can be divided into two biomes, namely the Succulent and Nama Karoo. The Succulent Karoo is the smaller of the two (Milton *et al*. 1997), but is richer in endemic species (Mucina *et al*. 2006a; Mucina *et al*. 2006b). The Succulent Karoo region extends from Namaqualand on the western coast of South Africa, through the Little Karoo and into the western part of the Eastern Cape Province. This region is characterised by low, but reliable, winter rainfall (Cowling *et al*. 1999; Hoffman *et al*. 2009), resulting in a high diversity and abundance of succulent species (Cowling *et al*. 1999; Mucina *et al*. 2006a; Linder *et al*. 2010). Conversely, the Nama Karoo receives variable quantities of rainfall sporadically, mainly during summer, and supports vegetation dominated by karooid shrubs (that are often deciduous during severely dry periods) and grass species (Mucina *et al*. 2006b).

In both the Nama and Succulent Karoo, temperatures often exceed 40°C during summer, and may drop below freezing during winter (Desmet & Cowling 1999). Plants have adapted to survive the extreme heat and cold by growing in bush clumps, with each bush clump consisting of various different plant species and plant growth forms (Milton *et al*. 1997). Padilla and Pugnaire (2009) showed that bush clumps facilitate the establishment of certain plants, particularly under dry conditions. Competition for water and nutrients among plants in bush clumps is often reduced through resource partitioning, with plants of different growth forms having roots at different depths (Carrick 2003; Anderson *et al*. 2004). The higher infiltration rates observed under bush clumps compared with bare areas may also decrease competition for water resources (Ludwig *et al*. 2005). While facilitation may be observed among plants in bush clumps, plants of similar growth form and root depth compete for the limited resources, and these plants may not perform better than plants growing in an open area (De Villiers *et al*. 2001; Blignaut & Milton 2005). Riginos *et al*. (2005) reported that shrubs in mesic shrublands may have both positive and negative impacts on seedlings establishing under them, with negative impacts increasing when nutrients are abundant.

Bush clumps are initially established by plants capable of withstanding extreme cold and heat, such as *Brownanthus ciliatus* and *Ruschia spinosa* (Yeaton & Esler 1990). As these plants mature, they inadvertently create suitable germination conditions for other, more sensitive, species and act as so-called nurse plants (Padilla & Pugnaire 2006). In the absence of heavy grazing, bush clumps expand in size, vegetation cover increases, and the likelihood of erosion is reduced (Fen-Li 2006; Seifan & Kadmon 2006). Since bush clumps occur in the absence of overgrazing, seeds of plants growing in well managed semi-arid areas will normally have suitable germination sites. Overgrazing results in bush clumps disintegrating, leading to sparser vegetation (Milton 1992; Lechmere-Oertel *et al*. 2005; Seifan & Kadmon 2006). Bare inter-clump patches are, however, normally colonised by pioneer species (Wiegand & Milton 1996), which protect these areas against erosion during the wet season.

In the Karoo, fewer seedlings establish successfully on bare ground than they do in suitable germination micro-sites, mainly due to the extreme temperatures and low, variable rainfall (Milton 1995a). Micro-catchments are therefore vital for successful germination and establishment of seedlings, as they act as water, nutrient and seed traps (Coetzee 2005; Esler *et al*. 2006). Naturally, these micro-sites are created by ecosystem engineers such as meerkats (*Suricata suricatta*), aardvark (*Orycteropus afer*), bat-eared foxes (*Otocyon megalotis*) and other animals that excavate soil, creating ‘hollows’, during their search for food (Dean & Milton 1991; Whittington-Jones 2006). These hollows accumulate water during rainfall events, and organic matter caught in these sites will decompose over time, increasing the nutrient status of the soils in the micro-catchments relative to the soil outside them. Micro-catchments are therefore areas with higher nutrient and water availability in a matrix of lower moisture availability, and when wind-dispersed seeds are trapped in these small hollows, increased nutrient and water levels in the hollows assist germination and aid establishment (Lesoli 2011). The loss of ecosystem engineers through persecution and habitat alteration leads to a reduction in naturally-generated germination sites (Bragg *et al*. 2005), thereby reducing the likelihood of autogenic recovery of the vegetation.

Threats to the Karoo region of South Africa include habitat loss through mining and urban expansion, habitat degradation through agriculture, fragmentation through road and fence construction and the potential effects of climate change (Malcolm *et al*. 2006). The latter includes increased frequency of summer droughts, higher maximum temperatures, reduced rainfall, and increased rainfall stochasticity in an already arid, stochastic-prone environment (SCBD 2009; Naidoo *et al*. 2013). These shifts in the Karoo environment require rehabilitation to re-establish indigenous and resilient vegetation to secure its long-term future (SER 2004). Major components in the rehabilitation of degraded areas are the restoration of vegetation cover and functional diversity, and reduction of soil loss. This will increase the ecosystem's resilience to extreme drought and flooding events expected because of climate change (Alexander & Tibaldi 2012).

1.3 AGRICULTURAL INFLUENCE

1.3.1 BACKGROUND

Fox (2011) stated that the majority of the pressure on a country's natural resources was to supply food to growing populations. Along with an increase in population size, South Africa has also experienced an increase in Gross Domestic Product during the post-Apartheid period (Lambrechts *et al*. 2012), which has resulted in an increase in more intensive livestock husbandry in areas with adequate rangelands, as discussed by Holechek (2012).

1.3.2 CROP CULTIVATION

In South Africa, an estimated 78.6 per cent of the country's land surface is used as agricultural land (Department of Agriculture, Forestry and Fisheries 2012). The Karoo, South Africa's semi-arid south-western interior, is mostly too arid for crop cultivation. However, Schoeman and Scotney (1987) found that an area of 1 920 km^2 in the Karoo region was under crop cultivation at the time of their study, even though only approximately 200 km^2 was suitable for rain-fed cultivation. Previous agriculture of alluvial areas largely consisted of subsistence farming (Beinart 2003), likely similar to the flood-irrigation farming still continuing in the Little Karoo region (Le Maitre *et al*. 2007). As supplies (such as forage for ostrich) became more readily available through road transport networks (Cupido 2005), irrigated fields have become abandoned. Dean and Milton (1995) found that even if undisturbed vegetation is present nearby, these abandoned fields take a long time to recover, and Boardman *et al*. (2003) found high levels of erosion prior to vegetation establishment in these areas.

1.3.3 PAST AND PRESENT PASTORALISM PRACTICES

Due to the aridity of the Karoo region, it is used predominantly as rangeland for game and livestock. The majority of rangeland is used as grazing for sheep (for wool and meat production) and cattle (Todd *et al*. 2009) and the Little Karoo region is used as rangeland for the intensive husbandry of ostrich (Deeming 1999; Thompson *et al*. 2005). Indigenous pastoralists and early European settlers in the arid and semi-arid regions of South Africa adopted nomadic lifestyles (Boonzaaier *et al*. 1996; O'Farrell *et al*. 2008). Though some authors claim that this method of pastoralism degraded the vegetation, the effects could potentially be less severe than those of settled ranching (Miller 2000; Harris 2010), as it prevented the continuous degradation of specific areas through overgrazing over a long time period.

Originally, the main livestock kept by the Khoikhoi were sheep (Boonzaaier *et al*. 1996), but cattle may have been kept in conjunction with sheep as early as the sixth century AD (Orton *et al*. 2013), long before Western colonisation. When the Karoo region was initially settled by European colonists, the nomadic herding lifestyles were mimicked by the settlers (Penn 1986; Beinart 2003), but were replaced by settled ranching through the use of legislation (Penn 1986; Archer 2000). This resulted in herds constantly browsing and grazing in specific camps over long periods of time, which severely degrades the environment if stocking rates exceed the rangeland's carrying capacity (Van Rooyen 2002; Teague & Dowhower 2003; O'Farrell *et al*. 2008).

In some arid regions in southern Africa, the main livestock ranching method is one of transhumance, mainly as a response to seasonal drought and cold (Scoones 1992). The nomadic herder lifestyle is also used on the Tibetan Plateau of western China, with these rangelands being less degraded than other agricultural land in the area (Miller 2000). Western *et al*. (2009) indicated that the shift from transhumance, or nomadic ranching, to settled ranching in South Africa resulted in a decrease in wildlife numbers, most probably because of direct displacement of wildlife by livestock and a reduction in grass production.

1.3.4 THE CARRYING CAPACITY CONCEPT, AND GAME RANCHING IN THE KAROO

In the 1880's, the so-called carrying capacity of rangelands became an important concept (Sayre 2008). This concept delineates the number of livestock (large stock units, or LSU) that can be kept per unit area sustainably during the period of greatest stress (Johnston *et al*. 1996; Allen *et al*. 2011). Landowners use the carrying capacity to determine the densities at which livestock will be stocked. However, the Karoo landscape can support very few livestock per unit area, and farms can therefore rarely support economically viable livestock herds at the prescribed carrying capacity (Herling *et al*. 2009). Additionally, the carrying capacity concept is not suited for use in stochastic environments such as the Karoo (McLeod 1997), and fixed stocking rates should therefore not be used in these areas. Allen *et al*. (2011) and Archer (2004) also stated that the carrying capacity of a specific area is not fixed, but constantly changing, as influenced by factors such as rainfall, and McLeod (1997) suggests that an interactive model should be used to determine stocking rates in stochastic environments. Coetzee (2002) reiterated the importance of adjusting stocking rates in the Karoo according to the environmental parameters of a specific year, due to the variability of rainfall and forage production in this region.

In recent decades, many landowners have started incorporating game ranching with traditional livestock farming (Du Toit 2007). Though some authors have criticised game ranching and the often-associated hunting as a threat to conservation (Geist 1985), many believe that the correct application of game ranching could aid the conservation of threatened animals that are not adequately protected in proclaimed protected areas (Du Toit 2007; Carruthers 2008). It may also be more economically viable than pure livestock farming, particularly in the Karoo region (Dlamini 2012). Overstocking with game, however, could have the same disastrous effects on rangeland as overstocking with livestock (Van Rooyen 2002). In fact, it may be more difficult to manage grazing by game, as game are more difficult to corral or move from one camp to another than livestock, and it may be difficult to calculate the population of some game species accurately (Bothma 2002).

1.3.5 IMPACTS OF RANGELAND OVEREXPLOITATION

Degradation of rangelands due to overstocking often results in a reduction or loss of palatable species, overall loss of vegetation cover due to a loss of mature plants, and reduced seeding in plants (Dean *et al* 1995; Milton 1995a; Todd & Hoffman 1999; Esler *et al*. 2006; Todd 2006; Anderson *et al*. 2010; Alkemade *et al*. 2012). The excessive trampling associated with large herds of livestock also result in increased soil compaction (Torre *et al*. 2007), altered water infiltration and storage patterns (Le Maitre, *et al.* 2007; Du Toit *et al*. 2009), loss of species that are sensitive to trampling (Hendricks *et al*. 2005), increased erosion rates (Loch 2000; Vetter *et al*. 2006) and bush encroachment by toxic or well-defended species

(Millennium Ecosystem Assessment 2005; Todd & Hoffman 2009). Overall, plant diversity may decrease under increased grazing pressure (Haarmeyer *et al*. 2010). Anderson and Hoffman (2007) reported lower total vegetation cover in communal lands (which experienced heavier grazing pressure) than privately owned land. They also observed that increased grazing pressure led to a decrease in succulents and woody shrubs (and increase in dwarf shrubs) on the Namaqualand lowlands, and a decrease in perennial grasses in the uplands. A model by Williams and Albertson (2006) indicates that grass cover in arid areas decreases with increased rainfall variability, and that grasses are particularly prone to degradation in arid and semi-arid areas during times of drought. The Karoo ecosystem is caught in a continuous spiral of degradation and biodiversity loss, as a reduction in palatable plants (due to overgrazing) results in overgrazing of the remaining palatable plants, which in turn leads to reduced seeding and lower germination levels. This results in a decrease in mature palatable plants, and an increase in the abundance of unpalatable species. Dean and Macdonald (1994) found a mean decrease in stocking rates of 44 per cent between 1911 and 1981 for most of the Karoo magisterial districts studied. This reduction was probably due to a decrease in productivity of South African arid and semi-arid rangelands due to overexploitation by livestock farmers.

With severe degradation, the rangeland crosses a threshold, and is forced into a new stable state (Tainton & Hardy 1999; Bestelmeyer 2006), maintained through various climatological, biochemical, biological and hydrological feedbacks (Laycock 1991; Asner *et al*. 2004), and which is subsequently resistant to change (Suding *et al*. 2004). This new stable state is dominated by annual and geophytic species, or species that are unpalatable to most game and livestock (Milton & Hoffman 1994; Sasaki *et al*. 2007; Rutherford & Powrie 2010). Contrarily, nurse plants and their dependent plant species become less abundant under heavy grazing regimes. After heavy grazing, the recruitment of palatable species into the new stable state is suppressed through the lack of a seedbank of the palatable species (Dreber *et al*. 2011), the absence of an external seed source nearby (Pueyo & Alados 2007), chemical suppression through allelopathy by established unpalatable plants (Squires & Trollope 1979; Vetter *et al*. 2006) and competition from established plants (Milton 1995b).

1.4 MINING

Another source of environmental degradation in the Karoo is mining for gravel and ore. Minerals that have been mined in the Karoo region to date are uranium and gypsum (Brabers 1976; Schmidt 2002; Scholtz 2003; Cole 2009), with the mining of methane (natural gas) possible in the near future (De Wit 2011). Copper and silver are mined in igneous deposits in the northwestern Karoo (Bushmanland), and diamonds and titanium are mined from coastal and alluvial sands in the Karooid areas of South Africa's West Coast region (De Beers Consolidated Mines 1976; Hammerbeck 1976; Carrick & Krüger 2007).

The stockpiling of parent material containing uranium is particularly dangerous, as the radioactive material can contaminate fauna and flora, in both terrestrial and aquatic ecosystems (Darwish *et al*. 2011). Scholtz *et al*. (2006) found that uranium-containing stockpiles contaminated grazing, as well as local streams and their associated aquatic communities. Uranium poses a health risk to humans, as uranium exposure results in kidney damage, and may ultimately cause cancer. Furthermore, landowners are often unaware of uranium contamination, and subsequently use contaminated water for various purposes, including the irrigation of crops.

Mining, particularly strip-mining, is usually destructive to the environment, and often denudes an area, as well as removing the associated seedbank and seedling germination sites (Cooke & Johnson 2002). The reduced vegetation cover exposes the soil to erosion, leading to a loss of topsoil, even with minimal rainfall (Loch 2000; Ludwig *et al*. 2005). Denuded areas also affect the hydrological system, as eroded soil from mining areas increases siltation and turbidity of water bodies, and elevates their potassium, aluminium and iron concentrations (Mol & Ouboter 2004). Hilson (2002) also reported that increased levels of human activity in mined areas, coupled with poor sanitation, can pollute previously productive land, thereby reducing the aesthetic and economic value of the land.

The mining of rock, gravel and sand for road construction generally takes place at quarries and borrow pits, which are (due to transport costs) often situated close to major roadways. These borrow pits supply gravel for the resurfacing of roads, and each generally supplies gravel for a stretch of road approximately 5-10 km in length (Beukes 2008). Mining of gravel is similar to strip mining, as it removes all the plant material from an area, along with the valuable topsoil and associated seedbank, and natural recovery of these areas is unlikely (Price *et al*. 2005). This results in the formation of barren, inundated sites deprived of germination microsites and plant propagules post-mining (Elmarsdottir *et al*. 2003; Burke 2008; Commander *et al*. 2013), and, where areas are sloped, exposure to heavy erosion (Darwish *et al* 2011).

According to the Minerals Act No. 50 of 1991, mining companies remain responsible for a site damaged by mining and associated activities until such time as rehabilitation meets the conditions specified in the environmental management plan. Only then is a closure certificate issued that makes resale of the land legal. Mined sites in arid areas can take decades or centuries to regenerate without human intervention (Ogle & Redente 1988). Hence there is a need to employ active rehabilitation methods if they are to recover (Price *et al*. 2005). The objective of mine rehabilitation should therefore be to rehabilitate the impacted area to a state with sufficient vegetation cover to reduce surface runoff, increase infiltration, reduce erosion and support a variety of life forms (detritivores, pollinators and herbivores). In turn this leads to improved ecosystem functioning, increasing biodiversity and return of grazing capacity and other values to the impacted area.

1.5 AUTOGENIC RECOVERY: CAN NATURE ‘HEAL’ ITSELF?

Environmental autogenic recovery concerns the recovery of ecosystems without human intervention, and is a process driven by the species within the ecosystem (Le Houérou 2009). In Karooid areas with high rainfall, autogenic recovery may occur, even in the presence of disturbance (De Abreu *et al*. 2011). Recovery, however, is slow – an example being altered vegetation on campsites abandoned by indigenous herders in the Seacow Valley approximately 220 years ago (Sampson 1986). Wiegand and Milton (1996) and Seymour *et al*. (2010) also discussed the slow recovery of semi-arid areas.

Kassas (1970) stated that areas with low rainfall will have low seedling recruitment during dry years, but even in above-average rainfall years, seedling recruitment may be low if preceded by a number of dry years. Due to the low and variable rainfall, arid and semi-arid regions across the world may take decades to recover without human intervention (Ogle & Redente 1988). However, Burke (2014) found that autogenic recovery took place in the southern Namib Desert within a period of 5-7 years, likely due to above-average rainfall, undisturbed subsurface soils and the presence of undisturbed vegetation adjacent to the disturbed areas (which could provide seeds for autogenic recovery to take place). Despite implementation of various alternative grazing regimes by livestock farmers, such as Acocks' non-selective grazing method (Hoffman 2003) and the non-selective Savory Grazing Method (Savory & Parsons 1980; Beukes *et al*. 2002), large sections of the arid and semi-arid interior of South Africa are still degraded and in need of restoration or rehabilitation (Dean *et al*. 1995). Although non-selective grazing has been suggested as a natural method of rehabilitating degraded rangelands, the loss of suitable seed germination and seedling establishment sites, coupled with a loss of mature palatable plants, may mean it takes decades to be successful if used as the only method of veld rehabilitation (Beukes & Cowling 2003). Simply removing livestock and game from the degraded areas may also not yield beneficial results, as it takes many decades for the abundance of drought-resistant vegetation cover to increase, and some plant species may fail to return (Wiegand & Milton 1996; Snyman 2003; Todd & Hoffman 2009; Seymour *et al*. 2010; Hanke *et al*. 2013). Rahlao *et al*. (2008), however, observed an increase in vegetation cover and change in species composition after 67 years of livestock exclusion in the Worcester-Robertson Valley.

The inability of vegetation to regenerate after resting is partly due to the stability of post-disturbance vegetation; areas disturbed by overgrazing are often colonised by pioneer and unpalatable species (Milton & Hoffman 1994; Rutherford & Powrie 2010). These plants (particularly annuals) thrive under regular disturbance, and the synergistic effect of disturbance and inhibition by annual plants prevents the successful establishment of longer-lived and more palatable species of the next successional sere (Seifan & Kadmon 2006). The established plants often maintain themselves in a stable state through chemical interference (Squires & Trollope 1979;

Vetter *et al*. 2006) or by outcompeting seedlings of other species through rapid uptake of water and nutrients (Milton 1995b).

Disturbed areas often serve as invasion sites for exotic species such as *Pennisetum setaceum* (Goergen & Daehler 2001), *Atriplex inflata* and *Salsola kali* (O'Farrell & Milton 2006). These exotic species are capable of outcompeting native species due to their faster growth rates, more rapid recovery from disturbances and high reproductive rates. Invasion by exotic species results in a change in ecosystem functioning, as they may alter the soil nutrient status, thereby outcompeting indigenous species (Le Maitre *et al*. 2011) or increase the likelihood of disturbances (such as fire) that native species are not adapted to (Rahlao *et al*. 2009). Invasion of an ecosystem by exotic species inhibits the autogenic recovery of vegetation to a pre-disturbance and pre-invasion state (Steers & Allen 2010), even after the invading species have been cleared (Galatowitsch & Richardson 2005; Le Maitre *et al*. 2011; Marchante *et al*. 2011). It is therefore recommended that active rehabilitation, possibly including the transplanting of cultivated indigenous species, should be undertaken to increase the likelihood of success (Laycock 1991; Milton & Dean 1995; Le Maitre *et al*. 2011; Marchante *et al*. 2011).

1.6 HEALING THE LAND: REHABILITATION AND RESTORATION

1.6.1 BACKGROUND AND TERMINOLOGY

Regardless of the cause of degradation, the rehabilitation of severely degraded areas involves the reintroduction of indigenous vegetation cover, through reseeding or introduction of nursery-grown plants (Palmerlee & Young 2010). These plants replace the vegetation lost during the degradation of the site. Rehabilitation projects should also strive to restore soil and water processes, allowing the site to remain vegetated and productive in the long term (SER 2004).

In the literature, the terms restoration and rehabilitation are used interchangeably, regardless of the respective differences in meaning. Restoration refers to the conversion of degraded areas to their pre-disturbance state (Callicott *et al*. 1999; Aronson *et al*. 2007). This not only pertains to the vegetation cover and species composition, but to all aspects of the ecosystem, including the ecological processes present therein (Cairns 1988; Bradshaw 1997). Rehabilitation refers to the conversion of degraded areas to a functional state that may or may not be identical in biotic composition with the pre-disturbance state (Callicott *et al*. 1999). The Society for Ecological Restoration (2004) stated that a degraded area has recovered, whether through rehabilitation or restoration, when it is able to maintain itself and adapt to normal environmental disturbances without further anthropogenic inputs. The complete restoration of degraded areas is normally not possible, nor economically feasible, whereas rehabilitation of degraded areas is more manageable and can be achieved through some effort and funding (Cairns 1988). For this study, the definitions as outlined above will be followed.

1.6.2 REHABILITATION NEEDS IN THE KAROO

Two main types of rehabilitation needs exist in the Karoo: the return of forage plant species to areas from which they have been lost (Simons & Allsopp 2007), and the revegetation of bare areas to return the vegetation to a self-maintaining state (Aronson *et al*. 1993). The former need focuses on the reduction of unpalatable plants and re-establishment of palatable plants in the landscape (DiTomaso 2000), and is not dealt with in this project. The latter need focuses on the rehabilitation of a degraded area to a state where hydrological functioning, biological activity and vegetation cover is returned to the landscape (SER 2004), which is the focus of this study.

1.6.3 RESEEDING VERSUS REPLANTING REHABILITATION

The introduction of plants during active rehabilitation projects can be performed through reseeding the areas with palatable or ecologically important species (Milton 1994; Milne 2009; Chen *et al*. 2012), or by planting large individuals of palatable species (Padilla *et al*. 2009; Palmerlee & Young 2010). The rationale behind replanting is that seedlings will have well-developed root systems, and be able to grow more rapidly than seeds would. Also, by transplanting nursery-grown stock into the veld, one can largely control the densities of certain shrubs, and space plants in order to create heterogeneous vegetation (Hanke *et al*. 2013). The nursery-grown stock may also have higher survival rates than seeds sown (Simons & Allsopp 2007).

With reseeding rehabilitation, germination is random, unpredictable and unreliable (Simons & Allsopp 2007), and seedlings would be more likely to establish in bush clumps that the seeds get blown into, rather than in the bare areas where vegetation cover is most urgently required. Chen *et al*. (2012) found that reseeding had a significant positive effect on the recovery of a burnt semi-arid rangeland in Idaho, USA, and Kulpa *et al*. (2012) found that slope and aspect strongly influenced the re-establishment of reseeded species relative to unseeded and exotic species. Although dry soil can be mitigated through the use of micro-catchments that increase soil moisture levels, Hanke *et al*. (2011) showed that an increase in soil moisture is not observed after small rainfall events without surface runoff. This may complicate the rehabilitation of degraded sloped areas, as the low surface run-off would not accumulate in the hollows, and the area may therefore not receive the beneficial increase in water availability commonly associated with this soil preparation technique.

1.6.4 SOIL PREPARATION TECHNIQUES

There are various soil preparation methods which can increase the number of potential germination sites. The economic costs of rehabilitation, coupled with the perceived benefits of rehabilitating the veld, dictates which of these methods will be used. Methods commonly employed include the use of hollows (Snyman 2003; Coetzee 2005; Esler *et al*. 2006; Lesoli 2011), ripping or ploughing the soil (Kinyua *et al*. 2010), the addition of mulch or manure (Beukes & Cowling 2003; Coetzee 2005; Hanke *et al*. 2013), or a combination of the above. Through use of manure, Hanke *et al*. (2013) effectively stemmed erosion and established drought-resistant vegetation, but increased the abundance of exotic species when compared with brush packing, micro-catchments, mineral fertiliser and simple livestock exclusion. Lesoli (2011) recorded higher germination rates of reseeded grasses in micro-catchments than outside them, indicating that the micro-catchments act as effective seed traps and suitable germination sites.

Reseeded areas can be irrigated in order to provide water during inter-rainfall periods, though this method is expensive and time-consuming (Bainbridge 2002; Padilla *et al*. 2009). Padilla *et al*. (2009) recorded higher survival rates of mid- and late-successional species used in trials when watering was provided, but high survival rates of mid-successional species were recorded even without watering during the dry season. Palmerlee and Young (2010) found that reseeding was more cost-effective than planting nursery-grown plants. The study was, however, done in an area with a Mediterranean climate and a higher mean annual precipitation than in the Karoo. In the Karoo, temperature extremes may be combined with periodic droughts, and low annual precipitation. The unpredictability and severe conditions in the Karoo potentially reduce the cost-effectiveness of reseeding as opposed to replanting. To date, reseeding is widely used in the Karoo, but is sometimes coupled with transplanting (Milton 1994; Milne 2010; De Abreu 2011). In a study on the effectiveness of reseeding rehabilitation in combating erosion and invasion by exotic species, Pyke *et al*. (2013) found reseeding did not prevent erosion during the first year, but if seedlings established well (due to high moisture availability), they could reduce erosion rates in following years. Older reseeded areas also proved to be more resistant to invasion by exotic species than newly-reseeded areas.

1.6.5 PREVIOUS STUDIES ON REHABILITATION SUCCESS

While some studies have focussed on the success of various rehabilitation treatments at specific sites (Beukes & Cowling 2003; Visser *et al*. 2004; Van den Berg & Kellner 2005; De Abreu 2011; Hanke *et al*. 2013), few have attempted to determine the success of various treatments in a large geographical area with variations in environmental conditions. In general, previous studies have identified the following (apart from soil preparation techniques) as factors that influence the success of rehabilitation projects: water availability (Mganga *et al*. 2010); slope and aspect (Kulpa *et al*. 2012); and presence of alien invasive species at the rehabilitated area (Galatowitsch & Richardson 2005; Marchante *et al*. 2011). Since semi-arid regions across the globe, including South Africa's Karoo region, experience the majority of their rainfall during specific seasons (Whitford 2002; Van den Berg & Kellner 2005), the season chosen for reseeding may govern the success thereof. Sowing seeds during the wet season would lead to higher germination and survival rates than the sowing of seeds in the dry season. However, the high temperatures associated with the Karoo summers could cause excessive stress to seedlings establishing themselves during this period; success of reseeding may thus be related to a combination of rainfall and temperature.

Beukes and Cowling (2003) found that the use of gypsum and/or organic mulch increased water infiltration and improved the establishment and survival of both reseeded and naturally seeded species. Van den Berg and Kellner (2005) used a combination of ripping, brush packing and addition of manure that resulted in the highest establishment of reseeded species in their study. They also showed annual species rather than longer-lived reseeded species dominated the vegetation in the control plots (where no soil preparation treatments were implemented). Visser *et al*. (2004) recorded the best results of rehabilitation when using a combination of ripping, brush packing and reseeding, while tilling alone was the most cost-effective treatment. Kinyua *et al*. (2010) showed that tilling alone increased vegetation cover, but such vegetation cover was dominated by forbs and annual grasses. Reseeding with perennial grasses is therefore necessary in order to establish longer-lived species in degraded areas. De Abreu (2011) found ripping as the most cost-effective rehabilitation method to use, but was the least effective method used in trials near Oudtshoorn. In that study, the use of micro-catchments proved effective in rehabilitating degraded rangelands.

Simons and Allsopp (2007) altered microhabitats through the use of brush packing and creation of micro-catchments, which increased the abundance of herbaceous species, but did not significantly increase the cover of perennial species. Their study also had very low germination of reseeded species, with only 90 seedlings establishing of the 20 000 seeds sown. Snyman (2003) recorded that, rather than using hollows, a combination of hollows and soil ripping resulted in better establishment of reseeded species. This could be due to the faster water infiltration rates observed using the combination method. Additionally, that study showed that simply reseeding an area does not yield an increase in reseeded species cover. In an evaluation of treatment effectiveness, Van den Berg and Kellner (2005) used a combination of ripping, brush packing, reseeding and addition of manure, which was more effective in establishing reseeded species than any other combination of these treatments.

1.6.6 ASSESSING REHABILITATION SUCCESS

The success of rehabilitation is often measured according to three categories: species diversity, vegetation structure or ecological processes (Ruiz-Jaen & Aide 2005a), each with multiple sub-categories. These three categories give an indication of how successful the rehabilitation was in restoring some of the ecosystem structure and function, and include environmental parameters such as vegetation cover (Schulz *et al*. 2010), vegetation clumping, species diversity within clumps, water run-off speed, water infiltration rates and erosion control effectiveness (De Abreu 2011).

Rehabilitated areas are normally compared to benchmark sites to determine how successful the rehabilitation was (SER 2004). Characteristics of restored environments include species assemblages similar to benchmark sites, the dominance of indigenous species, the ability to maintain itself, and the reduction or elimination of threats to the ecosystem's health (SER 2004). Rehabilitation success can also be measured by the return of the rangeland's economic value (through supporting livestock), and therefore the ability of rangeland to contribute to economic development (Brown & Lugo 1994; Seymour *et al*. 2010). A final measure of rehabilitation success is the re-establishment of critical ecosystem processes, such as litter production, nutrient cycling or hydrological patterns (SER 2004; Ruiz-Jaén & Aide 2005b; De Abreu 2011).

Though the simple return of vegetation post-rehabilitation (regardless of species composition) could be viewed as success, I measured success by the abundance of reseeded species post-reseeding (or, with the longer-term chapter, at the time surveys were done).

1.7 RATIONALE AND AIM OF THE STUDY

An understanding of the factors affecting the success of reseeding rehabilitation in the semi-arid Karoo is valuable, especially when the potential impacts of climate change in this region are considered. Though a substantial amount of research has been done on arid and semi-arid rangeland rehabilitation, most of this research has focused on the evaluation of rehabilitation methods at a specific site, or under controlled environmental variables. Few have attempted to determine the effectiveness of the commonly-used rehabilitation methods under a variety of rainfall, soil and other environmental factors.

This project will aim to determine the main factors affecting the success of rehabilitation in the semi-arid rangeland of South Africa's Nama and Succulent Karoo regions through surveys of areas rehabilitated between 2007 and 2012. The study will also determine the influence of seasonal temperatures on the germination of some commonly-used species, and the drought tolerance of commonly-used species. Field experiments will test hypotheses regarding the effectiveness of the addition of nutrients and mulch, and the construction of micro-catchments in establishing reseeded species.

The findings of this study will aid future rehabilitation projects by quantifying the importance of environmental factors (normally beyond the control of landowners) and rehabilitation methods implemented (which are under the landowners' control). Suggestions will be made to help landowners and individuals involved with rehabilitation increase the likelihood of success in projects initiated in the stochastic Karoo environment.

Plains zebra grazing in a recently reseeded area.

An exposed *Osteospermum sinuatum* seedling browsed heavily by hares and steenbok.

CHAPTER 2: THE EFFECT OF TEMPERATURE ON SEED GERMINATION AND SEEDLING SURVIVAL FOR THREE PLANT SPECIES COMMONLY-USED FOR RANGELAND REHABILITATION IN THE KAROO

ABSTRACT

The influence of temperature on seedling germination and survival on three Karoo plant species commonly used in reseeding rehabilitation was tested using germination trials. Trials were carried out in a germination chamber on seeds of a perennial shrub (*Osteospermum sinuatum*), a pauciennial herb (*Lessertia annularis*) and a perennial grass (*Fingerhuthia africana*). Experimental temperature regimes simulated the temperatures experienced in the Karoo region during summer, winter and autumn/spring. Cox proportional hazard regression models showed that overall germination rates were generally faster under moderate temperatures, but *O. sinuatum* germinated most rapidly under warmer temperatures. The models also indicated that *O. sinuatum* had the highest overall survival, whereas *F. africana* had the overall lowest survival. Though temperature had a significant impact on the germination and survival of these three species, rainfall may be a more significant germination cue under field conditions. Landowners should therefore attempt to perform reseeding rehabilitation during periods where both rainfall and temperature is favourable for the species selected for use.

2.1. INTRODUCTION

Many research articles have focused on the effect of water availability on seed germination (Clauss & Venable 2000) and seedling survival (Haeussler *et al*. 1995; Alpert & Loik 2013; Rysavy 2014). Haeussler *et al*. (1995) found that germination of red alder (*Alnusrubra* sp.) was positively influenced by soil moisture levels during the main germination season, whereas survival was positively correlated with the soil moisture levels during the dry season. A number of recent studies dealing with plant establishment in degraded arid and semi-arid areas have focused on the germination cues affecting annual species (Facelli *et al*. 2005; Rivas-Arancibia *et al*. 2006; Tang *et al*. 2009), or endangered species (Traveset & Riera 2005). However, few studies have analysed the difference in germination rates among species commonly used in reseeding rehabilitation (Weiersbye & Witkowski 2002; Commander *et al*. 2009; James *et al*. 2012), and fewer still have investigated the effects of temperature on germination rate for commonly-used species (Ferrari & Parera, in press).

Because rainfall in arid zones is unpredictable, many shrub species, such as the long-lived *Osteospermum sinuatum* (DC.) Norl. (Asteraceae), undergo a marked increase in germination during periods of exceptionally high rainfall (Jurado & Westoby 1992; Wiegand *et al*. 1995). Though rainfall may be a common germination cue, successful germination may also be linked to specific temperature and moisture combinations (Flores & Briones 2001). Annual plants may increase their likelihood of survival in a stochastic environment by having a high proportion of dormant seeds (Claus & Venable 2000), and it is likely that *Lessertia annularis* Burch. (Fabaceae), a short-lived shrub commonly used in reseeding rehabilitation, follows this strategy.

The effect of temperature on germination appears to be very species-dependent. In a study by Ahmed *et al*. (2006), temperature treatments did not affect germination of *Solanum centrale*, an arid zone shrub, and they concluded that rainfall was probably the main germination cue. Commander *et al*. (2009) investigated the germination biology of eighteen species commonly used in the restoration of degraded Australian rangeland, and seven of these species had higher germination success when exposed to cooler temperatures. Similarly, Huang *et al*. (2003) found that a perennial shrub, *Haloxylon ammodendron*, germinated best under cool temperatures, whereas Tang *et al*. (2009) concluded that the short-lived *Olimarabidopsis pumila* had more successful germination under moderate temperatures than it did under high or low temperatures. Contrarily, Khan *et al*. (2002) reported increased germination of the halophytic shrub, *Salsola iberica*, under higher temperatures than under lower temperatures. Local studies investigating temperature as a significant germination cue of species commonly used in rehabilitation (particularly for species used in the arid Karoo region) are rare. Henrici (1935) reported higher germination rates of Karoo plants under lower temperatures, and Henrici (1939) showed that most species responded well to alternating high and low temperatures.

The Karoo region of South Africa consists of two biomes: the predominantly winter-rainfall Succulent Karoo (Mucina *et al*. 2006a), and the predominantly summer-rainfall Nama Karoo (Mucina *et al*. 2006b). Temperatures in both these biomes fluctuate between seasons, with very hot summers and cold winters. Species used in reseeding rehabilitation are therefore exposed to a great range in temperatures, which could affect successful establishment. Temperature may not be the only germination cue; for example, Thomas *et al*. (2010) showed that temperature, water availability and fire cues influenced seed germination in a fire-prone environment. Since fire is a rare occurrence in the Karoo region, and indigenous plant species do not respond well to it (Rahlao *et al*. 2009), it is likely that temperature and rainfall may be the main germination cues. Day length, as a function of the respective seasons, may also influence germination success (Beneke *et al*. 1993; Adondakis & Venable 2004; Zia & Khan 2004). We did not, however, investigate this as a germination cue, and focused on temperature as a determinant of germination.

In this study, I selected three species with high establishment rates in rehabilitation projects (Chapter 4): two shrubs, the long-lived *Osteospermum sinuatum* and short-lived *Lessertia annularis*, and one grass, *Fingerhuthia africana* Lehm. (Poaceae). I investigated the effect of temperature on these species in terms of: (1) total germination success; (2) germination rates among species and seasons; (3) drought survival among species; and (4) intra-specific drought survival for seedlings established during different seasons.

2.2. MATERIALS AND METHODS

I performed germination and seedling survival trials in germination chambers. Seeds of each species were sown in separate 2 L containers, in a well-mixed mixture of fine gravel and clay (in a 19:1 ratio). Individual seeds of *O. sinuata* and *L. annularis* were large and therefore easy to count, and 100 viable seeds of each species were used per season in the study. It was assumed that large seeds that were mature and showed no signs of desiccation or predation by seed-boring insect larvae were viable. With *F. africana*, one gram of seeds, approximately 273 viable seeds (Renu-Karoo, unpubl.), was used per season. According to Van Rooyen and De Villiers (2004), the physiological dormancy in South African arid regions normally wears off after six months, resulting in increased germination success. Valencia-Díaz and Montaña (2003) found an increase in germination for a desert shrub, *Flourensia cernua* (Asteraceae) when seeds were between five and eight months old, with decreases in germination success for seeds younger or older than that. Seeds used in this study were collected six months prior to planting, in an attempt to have the highest likelihood of germination.

Seeds were watered every three days, and exposed to a light-dark cycle of 12h:12h, at the mean seasonal minimum and maximum temperatures collected at Oudtshoorn for the period March 2012 – February 2013 (Table 2.1). I recorded the number of seedlings daily. From 21 days after sowing, watering was withheld. Seedlings were then exposed to a light-dark cycle of 12h:12h, at 25°C, regardless of the seasonal temperatures they were exposed to during germination. This was done in order to test the overall survival of species in an environment where temperature is kept constant. It was also to test whether seedling establishment season affected later drought survival. I then recorded the number of dead seedlings daily; seedlings were classified as dead when stems showed considerable wilting, and when the plants would not recover if water was provided. Seedling height was also measured as an index of inter-seasonal individual performance for each species. For the two dicotyledonous plants, the height from ground level to the apical bud was measured, while the length of the first leaf was recorded for the monocotyledonous *F. africana*.

2.3. STATISTICAL ANALYSIS

The total germination success (measured as the total number of seeds that germinated) among species and seasons was analysed with a Chi-square 3x3 contingency test. Germination rates among species and seasons were compared by fitting a Cox proportional hazard regression model to the days since sowing and the emergence of seedlings (Allison 1995). This method of survival analysis is a good semi-parametric method to analyse survival data, and combines partial likelihood estimation with proportional hazards (Allison 2010). Models were fitted for each species (to compare germination rates among seasons), and for each season (to compare germination rates among species).

The heights of dead seedlings were compared using Kruskal-Wallis non-parametric ANOVA and multiple comparisons by mean ranks post-hoc, to determine whether there were seasonal differences in the performance of each species. Cox proportional hazards regression models were used to compare drought survival among species, and among species under different germination temperature regimes. See Traveset and Riera (2005) and Kolb and Barsch (2010) for further details. I used the "coxph" function of the "survival" package (Therneau & Grambsch 2000) in R 3.1.0 (R Core Team 2014) to determine differential germination and mortality.

2.4. RESULTS

2.4.1. OVERALL GERMINATION

A total of 257 seeds germinated during the trials (Table 2.1). The Chi-square contingency test indicated a significant difference in number of seedlings observed among species and seasons ($\chi^2 = 21.32$; df = 4; $p < 0.001$). Highest germination success was observed under winter temperatures for *F. africana*, and during summer for *O. sinuatum*, whereas *L. annularis* did not have a higher germination success under any particular temperature regime.

2.4.2. INTER-SEASONAL GERMINATION RATES

The germination rate of *F. africana* was unaffected by changes in temperature regime (Wald test = 1.13; df=2; $p>0.05$), while *O. sinuatum* germinated more rapidly under summer temperatures than under winter or autumn/spring temperatures (Wald test = 10.33; df=2; $p<0.01$). Conversely, *L. annularis* germinated more slowly under winter temperatures than under autumn/spring or summer temperatures (Wald test = 10.53; df=2; $p<0.01$). Figure 2.1 illustrates the differential germination rates for the three species under the different temperature regimes.

Table 2.1: The seasonal minimum and maximum temperatures maintained during the germination trials, the number of seeds and percentage seeds per species that germinated in each season.

Season	Minimum temperature (°C)	Maximum temperature (°C)	No. of seeds germinated						
			F. africana		*L. annularis*		*O. sinuatum*		Total
			nr	%	nr	%	nr	%	
Autumn/spring	12	24	39/273	14	15/100	15	13/100	13	67
Summer	18	31	42/273	15	15/100	15	32/100	32	89
Winter	4	20	83/273	30	12/100	12	6/100	6	101
Total			164/819	20	42/300	14	51/300	17	257

2.4.3. INTER-SPECIES GERMINATION RATES

No difference in germination rates among the species was observed under summer (Wald test = 5.37; df=2; p>0.05) and winter (Wald test = 2.39; df=2; p>0.05) temperatures, while *L. annularis* had a faster germination rate than *O. sinuatum* and *F. africana* when exposed to autumn/spring temperatures (Wald test = 22.28; df=2; p<0.001). This difference was because the majority of *L. annularis* established within the first week, while seedlings of the other two species still established by the second (*O. sinuatum*) and third (*F. africana*) week (Figure 2.2).

2.4.4. SURVIVAL TIME

Seedling survival time differed among species when they germinated under summer (Wald test = 8.42; df=2; p<0.05), winter (Wald test = 9.20; df=2; p<0.05) and autumn/spring (Wald test = 6.70; df=2; p<0.05) temperatures. For summer and winter, *O. sinuatum* survived longer than *F. africana* and *L. annularis*, whereas *F. africana* died faster than *L. annularis* and *O. sinuatum* did when they were germinated under autumn/spring temperatures (Figure 2.4).

Species-wise responses to the different seasons indicated that *O. sinuatum* did not show higher mortality rates when germinated in any particular season (Wald test = 4.71; df=2; p>0.05), while *L. annularis* died more rapidly when they germinated under summer or winter temperatures than it did under autumn/spring temperatures

(Wald test = 16.52; df=2; p<0.001), and *F. africana* also survived longer if germinated under autumn/spring temperatures than it did when germinated under either summer or winter temperatures (Wald test = 11.10; df=2; p<0.01). Figure 2.3 illustrates the survival of each species when they germinated under each of the three temperature regimes.

2.4.5. INDIVIDUAL PERFORMANCE

No difference in seedling height was found among seasons for *O. sinuatum* (χ^2 = 3.70; df = 2; p > 0.05) and *F. africana* (χ^2 = 1.29; df = 2; p > 0.05). There were significant inter-seasonal height differences for *L. annularis* (χ^2 = 32.96; df = 2; p < 0.001), with mean heights of 60.93 mm for seedlings germinated under autumn/spring temperatures, 30.00 mm under summer temperatures, and 25.42 mm under winter temperatures.

2.5. DISCUSSION

2.5.1. GERMINATION SUCCESS AND RATES

The removal of soil moisture and day length as a factor influencing germination indicated the significance of temperature as a germination cue. Of the three species studied, only the short-lived shrub, *L. annularis* did not show a preference for germinating under warmer or colder temperatures. Similarly, Clauss and Venable (2000) found that rainfall may have more influence on the establishment of short-lived species than temperature has. Chapter 4 showed that *Lessertia* species had low establishment rates, with individuals present in only 20 per cent of the plots they were sown in, and successful establishment may therefore be significantly influenced by rainfall after reseeding.

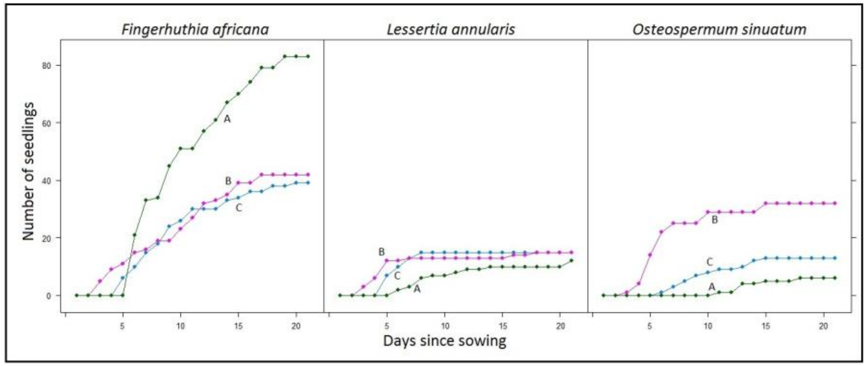

Figure 2. 1: Germination of the tested species under the three temperature regimes (A = winter, B = summer, and C = autumn/spring temperatures).

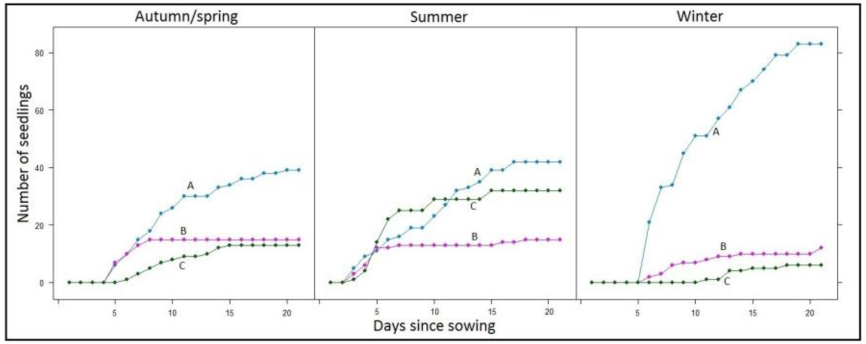

Figure 2.2: Germination rates among species (A = *F. africana*; B = *L. annularis*; C = *O. sinuatum*) under each temperature regime.

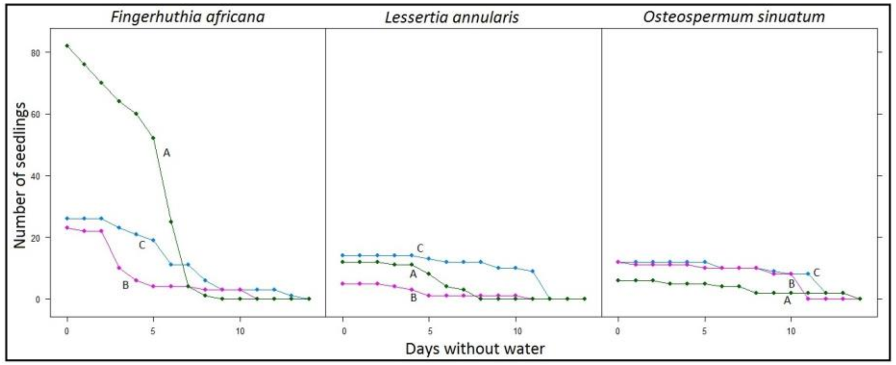

Figure 2.3: Mortality of each species when germinated under the different temperature regimes (A = winter; B = summer; C = spring/autumn).

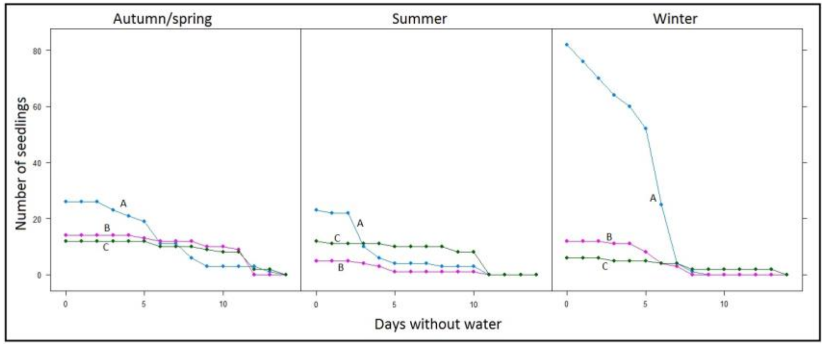

Figure 2.4: Mortality rates for the three species (A = *F. africana*; B = *L. annularis*; C = *O. sinuatum*) germinated under each of the temperature regimes.

F. africana was expected to have the highest germination success under summer temperatures, based on germination trials by Milton (unpubl. data) and Matthee (unpubl. data). All these trials, however, were performed under "natural" rather than simulated conditions, and seeds were therefore exposed to photoperiods of varying lengths. It may well be that the higher germination success observed for *F. africana* in the field during summer could be linked to an increase in day length associated with summer rather than the higher temperatures. Gramshaw (1972) found slightly higher germination rates under increased light for another grass species, *Lolium rigidum*. Two of the four grass species studied by Khan and Gulzar (2003) showed significant decreases in germination rates in the absence of light, and germination of these species was likely linked to an increased day length. However, in the same study, the highest germination rates of all grass species were under relatively high temperatures. Conversely, for *F. africana*, the findings of this and other chapters indicate that day length and moisture availability may be more significant cues than temperature.

O. sinuatum was expected to germinate best under lower temperatures, based on trials by Matthee (unpubl.), and the preference of some asteraceous species to germinate under cooler conditions (Beneke *et al*. 1993; Schütz *et al*. 2002). Schütz and Milberg (1997) found that germination of *Launaea arborescens* (Asteraceae), a semi-desert shrub, was opportunistic, with germination likely linked to the amount of moisture available, and period of moisture availability. It is probable that *O. sinuatum* also follows this opportunistic approach to the stochastic rainfall in the Karoo (Wiegand *et al*. 1995). As with *F. africana*, the deviation of observed germination from what I expected may be linked to day length, as period of light exposure is a significant germination cue in some asteraceous shrubs (Beneke *et al*. 1993).

Germination rates were largely linked to warmer temperatures, if water is not a limiting factor. In the Succulent Karoo, predominantly a winter rainfall area (Mucina *et al*. 2006a), seeds should be sown during autumn, in order to take advantage of the combined effect of early winter rains and relatively high temperatures. In the Nama Karoo, which experiences primarily summer rainfall (Mucina *et al*. 2006b), reseeding should be done at the start of spring, in order to maximise the period of growth prior to the onset of the warm summer period.

2.5.2. INDIVIDUAL PERFORMANCE AND SURVIVAL TIME

Of the three trial species, *O. sinuatum* had the highest overall survival rates. In a study on a similar long-lived desert shrub, *Ericameria nauseosa* (Asteraceae), seed size affected survival of seedlings (Benard & Toft 2007). Similarly, of the three species in this study *O. sinuatum* has largest seeds, which may explain its higher survival rate. An associated benefit of the larger seed could be the more rapid development of taproots (Benard & Toft 2007), a characteristic observed with *O. sinuatum* (Esler *et al*. 2006). This could explain the better survival of this species, the other two trial species being more shallow-rooted.

Season only affected individual performance in *L. annularis*. The higher individual performance recorded for specimens of this species under the moderate temperature regime could explain the higher survival rate of these seedlings relative to conspecifics that germinated under summer or winter temperatures. Seedlings of *L. annularis* and *F. africana* survived significantly better if they germinated under moderate temperatures than under warm or cold temperatures. For *L. annularis*, this is likely due to the faster growth rate (as measured by seedling height) observed for the species.

2.5.3. IMPLICATIONS FOR LANDOWNERS

The findings of this study indicate how the timing of sowing seeds of these three species relates to seasonal temperatures. It shows that *F. africana* should be sown at the end of winter, due to high cold-temperature germination and moderate seedling survival time, while *L. annularis* should be sown during spring or autumn, due to higher germination rates, higher individual performance and better survival. Due to good high-temperature germination success and germination rates, *O. sinuatum* should be sowed at the end of summer. The most drought-resistant species appears to be *O. sinuatum*, and this species would be the best choice of the three species for use in reseeding rehabilitation, provided that herbivory is excluded from rehabilitated areas. It is important, however, to acknowledge the effect of rainfall on germination, and that temperature may be a secondary germination cue, after soil moisture.

2.6 CONCLUSION

Temperature was a significant determinant of seedling germination. Overall germination was highest for *O. sinuatum* under summer temperatures, while *F. africana* germinated best under winter temperatures, and *L. annularis* did not have higher germination success under any particular temperature regime. *L. annularis* showed more rapid germination than the other two species, and germination rates were best overall during the spring/autumn temperature range. *O. sinuatum* had good survival under all temperature regimes, while *F. africana* had the lowest survival rates. The implications of the findings on landowners are discussed.

Seedlings of *Fingerhuthia africana* establish well during periods with adequate rainfall.

CHAPTER 3: DIFFERENCES IN GERMINATION AND SURVIVAL OF RESEEDED AND PIONEER SPECIES AMONG SEVEN COMMONLY-USED REHABILITATION METHODS

ABSTRACT

The restoration of degraded South African rangelands often consists of reseeding palatable species in conjunction with a variety of soil preparation techniques. This study evaluates the effect of micro-catchments, mulch and fertiliser in the establishment, survival and individual performance of *Osteospermum sinuatum* in unvegetated degraded areas at two sites within the semi-arid Karoo region. The use of micro-catchments proved most successful in establishing seedlings of the reseeded species, and a combination of hollows and mulch was most successful in cases where soil shrinkage cracks were present. The use of 2:3:2 fertiliser increased pioneer plant abundance and increased short-term individual performance of the reseeded species, but reduced *O. sinuatum* survival by 8% at the higher-rainfall site. Establishment and seedling survival was strongly dependent on the precipitation at each site, with treatment implemented and the abundance of pioneer plants as secondary determinants of success.

3.1 INTRODUCTION

As the agricultural component of a country's GDP increases, more strain is placed on the natural resources of the country, particularly on rangelands used for livestock production (Tilman *et al*. 2001; Steinfeld *et al*. 2006). Increases in utilisation of rangeland often lead to land degradation when livestock stocking rates (often based on economic rather than ecological considerations) exceed rangeland ecological capacity (Stafford *et al*. 2000; Smet & Ward 2005). The overutilization of rangelands often manifests itself through the loss of palatable plants, leading to reduced seed-setting and recruitment of palatable species, and relative increases in unpalatable species and pioneer-type plants (Milton 1995a; DiTomaso 2000; Esler *et al*. 2006). It also leads to reduced vegetation cover, increased soil degradation, and increased erosion (Evans 1996; Villamil *et al*. 2001). If left unchecked, environmental degradation has massive ecological, social and economic implications (Pellant *et al*. 2004). Rehabilitation and restoration projects are often implemented in an attempt to return the vegetation to the pre-overutilisation state; a task that is hampered by the altered vegetation often being maintained as a new stable state through hydrological, biogeochemical and climatic feedbacks (Laycock 1991; Asner *et al*. 2004). Autogenic recovery of the degraded areas is therefore highly unlikely to occur, and active intervention must be undertaken.

Reseeding and replanting rehabilitation are the two main methods used in the rehabilitation of degraded rangelands: with the former, seeds of palatable or preferred species are sown in the degraded area, while the latter consists of the planting of mature or semi-mature individuals of preferred species in the rehabilitation area (Houérou 1992). Despite reseeding being cheaper (Palmerlee & Young 2010), replanting is still more popular due to its success rate (Ruiz-Jaen & Aide 2005b). Even under relatively high rainfall, recruitment of seedlings following direct reseeding is usually low (Doust *et al*. 2006). Arid and semi-arid rangeland rehabilitation faces the additional problem low and extremely variable rainfall, which further decreases the likelihood of successful seedling recruitment if no soil preparation techniques are used (Hardegree *et al*. 2012).

In order to increase the success of rehabilitation, a variety of soil preparation methods is prescribed for use in general rehabilitation projects, but particularly for the rehabilitation of arid and semi-arid rangelands. These methods include the creation of micro-catchments, ripping, mulching, brush packing and the addition of fertilisers or manure (Green 1989; Friedel *et al*. 1996; Barac 2003 Snyman 2003; Kinyua *et al*. 2010). These methods normally attempt to create suitable germination sites, increase water infiltration and availability, reduce water loss through evaporation, or to promote seedling growth through the addition of nutrients. A combination of the above methods generally yields the most significant results, but costs of materials and labour can be high (Dregne & Chou 1992). The benefits derived from the rehabilitated ecosystem, however, often exceed the costs associated with rehabilitation, particularly in the short-term (Currie 2008; Yitbarek *et al*. 2012).

The relative successes of various rehabilitation methods have been tested in the past (Friedel *et al*. 1996; Snyman 2003; Kinyua *et al*. 2010), with varying results. However, such studies often consist of evaluating the success of different methods at one site, or one method between different sites. This study aims to determine the difference in the effectiveness of micro-catchments, mulch, fertiliser and a combination of methods in the initial establishment of reseeded species, the subsequent survival of seedlings and primary production at two sites differing in aridity and rainfall seasonality.

3.2 STUDY AREA

3.2.1 LOCATION

This study was performed at two sites approximately 100 km apart and separated by a mountain range. De Denne is situated 8.5 km southwest of Oudtshoorn, Western Cape, South Africa (S33°39'59.61''; E22°08'05.93''). The experimental plots are situated in an area used, up to ten years ago, as an ostrich feeding camp. Due to high levels of trampling and the associated soil capping, vegetation has not been able to establish in the area in the past, even with ostriches excluded.

The Wolwekraal Private Nature Reserve is located approximately 2 km north of Prince Albert, Western Cape, South Africa (S33°11'39.73''; E22°02'16.50''). The experimental plots are located on large, rectangular bare patches in the vegetation. The origin of the bare patches is unknown, but it is suspected that they were old cultivated fields. Though extensive soil capping is not present at the experimental plots, vegetation establishment on the bare patches has not been recorded for the period 2007-2011, most likely due to the aridity of the area that is exacerbated by accelerated rainfall runoff from bare soil.

3.2.2 CLIMATE

The De Denne site falls within the predominantly winter-rainfall Little Karoo region. The mean annual rainfall is 260 mm. Mean maximum temperature peaks during February (33°C), while the mean minimum temperature is lowest in July (4°C; South African Weather Service 2014). During the study period (9 July 2013 – 20 December

2013), the area received a total of 544 mm rain, with 349 mm falling during the first 12 months of the study, and 195 mm during the remaining 5 months.

Wolwekraal falls within the Greater Karoo, and experiences a weakly bimodal rainfall distribution, with the majority of the 176 mm mean annual rainfall occurring during autumn and spring (SAWS 2014). The mean maximum temperature peaks in February (34°C), with the mean minimum temperature reaching 3°C in August. During the study, Wolwekraal received a total of 389 mm rain, with 218 mm occurring during the first 12 months, and 171 mm during the remaining 9 months.

3.2.3 VEGETATION

The De Denne site is located within the Eastern Little Karoo vegetation of the Succulent Karoo biome, which is commonly dominated by succulents and smaller shrubs (Mucina *et al*. 2006a), while the Wolwekraal experimental plots are located in Prince Albert Succulent Karoo. The vegetation at Wolwekraal is ecotonal to the Nama Karoo biome, which is characterised by drought-deciduous shrubs and grasses (Mucina *et al*. 2006b).

3.3 METHODS

3.3.1 EXPERIMENTAL DESIGN AND CONSTRUCTION

At Wolwekraal, a single, large, bare area could not be found for use in this study. Instead, four smaller experimental plots were laid out, all similar in underlying geology, soil, stone cover and initial vegetation cover. Each plot was divided into four 5x5 m blocks, which were sub-divided to form four 2.5x5 m blocks and eight 2.5x2.5 m blocks per plot. The 2.5x5 m blocks were then randomly subjected to either a combination of hollows (H), or no soil preparation (reseeding only; R). The 2.5x2.5 m blocks received one of the following treatments: mulch (M), mulch and hollows (MH), mulch, hollows and fertiliser (MHF), or mulch and fertiliser (MF). These treatments were assigned to the blocks in a random manner. Figure 3.1 illustrates the layout of experimental plots at Wolwekraal. Eight replicates of each treatment were constructed on Wolwekraal. Hollows consisted of semi-circular, hand-dug depressions approximately 500 mm in diameter, and with a maximum depth of 150 mm, and were constructed at a density of five hollows per 2.5x2.5 m block. Mulch consisted of finely-chipped *Prosopis* branches, and was distributed among the appropriate blocks at a thickness of 5 mm. For the treatments including the addition of fertiliser, a slow-release NPK fertiliser (N:P:K ratio of 2:3:2) was used at rates of 30 g.m^{-2} (187.5 g per 2.5x2.5 m block). The fertiliser used was recommended by the manufacturer for the production of stronger root systems, in an attempt to increase seedling survival. Seeds of *Osteospermum sinuatum* (Asteraceae) and *Fingerhuthia africana* (Poaceae), species commonly used in reseeding rehabilitation, were sown on all the blocks. Seeds were sown at a density of 5 kg/ha, as recommended by the seed supplier. Construction and reseeding of all the Wolwekraal plots were completed on 23 March 2012.

At the De Denne experimental plots, a lack of space led me to use a modified Latin square design. A total of 42 plots, each 3 x 3 m in size and separated from each other by a 1 m-wide bare strip, were constructed. Six replicates of each treatment were assigned to the plots available, in a design that attempted the replication of every treatment in each column and row. Treatments were performed in an identical manner to treatments at Wolwekraal, including the reseeding with *O. sinuatum* and *F. africana*. Experimental plot construction and reseeding at De Denne were completed on 10 July 2012.

To reduce the likelihood of seed movement between plots, reseeding at both sites took place on wind still days, during light rain. The moisture of the rain resulted in the seeds sticking to the soil in the plots they were sown.

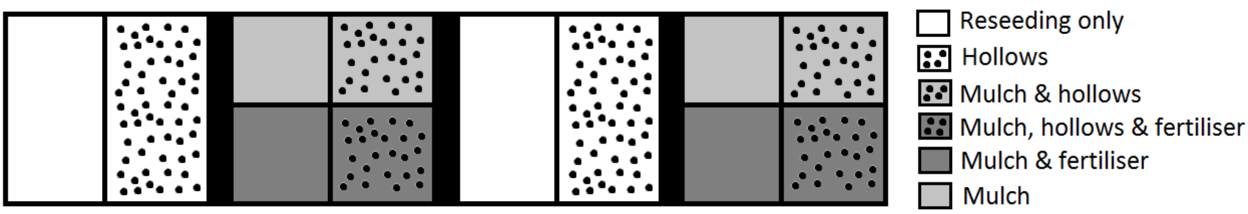

Figure 3.1: The layout of one experimental plot at Wolwekraal Nature Reserve. Treatments within each plot were assigned randomly to each of the plots.

3.3.2 DATA COLLECTION

Initial vegetation cover

Initial vegetation canopy cover at both sites was estimated visually directly after the construction of the experimental plots, in order to determine the baseline vegetation cover present. Species present in each plot were recorded, along with the number of specimens and estimated percentage canopy cover of each species.

Germination success and seedling survival

The experimental plots at Wolwekraal were surveyed again on 3 May 2012, three weeks after the first rainfall event exceeding 10 mm, in order to test the germination of the reseeded and unseeded species among treatments. All species present in each plot were recorded, as well as the number of specimens per species present inside and outside the hollows. Specimens were recorded as inside hollows if the base of their stem entered the soil inside the hollow, or along the hollow wall: this was done to determine whether more seedlings established inside the hollows than outside. Another survey was performed on 20 April 2013, in order to assess the survival of seedlings approximately a year after rehabilitation experiment was established. As with the previous survey, the species present in the plots, along with the number of specimens per species inside and outside the hollows, were recorded. The last survey, during which the number of specimens and percentage vegetation cover was recorded for each species, was on 16 December 2013, approximately 21 months after reseeding.

The experimental plots at De Denne were surveyed on 14 August 2012 (three weeks after rainfall exceeding 10 mm), to test the germination of reseeded and other species among treatments. Data were collected in the same manner as on the Wolwekraal plots. A second set of data collection was performed on 24 October 2012, to test short-term survival of seedlings between treatments. Data were again collected on 13 April 2013, and the last data collection took place on 26 December 2013. The last survey tested longer-term survival of seedlings after a winter with below-average rainfall and a partial summer drought. Plants were grouped according to their ecosystem function, and pioneer plants (the dominant group) were used along with the reseeded species in the analysis.

Seedling individual performance

To test the difference in individual performance of seedlings among treatments (at both experimental sites), the height (mm) of seedlings belonging to the reseeded species was recorded for all living specimens during April 2013 and December 2013. Height measurements were taken from ground level to the highest point of leaf attachment on the plant.

3.3.5 DATA ANALYSIS

Seedling frequencies

Since the germination of *F. africana* was extremely low for Wolwekraal (31 seeds germinated) and non-existent for De Denne (no seeds germinated), it was excluded from further analyses. Treatments were classified according the presence or absence of hollows, mulch and fertiliser in the respective treatments, and these explanatory variables were used in the analyses. Generalized Linear Models (GLM) were used to assess the strength of the explanatory variables (treatments, age and abundance of pioneers) in explaining the abundance of *O. sinuatum* at each site. For this analysis, data collected during each of the surveys were lumped, leading to potential temporal pseudoreplication. Models were adjusted until a minimum adequate model could be constructed for each site. Due to overdisperson and zero-inflation, quasipoisson errors were used in each GLM. Statistical analyses were performed using R version 3.1.0 (R Core Team 2014).

Individual performance

A random sample of 50 height measurements per treatment were taken from the data collected at De Denne during April 2013 and December 2013. Only treatments H, MH and MHF had a sufficient number of specimens alive for analysis. A Kruskal-Wallis and multiple comparison of mean ranks post-hoc test were used to determine whether there was a significant difference in seedling height among treatments for the April and December 2013 surveys. Too few seedlings remained at the Wolwekraal experimental sites to compare individual performance among treatments.

3.4 RESULTS

3.4.1 ESTABLISHMENT OF PIONEER PLANTS AND *OSTEOSPERMUM SINUATUM*

Pioneer plants

The abundance of pioneer plants at both Wolwekraal and De Denne was strongly influenced by the addition of fertiliser (Table 3.4), with plots at Wolwekraal treated with fertiliser having significantly more pioneer plants ($\bar{x}$ = 10.54 ± 20.05) than plots without fertiliser addition did ($\bar{x}$ = 6.08 ± 10.03). Similarly, more pioneer plants were present at De Denne in plots that received fertiliser ($\bar{x}$ = 35.47 ± 35.36) than plots that did not ($\bar{x}$ = 21.96 ± 30.32). The presence of hollows influenced pioneer abundance only at De Denne, with a higher abundance of pioneer plants in plots with hollows present than plots with hollows absent ($\bar{x}$ = 31.03 ± 35.36 and $\bar{x}$ = 17.33 ± 30.32, respectively). The position of the plants relative to the hollows influenced pioneer establishment only at Wolwekraal, with more pioneer plants establishing in hollows ($\bar{x}$ = 10.24 ± 21.26) than outside them ($\bar{x}$ = 6.23 ± 8.78). Time since sowing (age) was also a major influence on pioneer plant abundance at De Denne. These plants established well after the first major rainfall event, declined during the dry season, and re-established in greater abundance during the second wet season after plot establishment.

Table 3.1: Total *Osteospermum sinuatum* seedlings recorded for each treatment (M = mulch; F = fertiliser; H = hollows; R = reseeding only) at the Wolwekraal experimental plots during the three surveys.

Treatment	N	May 2012 Sum (%)	Apr. 2013 Sum (%)	Dec. 2013 Sum (%)	Percentage survival
H	8	49 (10.699)	44 (27.673)	8 (15.686)	16.33
M	8	36 (7.860)	9 (5.660)	3 (5.882)	8.33
MF	8	28 (6.114)	4 (2.484)	0 (0.000)	0.00
MH	8	210 (45.852)	52 (32.704)	22 (43.137)	10.48
MHF	8	112 (24.454)	42 (26.415)	15 (29.412)	13.39
R	8	23 (5.022)	8 (4.969)	3 (5.882)	13.04
Total	48	458	159	51	11.14

Reseeded *Osteospermum sinuatum*

At Wolwekraal, *O. sinuatum* abundance (Table 3.1) was influenced by the time since sowing, the use of mulch, the use of fertiliser, and the position relative to hollows (Table 3.3). The number of *O. sinuatum* decreased steadily with time, and no recruitment after the initial reseeding was observed.

At De Denne, the presence of hollows, position of plants relative to hollows, time since sowing and the abundance of pioneer plants influenced the abundance of *O. sinuatum* (Table 3.2; Table 3.3). The most influential predictor was time since sowing, and an overall decrease of *O. sinuatum* abundance was observed over time. Though more *O. sinuatum* were present in plots that contained hollows ($\bar{x}$ = 19.34 ± 22.54) than plots without hollows ($\bar{x}$ = 8.88 ± 14.86), plant position relative to hollows within these plots was a more significant predictor, with many more plants present in hollows than outside hollows ($\bar{x}$ = 32.79 ± 24.06 and $\bar{x}$ = 7.38 ± 12.26, respectively). *O. sinuatum* was less abundant in plots with a high abundance of pioneer plants.
The addition of mulch had a positive effect on *O. sinuatum* establishment, while the addition of fertiliser had a negative impact thereon (Table 3.3). Neither of these two factors influenced *O. sinuatum* abundance at De Denne.

Table 3.2: Total *Osteospermum sinuatum* seedlings recorded for each treatment (M = mulch; F = fertiliser; H = hollows; R = reseeding only) at the De Denne site during the four surveys.

Treatment	N	Aug. 2012 Sum (%)	Oct. 2012 Sum (%)	Apr. 2013 Sum (%)	Dec. 2013 Sum (%)	Percentage survival
H	6	531 (28.812)	238 (29.455)	169 (48.986)	173 (40.421)	32.58
M	6	215 (21.666)	65 (8.045)	0 (0.000)	0 (0.000)	0.00
MF	6	204 (11.069)	143 (17.698)	3 (0.870)	2 (0.467)	0.98
MH	6	422 (22.897)	184 (22.772)	88 (25.507)	139 (32.477)	32.93
MHF	6	465 (25.231)	177 (21.906)	85 (24.638)	114 (26.636)	24.95
R	6	6 (0.326)	1 (0.124)	0 (0.000)	0 (0.000)	0.00
Total	36	1843	808	345	428	18.72

Table 3.3: The minimum adequate models for reseeded *Osteospermum sinuatum* establishment on Wolwekraal and De Denne.

Predictors	Wolwekraal			De Denne		
	Estimate	Std Error	*t*-value	Estimate	Std Error	*t*-value
Intercept	-0.39	0.21	-1.85	4.67	0.20	23.66***
Age	-1.10	0.01	-8.32***	-0.10	0.01	-13.52***
Presence of hollows	NS	NS	NS	-0.43	0.18	-2.43*
Hollows position: Out	-0.93	0.17	-5.53***	-1.65	0.15	-11.00***
Presence of mulch	1.54	0.22	7.06***	NS	NS	NS
Presence of fertiliser	-0.49	0.19	-2.52*	NS	NS	NS
Pioneer abundance	NS	NS	NS	0.01	0.00	7.44***
	Dispersion parameter = 4.71			Dispersion parameter = 7.97		
	Null deviance = 1502.24 on 215 df			Null deviance = 5293.8 on 215 df		
	Residual deviance = 686.16 on 211 df			Residual deviance = 1764.9 on 211 df		

Significance: *p<0.05; **p<0.01; ***p<0.001

Table 3.4: The minimum adequate models for predicting occurrence of pioneer plants at Wolwekraal and De Denne.

Predictors	Wolwekraal			De Denne		
	Estimate	Std Error	*t*-value	Estimate	Std Error	*t*-value
Intercept	-0.13	0.20	-0.656	1.97	0.22	8.87***
Age	NS	NS	NS	0.05	0.01	5.14***
Presence of hollows	NS	NS	NS	0.58	0.17	3.38***
Hollows position: Out	-0.50	0.23	-2.170*	NS	NS	NS
Presence of fertiliser	0.96	0.23	4.19***	0.48	0.14	3.35***
	Dispersion parameter = 21.20			Dispersion parameter = 29.03		
	Null deviance = 3241.3 on 215 df			Null deviance = 7180.7 on 215 df		
	Residual deviance = 2793.2 on 213 df			Residual deviance = 5709.5 on 212 df		

Significance: *p<0.05; **p<0.01; ***p<0.001

Table 3.5: The mean height (mm) from a random sample of heights recorded for *Osteospermum sinuatum* seedlings during the surveys of April 2013 and December 2013 at the De Denne experimental site.

Treatment	April 2013		December 2013	
	N	x̄ height (SD)	N	x̄ height (SD)
H	50	111.14 (67.34) [ab]	50	117.86 (97.93) [a]
MH	50	92.52 (66.67) [a]	50	136.62 (84.95) [ab]
MHF	50	140.00 (103.59) [b]	50	139.58 (70.32) [b]

3.4.2 INDIVIDUAL PERFORMANCE

The Kruskal-Wallis and post-hocs indicated a significant difference in *O. sinuatum* seedling height at De Denne (Table 3.5) among treatments for both April 2013 ($H=9.220$; $df=2$, $N=150$; $p<0.05$) and December 2013 ($H=7.219$; $df=2$, $N=150$; $p<0.05$). Multiple comparisons of mean ranks indicated that heights recorded were significantly higher for treatment MHF than MH during April 2013 ($z=3.036$; $p<0.01$), and significantly higher for treatment MHF than H during December 2013 ($z=2.635$; $p<0.05$).

3.5 DISCUSSION

3.5.1 INITIAL GERMINATION

Overall, significantly more seedlings of *O. sinuatum* established at De Denne than Wolwekraal, most likely due to a difference in post-reseeding rainfall: Wolwekraal received a total of 41 mm rain between reseeding and the first counting of the seedlings, whereas De Denne received a total of 114 mm for the period between reseeding and seedling counting. Studies such as those of Otto *et al*. (2006) and Burke (2014) showed that the recovery rates of degraded areas are positively correlated with the amount of rainfall in an area. Mganga *et al*. (2010) also showed that higher moisture levels increase the likelihood of successful rehabilitation in semi-arid areas.

My study results indicate that simply reseeding an area does not yield significant germination of seeds, and that any of the soil preparation techniques implemented result in higher establishment rates than simply reseeding an area. Similarly, Snyman (2003) reported that reseeding alone is not sufficient to increase the abundance of reseeded species. Simons and Allsopp (2007) recorded a higher abundance of pioneer-type herbaceous plants, but not of perennial species, in plots that received soil treatments. So too, the vegetation at both Wolwekraal and De Denne was dominated by short-lived shrubs and forbs: the only common perennial plants present in the plots were the reseeded *O. sinuatum*. It is likely that longer-lived species will establish over time, as some individuals of slower-growing, longer-lived species established in some of the plots at Wolwekraal (e.g. *Gomphocarpus filiformis* and *Euphorbia braunsii*) and De Denne (e.g. *Crassula subaphylla*).

Successful establishment of *O. sinuatum* was strongly linked to the use of hollows and mulch in conjunction with reseeding. Likewise, De Abreu (2011), succeeded in re-establishing vegetation cover with the use of hollows. Construction of hollows significantly increased seedling germination. Hollows trap surface run-off during rainfall events, increasing the amount of plant available moisture and extending the period of moisture availability (Hanke *et al*. 2011). The higher moisture levels potentially act as a germination cue (Clauss & Venable 2000), increasing the germination rate of seeds present in the hollows. Litter is also trapped in hollows, increasing plant available nutrients through the breakdown of accumulated organic matter, and seeds trapped in hollows therefore had a higher likelihood of establishing successfully than seeds outside them.

The importance of mulch in influencing the establishment of *O. sinuatum* at Wolwekraal, but not at De Denne, may be linked to a difference in soil structure and behaviour. At Wolwekraal, soil shrinkage after rainfall was observed in all the hollows that did not receive mulch as an additional treatment. Mulch increases soil stability, and therefore decreases the likelihood of soil shrinkage cracks forming (Mulumba & Lal 2008). Although shrinkage may greatly improve infiltration rates (Ringrose-Voase *et al*. 1989), it may also break plant roots, leading to decreased growth rate and survival of seedlings attempting to establish in an area (Tan 2000). In treatment blocks that received mulch in conjunction with hollows, the shrinkage cracks were not observed, and this difference could explain why the use of mulch was a more important predictor than the use of hollows at Wolwekraal. At De Denne, no shrinkage cracks were observed, and the blocks that received hollows without mulch performed similarly to blocks that received both hollows and mulch.

3.5.2 SURVIVAL OF *OSTEOSPERMUM SINUATUM*

Between-survey survival of seedlings, as can be expected in semi-arid rangelands, was very low, with approximately half the seedlings dying within the first two months (after initial germination) at the De Denne site. There was relatively high rainfall during this period, and the mortality among seedlings was likely due to competition between seedlings (for example, see Suzuki *et al*. 2003). Later decreases in seedling abundance could be linked to higher temperatures and reduced rainfall, even though the seedlings probably had extensive roots by that time (Esler *et al*. 2006).

Between April 2013 and December 2013, a marked increase in seedling numbers was observed at De Denne for all blocks where hollows were present. This increase possibly reflects the moderately high rainfall and mild temperatures experienced during this period, as well as the fact that *O. sinuatum* individuals in hollows flowered and set seed during that period, while no flowering individuals were observed outside hollows.

At Wolwekraal, I observed a continuous decline in seedling abundance. The high mortality rate was probably because rainfall was lower at Wolwekraal than it was at De Denne during the study period (389 mm and 544 mm, respectively). Additional provisioning of water through irrigation may aid the establishment of reseeded plants. This may, however, not be economically sound and may increase mortalities during severe drought conditions or when irrigation is halted (Bainbridge 2002; Padilla & Pugnaire 2009).

3.5.3 SEEDLING PERFORMANCE

The difference in plant height observed between treatments MHF and MH at De Denne during April 2013 indicates that the addition of fertiliser does increase the growth rate of seedlings initially. However, the initial height difference had decreased substantially by December 2013, and was no longer statistically significant. The initial boost in above-ground growth did, however, come at a cost: during April 2013, a greater percentage of seedlings that originally established were alive in plots with treatment MH (20.85%) than they were in plots with treatment MHF (18.28%). A greater increase in *O. sinuatum* abundance occurred between April and December 2013 for plots with treatment MH than treatment MHF (57.95% and 34.12%, respectively). This could indicate that more flowering individuals were present (and more seeds set) in plots with MH than MHF, and that plants under treatment MHF spent more of their energy on foliage production than flowering.

Though some authors propose that the addition of fertilisers can aid the revegetation process (Call & Roundy 1991; Breen & Richards 2008), others have found that the addition of fertilisers had no effect on plant establishment, growth and survival (Stoneman *et al*. 1994; Breen & Richards 2010 Kinyua *et al*. 2010; Soliverez *et al*. 2012). Ceccon *et al*. (2003) used fertilisers to test their effect on seedling survival rates: one of the species studied had an increased mortality rate when fertiliser was added, while other species had increased survival rates. Liu *et al*. (2008) observed increased growth rates of a reseeded grass when fertiliser was added, but it did not affect grass survival rates. Conversely, my study showed that adding fertilizers initially increased performance of *O. sinuatum* seedlings, with negligible long-term effects, but adding fertilizers decreased survival rates. The decreased survival of *O. sinuatum* could be due to the synergistic effect of higher foliage production (resulting in higher transpiration losses and therefore higher mortality rates during dry periods) and increased competition levels with pioneers under high nutrient levels (for example, see Jauffret & Visser 2003).

3.5.4 MANAGEMENT IMPLICATIONS

The findings of this chapter indicate that rainfall likely influences how successful reseeding rehabilitation is. Though landowners cannot control the amount of rainfall their farms receive, they can attempt to implement soil preparation and reseeding shortly before good rains are expected. The soil preparation methods implemented by landowners are also within their control. The use of hollows is strongly recommended, as they resulted in very successful establishment of reseeded *O. sinuatum* in the trials. Mulch should be used to reduce water loss through evaporation, and to reduce the likelihood of soil shrinkage in soils prone to that phenomenon. The use of fertilisers is not recommended, as despite initially increasing production in *O. sinuatum*, it promoted the establishment of weedy species, which partly outcompeted the reseeded *O. sinuatum*, resulting in increased mortalities of the reseeded species. I recommend that landowners implement small-scale experiments on their properties, to determine the relative success of a variety of soil preparation techniques, and that the most successful technique is implemented on their properties.

3.6 CONCLUSION

Apart from the age of the experimental plots, the presence of hollows (and therefore seedlings' position relative to hollows), mulch, fertiliser and pioneer abundance significantly influenced the abundance of *O. sinuatum*. Pioneers appeared to dominate under high nutrient levels, while *O. sinuatum* had increased mortalities at the higher rainfall site when receiving fertiliser. Hollows acted as seed and water traps, aiding establishment of vegetation, particularly at De Denne.

(A)

(B)

(C)

(D)

Four experimental plots at De Denne after construction in July 2012 (A), and during surveys in October 2012 (B), April 2013 (C), and December 2013 (D). The presence of hollows in the back plots explains the difference in regeneration.

CHAPTER 4: THE INFLUENCE OF RAINFALL, SOIL PREPARATION AND SITE CHARACTERISTICS ON ESTABLISHMENT OF RESEEDED SHRUBS AND GRASSES

ABSTRACT

I investigated the effects of rainfall, commonly used rehabilitation methods and selected on-site environmental variables on the establishment of long-lived shrubs, short-lived shrubs and grasses. I compared the relationships between the abundance of reseeded plants and the predictor variables using generalized additive models (GAM) and generalized linear models (GLM) with quasipoisson errors. Results indicate that rainfall, particularly during the first three months after rehabilitation, has a strong influence on all three growth forms, with long-lived shrubs also positively influenced by mean monthly rainfall. Long-lived shrubs were positively associated with the use of hollows and mulch, whereas grasses were negatively associated with the use of ripping and mulching. I conclude that the use of hollows could aid the establishment of reseeded species, but that rainfall is an overriding factor in determining the success of rehabilitation efforts.

4.1. INTRODUCTION

Rehabilitation is performed in a variety of environments, from tropical rainforests to arid and semi-arid rangelands (Edwards *et al*. 2011; Hanke *et al*. 2011; Daisuke *et al*. 2013). Challenges faced when rehabilitating degraded areas range from high erosion rates prior to vegetation establishment in areas with high rainfall (Wagenbrenner *et al*. 2006; Lee *et al*. 2014) to sporadic vegetation establishment in areas with low and unpredictable rainfall (Burke 2014). Successful establishment events are probably linked to rainfall being sufficient to promote the germination and survival of reseeded species (Otto *et al*. 2006; Fehmi & Kong 2012).

In order to increase the likelihood of rehabilitation success in arid and semi-arid rangelands, landowners implement a variety of soil preparation methods. These methods mainly aim at breaking crusted soil surfaces, capturing nutrients, water and windblown seeds, increasing water infiltration, and decreasing evaporative water loss (Simons & Allsopp 2007; Chenn *et al*. 2007; Kinyua *et al*. 2010; Hanke *et al*. 2011; Singh 2012; León *et al*. 2013; Prats *et al*. 2013). These methods include the creation of micro-catchments (also known as hollows or the ponding method), ripping or ploughing the degraded areas, and placing a layer of mulch or manure on the soil surface (Snyman 2003; Coetzee 2005; Van den Berg & Kellner 2005; Esler *et al*. 2006; Kinyua *et al*. 2010; Hanke *et al*. 2013; Chambers *et al*. 2014). To increase the relative abundance of palatable species in post-rehabilitation vegetation, reseeding with these species is employed (Visser *et al*. 2004; Palmerlee & Young 2010).

A lack of rainfall is sometimes quoted as the main factor affecting rehabilitation success, as the failure of timely rains results in low recruitment. Low post-germination rainfall may also result in mass mortalities of seedlings (Abbott & Roundy 2003). Alternative causes of rehabilitation failure include the lower success rates of the soil preparation techniques used (Snyman 2003) or the use of old seeds or seeds with low inherent viability (Mganga *et al*. 2010; Kirby *et al*. 2011; Opiyo *et al*. 2011).

This study aims to determine the significance of rainfall during the first three months after reseeding (hereafter called initial rainfall), long-term mean monthly rainfall after reseeding, soil preparation methods used during rehabilitation and selected on-site environmental variables (such as stone, litter and vegetation cover, and slope steepness) in determining the establishment of reseeded plant species. Three growth forms were used in the study, namely long-lived chamaephytes, short-lived chamaephytes and hemicryptophytes. The aims were to study how the abundance of reseeded species is affected by: (1) rainfall; (2) soil preparation techniques; and (3) age, litter, mulch, slope and vegetation cover.

4.2. STUDY AREA

This study was observational rather than experimental, and involved the post-reseeding assessment of nineteen sites in semi-arid rangeland in the Karoo region, South Africa (Figure 4.1). Most of the sites were on mines or privately-owned ranches, which varied in land use history and rehabilitation approach. The sites were situated in a variety of soil and vegetation types, under a range of post-rehabilitation climatic conditions, and were exposed to various soil preparation techniques. The majority of the sites had clay-rich soil, but some had sandy or silt-rich soils. Seven of the nineteen sites were located within the Succulent Karoo biome, with the remaining twelve sites located in the Nama Karoo biome (Appendix 1). The Succulent Karoo is dominated by succulents, which require low but predictable winter rainfall (Mucina *et al*. 2006a), while the Nama Karoo is dominated by grasses and drought-adapted shrubs capable of surviving under the low and unpredictable rainfall regime typical of this biome (Mucina *et al*. 2006b).

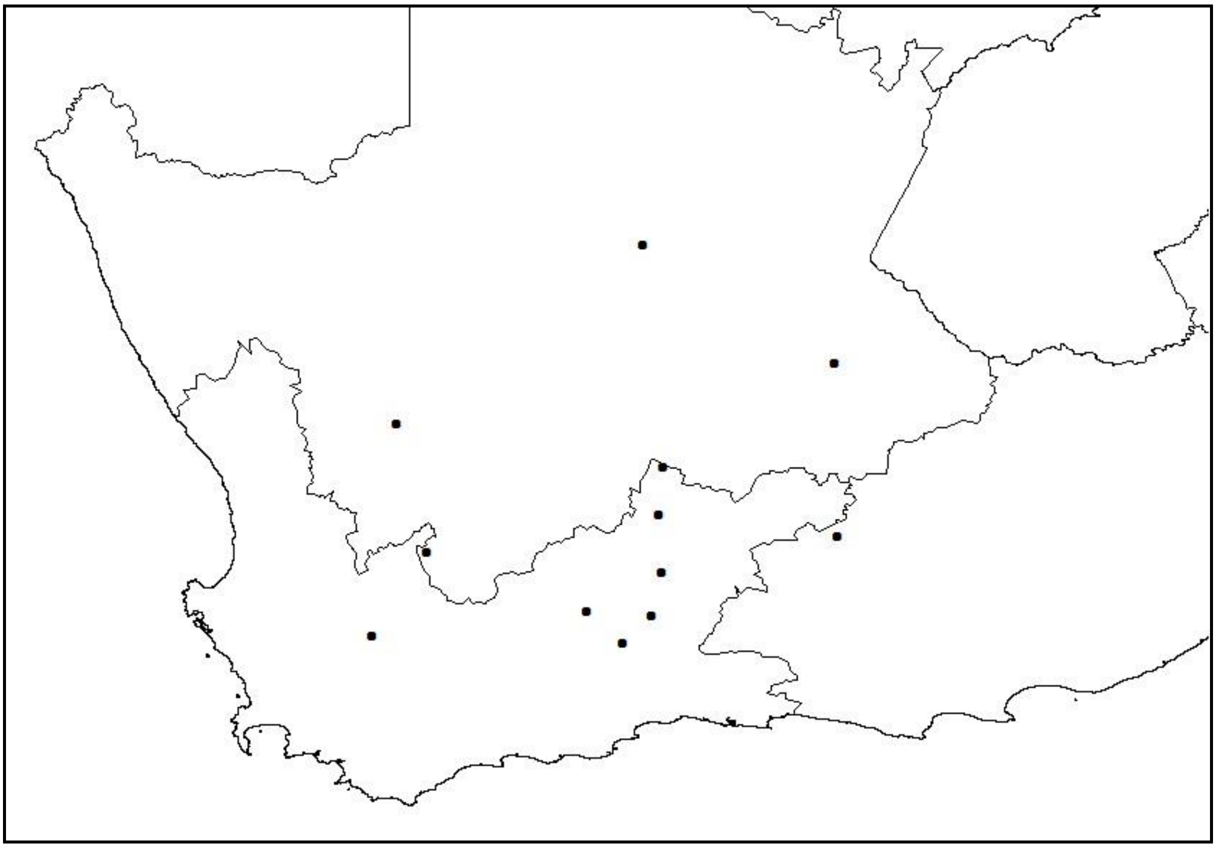

Figure 4.1: Location of the main sites surveyed for this chapter.

4.3. MATERIALS AND METHODS

4.3.1. DATA COLLECTION

The 19 sites were surveyed between April 2012 and November 2013, coinciding with the growing phase of the vegetation, winter and summer months in the Succulent Karoo and Nama Karoo respectively. At each site, seeds had previously been sown at densities of 5 $kg.ha^{-1}$ (as recommended by the seed supplier). At each site, 3x3 m survey plots were laid out randomly at a density of ten plots per hectare. In cases where the rehabilitated area was larger than 3 ha in size, a total of 30 plots were surveyed.

For each plot, the soil preparation treatment used was recorded: treatments were classified as ripping (R), hollows (H), mulching and/or brush-packing (M) or reseeding without soil preparation (S). Other environmental variables recorded for each plot were age (time since rehabilitation was implemented), slope steepness, total vegetation canopy cover (%), branch cover (%), litter and mulch cover (%), stone cover (%) and bare soil (%). Photographs were taken of each plot from the northern direction for future reference. The species used for reseeding at each site were recorded using data from the seed supplier or information provided by the land managers, and the number of individuals of these species was recorded for each plot. These plants were then grouped by growth form, and the total number of plants per growth form was then used in data analysis. For the analyses, the absolute numbers were used. A total of 202 plots were done in areas where long-lived shrubs were sown, 116 plots where short-lived shrubs were sown, and 213 plots where grasses were sown.

Rainfall data for the period after rehabilitation at each site were obtained from the South African Weather Service for the weather station closest to each site. From these data, the initial rainfall recorded in each area was calculated, as well as the mean monthly rainfall for each area between the time of reseeding and the date of data collection.

The age, initial rainfall, mean monthly rainfall, soil preparations used, species sown, abundance of reseeded species and mean abundance per hectare of reseeded species is summarised per site in Appendices 2-4.

4.3.2. DATA ANALYSIS

To find how the predictor variables affected the number of seedlings that were present at the various sites, the data of long-lived shrubs, short-lived shrubs and grasses were analysed separately. Initially, an exploratory analysis with generalized additive models (GAM) was performed, to determine the strength and influence of the various predictor variables on the number of reseeded individuals that established in an area. The smoothing parameter was applied to the slope, vegetation cover, initial rainfall, mean monthly rainfall, litter and mulch cover, bare soil, and stone cover.

Once the applicable predictor variables were determined, generalized linear models (GLM) with quasipoisson error distribution (due to zero-inflation and overdispersion) were used to assess and compare the relative strength of each predictor in the model. Models were adjusted until a minimal adequate model could be constructed for each growth form.

Statistical analyses were performed with the statistical package R version 3.1.0 (R Core Team 2014), and the mgcv package was used for the generalized additive models (Wood 2011).

4.4. RESULTS

4.4.1. LONG-LIVED SHRUBS

The initial GAM indicated that the following predictor variables explained 88.9% of the deviance: treatment used, initial rainfall, mean monthly rainfall, percentage bare soil, percentage vegetation, percentage branches, percentage litter/mulch, percentage stone cover, and slope steepness (Table 4.1).

The GLM showed that only mean monthly rainfall had a positive effect on shrub establishment, while it was also the most important predictor of successful establishment (Table 4.2). Initial rainfall, percentage branches and percentage litter/mulch had strong negative influences on the abundance of reseeded plants (Table 4.2). Higher abundance of reseeded plants were observed when hollows or mulch/brush packing were implemented rather than simple reseeding, whereas the abundance of reseeded plants in areas where the soil was ripped prior to reseeding was similar to those that received reseeding only (Table 4.2). The contradictory negative impact of litter/mulch and positive influence of mulch as a treatment is explained in the discussion.

Osteospermum spp. were recorded in 47% of the plots in which they were sown, whereas *Eriocephalus*, *Salsola* and *Tetragonia* species appeared in less than 25% of plots (Table 4.3).

4.4.2. SHORT-LIVED SHRUBS

Age of the sites surveyed, initial rainfall, vegetation cover, stone cover and slope steepness explained 74.8% of the deviance in the GAM (Table 4.1). The GLM, however, indicated that neither slope steepness nor the stone cover influenced the abundance of reseeded short-lived shrubs significantly (Table 4.2). Instead, overall vegetation cover had the strongest influence on these reseeded plants (Table 4.2), followed by the age of the rehabilitated site and initial rainfall. Soil preparation used was initially included in the model, but did not yield statistically important results, and was removed as predictor variable. Short-lived shrubs (*Lessertia* spp.) were recorded in 20% of plots in which they were sown (Table 4.3).

4.4.3. GRASSES

The GAM indicated that the following predictor variables explained 81.8% of the deviance in the model: age, initial rainfall, mean monthly rainfall, slope, vegetation cover, branch cover, and bare soil present (Table 4.1). Though the mean monthly rainfall did not have a significant influence on the abundance of the plants, the removal of this predictor resulted in a significant increase in deviance (F = 27.401; p<0.001), and it was therefore included in the GLM. Though soil preparation treatment used did not influence the abundance of reseeded grasses according to the GAM, it was also included as a predictor variable in the GLM, in order to test whether grasses were more prevalent in plots that received soil treatments than plots where only reseeding took place.

The GLM showed that initial rainfall had the most significant effect on reseeded grasses, followed by the age of the rehabilitated site: both these had strong negative effects on grass abundance (Table 4.2). The use of ripping as soil treatment had a strong negative impact on grass abundance compared to simple reseeding. The effects of using mulch, hollows and simple reseeding on grass abundance were similar.

Reseeding of grasses (present in 49% of sown plots) was generally more successful than reseeding of shrubs (present in 25% of plots). The grass species that established in the lowest proportion of plots sown was *Stipagrostis obtusa* (Table 4.3).

4.5. DISCUSSION

4.5.1. RAINFALL AS A DETERMINANT

Rainfall was one of the most significant factors that determined the abundance of reseeded species. Otto *et al*. (2006) found that overall vegetation recovery rates on the Canary Islands were closely linked to mean annual precipitation. Similarly, Burke (2014) partly attributed the successful establishment of vegetation in the Namib Desert to an exceptionally wet rainy season. Similarly, this study found that long-lived shrubs establish best with an increase in mean rainfall. Jürgens *et al*. (1999) reported that perennial species recovered well from drought-induced mortalities during years of good rainfall, but that recovery was species-specific, and not always linked to rainfall. This also mirrored, for plants belonging to smaller growth forms, the findings of Fensham *et al*. (2005), who showed that rainfall was important in the establishment of woody species: higher establishment rates were linked to above-average rainfall.

Van den Berg and Kellner (2005) linked the successful establishment of reseeded species to high initial and long-term rainfall. Species that were not reseeded, particularly pioneer species, also established well, with pioneer species even establishing in plots where no soil treatment took place. Rainfall is therefore a major driver in the re-establishment of vegetation in degraded areas, and may override the effects of soil preparation.

4.5.2. SOIL PREPARATION AS A DETERMINANT

For long-lived shrubs, the use of hollows and/or mulch is strongly advised, as these plants occurred in higher abundance under these treatments than they did with reseeding alone. The positive influence of these two treatments was also observed in Chapter 3, where more *O. sinuatum* established when these two treatments were used in conjunction than when reseeding only was performed. Hollows act as water traps, capturing run-off during rainfall events, increasing the amount of water available to seedlings, prolonging the period of water availability and therefore acting as suitable sites for seeds to germinate (Hanke *et al*. 2011; Lesoli 2011). Similarly, mulch increases the likelihood of successful establishment by acting as seed traps, increasing water infiltration, reducing evaporation loss and increasing the period of water availability (Beukes & Cowling 2003). As with the relationship between mean monthly rainfall and long-lived shrub abundance, the abundance of these plants relative to soil preparation implemented appears to be driven by the increased availability of water for extended periods of time.

For short-lived shrubs, treatment used had very little influence on plant establishment. This is contrary to the findings of Simons and Allsopp (2007), where herbaceous cover increased when micro-catchments and brush packing were used. Their study did, however, have very low establishment rates (90 seedlings established of 20 000 seeds sown) and did not span areas with differential precipitation, and it is therefore not surprising that the influence of rainfall and vegetation cover was more significant than soil preparation was in my study. Grubb (1988) suggested that ephemeral species such as these might survive in an area due to seasonal or stochastic weather events rather than disturbance (such as the removal of vegetation cover, or the hollows created by digging animals or landowners during rehabilitation), and that idea appears to be supported by this study.

The negative effect of ripping on the abundance of grasses is contrary to the findings of Kinyua *et al*. (2010), who found that ripping tripled grass cover. Their study was performed in an area with high and relatively predictable rainfall, and the negative result found here may be the synergistic result of ripping combined with low and unpredictable rainfall. Van den Berg and Kellner (2005), however, also found that reseeded species established best when ripping was implemented, particularly when organic matter was added. Van Oudtshoorn *et al*. (2011) evaluated the difference between ripping and ploughing in establishing reseeded species and promoting succession on old croplands, and found that ploughing improved the establishment of reseeded species, while also removing unwanted exotic species. It is likely that the Karoo's low and unpredictable rainfall may limit the effectiveness of this method.

Table 4.1: The Generalized additive models for long-lived shrubs, short-lived shrubs and grasses. For the predictor variable "treatment", H = hollows, M = mulch/brush packing, R = ripping, as compared to simple reseeding. NS refers to predictor variables that were not significant in explaining deviance, and they were excluded from the respective models.

Predictors:	Long-lived shrubs			Short-lived shrubs			Grasses		
Parametric coefficients:	Estimate	SE	*t*-value	Estimate	SE	*t*-value	Estimate	SE	*t*-value
Intercept	-5.29	1.15	-4.61***	-6.03	5.33	-1.13	-6.56	2.09	-3.14**
Treatment: H	4.57	1.15	3.98***	NS	NS	NS	NS	NS	NS
M	4.53	1.16	3.92***	NS	NS	NS	NS	NS	NS
R	1.57	1.22	1.28	NS	NS	NS	NS	NS	NS
Smooth terms:	Edf	Ref. df	*F*	edf	Ref. df	*F*	edf	Ref. df	*F*
Age	NS	NS	NS	4.43	4.97	7.87***	1.33	1.43	24.20***
Bare soil (%)	7.26	8.09	3.60***	NS	NS	NS	8.23	8.78	4.67***
Branches (%)	3.12	3.80	5.13***	NS	NS	NS	5.03	6.07	3.30**
Litter/mulch (%)	5.80	6.72	4.02***	NS	NS	NS	NS	NS	NS
Rain, initial	1.77	2.07	20.46***	1.00	1.00	10.36**	7.90	7.98	4.91***
Rain, mean monthly	3.92	4.44	9.09***	NS	NS	NS	2.61	2.95	2.13
Slope	4.37	5.21	2.82*	6.48	6.81	4.20***	4.04	4.89	3.33**
Stones (%)	7.17	8.03	3.49***	1.00	1.00	17.22***	NS	NS	NS
Vegetation cover (%)	6.02	7.05	3.69***	8.67	8.94	5.97***	8.70	8.95	3.30***
	R^2=0.84			R^2=0.88			R^2=0.83		
	GCV=3.24			GCV=1.31			GCV=6.42		
	Deviance explained: 88.9%			Deviance explained: 74.8%			Deviance explained: 81.8%		

Significance: **p*<0.05, ***p*<0.01, ****p*<0.001

Table 4.2: Generalized linear models for the abundance of long-lived shrubs, short-lived shrubs and grasses, with age, percentage branches, litter and vegetation, rain (initial and mean monthly) and treatment (H = hollows, M = mulch/brush packing, R = ripping, as compared with reseeding only) as predictors. NS refers to predictor variables that were not significant in the model, and they were removed from their respective models.

	Long-lived shrubs			Short-lived shrubs			Grasses		
	Estimate	SE	*t*-value	Estimate	SE	*t*-value	Estimate	SE	*t*-value
Intercept	-0.57	0.21	-2.65**	-1.07	0.87	-1.24	4.24	0.46	9.16***
Age	NS	NS	NS	-0.10	0.03	-2.84**	-0.02	0.01	-2.48*
Branches (%)	-0.04	0.01	-5.81***	NS	NS	NS	NS	NS	NS
Litter/mulch (%)	-0.01	0.00	-3.00**	NS	NS	NS	NS	NS	NS
Rain, initial	-0.03	0.00	-7.71***	0.01	0.01	2.65**	-0.01	0.00	-4.44***
Rain, mean monthly	0.11	0.01	10.76***	NS	NS	NS	NS	NS	NS
Slope	-0.22	0.05	-4.49***	NS	NS	NS	NS	NS	NS
Treatment: H	4.99	1.71	2.93**	NS	NS	NS	0.16	0.40	0.40
M	5.50	1.71	3.21**	NS	NS	NS	-0.69	0.40	-1.74
R	0.80	1.77	0.45	NS	NS	NS	-1.00	0.43	-2.36*
Vegetation cover	NS	NS	NS	0.04	0.01	3.26**	NS	NS	NS
Model statistics	Dispersion parameter = 5.80			Dispersion parameter = 4.71			Dispersion parameter = 23.75		
	Null deviance = 3626.6 on 201 df			Null deviance = 390.89 on 115 df			Null deviance = 5021.1 on 212 df		
	Residual deviance = 956.32 on 193 df			Residual deviance = 278.35 on 112 df			Residual deviance = 3639.5 on 207 df		

Significance: **p*<0.05, ***p*<0.01, ****p*<0.001

Table 4.3: A comparison of establishment for species and growth forms reseeded at sites surveyed.

Species	Number of plots reseeded	Number of plots present	Percent present
All grasses	**358**	**177**	**49.44%**
Cenchrus ciliaris	88	51	57.95%
Cynodon dactylon	42	29	69.05%
Digitaria eriantha	20	4	40.00%
Eragrostis curvula	12	10	83.33%
Fingerhuthia africana	126	56	44.44%
Sporobolus iocladus	13	13	100.00%
Stipagrostis obtusa	57	10	17.54%
Lessertia spp.*	112	23	20.54%
All long-lived shrubs	**403**	**101**	**25.06%**
Eriocephalus ericoides	69	5	7.25%
Garuleum bipinnatum	19	8	42.11%
Osteospermum aghilliana	17	8	47.06%
Osteospermum sinuatum	85	40	47.05%
Pentzia incana	58	23	39.66%
Salsola calluna	38	8	21.05%
Tetragonia spicata	117	9	7.69%

*Three *Lessertia* species were recorded: *L. annularis*, *L. frutescens* and *L. microphylla*

4.5.3. AGE AS A DETERMINANT

Short-lived shrubs and grasses occurred in lower abundance on older sites than they did on younger sites. At sites surveyed for this study, this can be attributed to natural self-thinning due to intra- and inter-specific competition for resources (see Zhu *et al*. 2014) or drought (see Jürgens *et al*. 1999; Milton & Dean 2000). Kinyua *et al*. (2010) showed that vegetation cover decreased naturally over time, as individuals of reseeded species died (which also led to a decrease in abundance of reseeded species). Without subsequent reseeding, *Cenchrus ciliaris* remained the only significant contributor to percentage cover (of species sown) after a decade. Haase *et al*. (1997) found that intra-specific competition for water and other resources could explain self-thinning over time, which results in a decrease in numbers, but not necessarily in cover. My study, however, looked at the number of individuals of reseeded species rather than cover of reseeded species. This was done due to vegetation cover potentially being linked to growth of existing plants rather than plant establishment. It is therefore not an accurate measure of overall establishment (see Milton & Dean 2000).

4.5.4. LITTER, MULCH, SLOPE AND VEGETATION COVER AS DETERMINANTS

The difference in effect between mulch (positive) and percentage litter/mulch (negative) can be ascribed to the methodology implemented, because percentage litter and mulch were grouped for data collection and analysis. When I excluded cases with mulching as a treatment, a strong positive correlation was found between vegetation cover and the amount of litter present (r_s=0.538; p<0.001). It is likely that the higher abundance of plants (leading to increased litter production and therefore the higher litter abundance) resulted in higher mortalities of reseeded shrubs at seedling level, thereby explaining the negative trends observed. Many long-lived shrubs, such as *Osteospermum sinuatum*, can be viewed as climax or sub-climax species (Visser *et al*. 2004). Their reduced establishment in areas with high levels of interspecific competition thus ties in with Grubb's (1988) suggestion that intolerant species (such as these climax species) require disturbances to persist on regional scales. Milton and Dean (2000) found that a grass species, *Stipagrostis ciliata*, initially established better during wet years in plots where conspecifics were removed than in plots where no clearing of conspecifics occurred. It is likely that similar intra- and inter-specific competition governed the establishment of long-lived shrubs at sites surveyed with this study.

Although brush packing can aid protection of reseeded long-lived shrubs against large mammalian herbivores (see Flores & Jurado 2003), it also provides shelter for rodents. Seed predation by rodents can have a major impact on the availability of seeds for germination (Anderson & MacMahon 2001; Doust *et al*. 2008; Richardson & Kluge 2008), and this was likely the case at sites in this study.

Slope significantly affected only long-lived shrubs, their abundance decreasing with an increase in steepness. This could also relate to water availability: run-off could be higher on steep than on less steep slopes. Water availability would therefore be higher on flatter areas, favouring the establishment of long-lived shrubs there.

The higher abundance of short-lived reseeded shrubs in areas with higher existing vegetation cover could be due to the facilitative effect of existing vegetation. Maestre *et al*. (2001) reported higher establishment rates and survival of shrubs transplanted close to existing grass tussocks. Padilla and Pugnaire (2006) also discussed the occurrence of these so-called nurse plants, and the positive effects they have on seedlings establishing in a harsh environment.

4.5.5. OVERALL SUCCESS

Generally, establishment of all three growth forms appeared stochastic, similar to "boom or bust" situations, with most rehabilitation efforts having either successful or poor establishment of reseeded species. Apart from the factors investigated, temperature (coupled with rainfall) after reseeding could have a significant effect on the recruitment of reseeded species (Hoffman & Cowling 1987; Van Rooyen & De Villiers 2004). According to the findings op Chapter 2, temperature has a significant effect on three species commonly used in reseeding rehabilitation, namely *Fingerhuthia africana* (a grass), *Lessertia annularis* (a short-lived shrub) and *O. sinuatum* (a long-lived shrub).

Based on the findings of this chapter, the successful establishment of long-lived shrubs is more likely in an area with low initial rainfall, but with moderately high mean monthly rainfall over an extended period, and with hollows or mulching as soil preparation treatment. The establishment of the single genus of short-lived shrub investigated is more likely to be successful on sites with moderately high levels of vegetation cover remaining combined with high initial rainfall. Grasses establish better in areas with moderate to low rainfall, in conjunction with the implementation of simple reseeding or micro-catchments.

4.6. MANAGEMENT IMPLICATIONS

Though managers have control over certain aspects of rehabilitation, such as treatments used and sites selected, the overriding factor determining rehabilitation success appears to be rainfall – a factor beyond landowners' control. However, landowners can implement certain measures to increase the likelihood of rehabilitation success. Seeds can be sown during months with the highest likelihood of sufficient rainfall. In the Succulent Karoo, reseeding should take place at the end of autumn, whereas reseeding in the Nama Karoo should take place from mid-spring to early summer. Using hollows or mulching could increase the likelihood of reseeded long-lived shrubs establishing. Hollows trap water, windblown and water-transported seeds and nutrients, thereby creating favourable sites for establishment, whereas mulch act as seed traps and reduce evaporative losses of soil moisture. Landowners also have control over the selection of species for rehabilitation. Shrubs that established best were *Osteospermum sinuatum*, *Garuleum bipinnatum* and *Pentzia incana*, while the most successful grasses were *Eragrostis curvula*, *Cynodon dactylon*, *Cenchrus ciliaris* and *Fingerhuthia africana*. As the different plant growth forms responded differently to rainfall in the study, sowing seeds of a variety of growth forms could improve the likelihood of success. Landowners may also select sites to be rehabilitated based on the ease of their rehabilitation, with relatively flat areas having higher success in establishing long-lived shrubs, and areas with more existing vegetation leading to better establishment of short-lived shrubs.

4.7. CONCLUSION

Rainfall was the most significant factor influencing the establishment of all growth forms: areas that received low initial rainfall but high long-term rainfall favoured establishment of long-lived shrubs, whereas successful establishment of short-lived shrubs and grasses was greatest in areas that respectively experienced high and low initial rainfall. Establishment of long-lived shrubs was hindered by the abundance of litter and branches. Abundance of litter is associated with litter-producing vegetation already in an area, and these plants may outcompete seedlings of reseeded shrubs, thereby preventing their establishment. In order to establish long-lived shrubs, the use of hollows and mulching is recommended, while to establish grasses, simple reseeding or the use of hollows is advocated. It is likely that factors that were not studied, such as temperature or stochasticity of rainfall, could influence the success of reseeding rehabilitation projects.

Hand-dug hollows containing water two days after rainfall at a rehabilitated site near Oudtshoorn.

CHAPTER 5: SYNTHESIS AND CONCLUSION

5.1. SUMMARY OF MAJOR FINDINGS

Overstocking of rangelands, cultivation of marginal lands, mining of gravel and minerals and road construction have led to continued environmental degradation of the semi-arid Karoo ecosystem (Dean & Macdonald 1994; Milton & Dean 1995). Due to slow or non-existent autogenic recovery (Sampson 1986; Ogle & Redente 1988), active intervention through rehabilitation is required. The rehabilitation of degraded areas often consists of reseeding the area with palatable or climax species. Germination and seedling survival, however, is low in these semi-arid areas (Simons & Allsopp 2007), and soil preparation techniques such as the creation of micro-catchments, soil ripping, brush packing and mulching may be used to increase the likelihood of successful rehabilitation (Coetzee 2005; Esler *et al*. 2006). This study investigated how successful the establishment of reseeded species were under a variety of soil preparation techniques. I also investigated the significance of rainfall in determining establishment success, and the influence of temperature on germination and drought tolerance of species.

Rainfall was the factor that most significantly influenced the success of rehabilitation projects, as measured by the number of reseeded plants present at the sites surveyed. The *in situ* experiments showed that *O. sinuatum* had a higher germination and survival rate at De Denne, likely due to the higher rainfall experienced at that site. In the surveys done on farms where reseeding has been performed in the past, perennial shrubs performed best if they received a lower amount of rain directly after reseeding (probably because of the higher levels of competition from annuals when higher rainfall is experienced in an area), but higher mean monthly rainfall. High initial rainfall favoured establishment of pauciennial (short-lived) shrubs, while low to moderate rainfall favoured grasses.

Temperature also had a significant effect on the germination of *F. africana*, *L. annularis* and *O. sinuatum*. Overall germination rates were faster under moderate temperatures; however, *O. sinuatum* germinated fastest under summer temperatures, while *F. africana* germinated fastest under winter temperatures. Species showed a difference in drought tolerance, with *O. sinuatum* and *F. africana* being the most and least drought tolerant respectively. Although temperature has a significant influence on germination and survival of seedlings, rainfall may be an overriding factor.

The establishment of reseeded species also depended on the soil preparation method implemented. The creation of hollows proved effective at both experimental sites, and also improved establishment of long-lived shrubs at the sites visited for chapter 4. In the same surveys, the addition of mulch increased establishment of long-lived shrubs, but decreased establishment of grasses. The addition of mulch improved the establishment of *O. sinuatum* at Wolwekraal, where soil shrinkage cracks impacted negatively on the establishment of this species in plots where hollows were present and mulch absent. The addition of 2:3:2 fertiliser increased short-term growth rate of seedlings, but reduced survival of seedlings by up to eight per cent. A lower abundance of reseeded *O. sinuatum* was recorded in plots that had a high abundance of pioneer plants.

5.2. SIGNIFICANCE OF STUDY

Low success rates in many rehabilitation projects make understanding factors influencing the success of rehabilitation projects of paramount importance. Of the few studies on rehabilitation success undertaken in the Karoo ecosystem, most have focused on localised experiments, or have only investigated the effects of one or two factors on seedling establishment. Studies have rarely evaluated the relative significance of rainfall, soil preparation methods and environmental factors (such as vegetation, litter and stone cover) as determinants of rehabilitation success. My research has indicated clearly that rainfall is the main determinant of reseeding success, followed by temperature, soil preparation technique implemented, presence of mulch and litter, and the abundance of pioneer plants. My research thus supports the findings of Otto *et al*. (2006) and Burke (2014) that vegetation recovery is strongly linked to moderately high rainfall.

Chapter 4 indicated that certain species are excellent choices for reseeding, as they establish well under a variety of conditions. The shrubs with the highest establishment rates are *O. sinuatum, Garuleum bipinnatum* and *Pentzia incana*, while *Eragrostis curvula*, *Cynodon dactylon*, *Cenchrus ciliaris* and *F. africana* are the grass species that established best. The long-lived shrub and grass species (*O. sinuatum* and *F. africana*, respectively) tested for germination seasonality indicated that a seasonal preference exists. Contrary to what was expected, *O. sinuatum* germinated best under warmer temperatures, while *F. africana* germinated best under cooler temperatures.

My results also indicate that simply sowing seeds of preferred species will not necessarily result in successful establishment, as these seeds apparently require suitable microclimatic conditions to germinate and survive. Though expensive and time-consuming, the creation of micro-catchments is clearly an effective soil preparation technique, as many species established successfully in micro-catchments.

5.3. IMPLICATIONS FOR FUTURE REHABILITATION

Of the factors considered, rainfall and temperature had the most significant effect on germination of seeds sown, and both are beyond the control of landowners. However, landowners can respond by selecting the most ideal time for reseeding, and by implementing soil preparation methods that increase the likelihood of success. During years when adequate rainfall is expected, seeds in the predominantly summer-rainfall Nama Karoo should be sown during early spring, while in the Succulent Karoo (which is predominantly a winter-rainfall area), seeds should be sown during early autumn. Germination of *F. africana* was most successful under cooler temperatures, which could indicate that this species is adapted to germinate during mid-spring cold fronts, when cooler temperatures and longer day length coincide. Equally sowing *O. sinuatum* in mid-autumn may be optimal for germination success, as temperatures are still relatively warm and days long. The creation of micro-catchments to trap water during rainfall events could result in seedlings having access to higher levels of water for longer periods of time, aiding successful establishment. I therefore recommend that this soil preparation is implemented, especially in areas where rainfall is variable in amount and timing.

Since species belonging to the three growth forms investigated in chapter 4 responded differently to the various factors used in the models, it is advisable that landowners sow seeds of more than one growth form when rehabilitating degraded areas. Reseeding a combination of growth forms, although more expensive, would probably result in at least one of the growth forms establishing under the conditions experienced at the rehabilitation site. This would halt further degradation, providing landowners an opportunity to attempt further rehabilitation.

The fact that pioneer plants established well at both Wolwekraal and De Denne indicate the potential significance of employing pioneer species in rehabilitation. Instead of avoiding the intermediate steps of succession by reseeding only climax species, it might be advisable to establish pioneer plants prior to the re-introduction of climax species. Based on species that established well at experimental and surveyed plots without being reseeded, suitable pioneer plant species to use include *Lepidium africanum*, *Chenopodium mucronatum*, *C. murale* and *Oncosiphon* spp. Anderson *et al*. (2004) found *Cephalophyllum inaequale* suitable for the rehabilitation of degraded rangelands in Namaqualand, and similarly useful species can be used in other areas of the Karoo. These plants could improve soil conditions, allowing more successful colonisation by reseeded climax species (Marrs *et al*. 1982). Once pioneer plants have established and are maintaining themselves, climax species could be reseeded, especially if there are no mature specimens nearby to act as seed sources. Competition between pioneers and reseeded climax species could be an issue, and further research therefore has to be done on this aspect of rehabilitation (see section 5.5 for research possibilities).

5.4. LIMITATIONS OF THE STUDY

The main limitation of the study was the high variability of the data. In chapters 3 (experimental trials on effect of soil preparation on *O. sinuatum*) and 4 (chapter on the influence of soil preparation, rainfall and other environmental factors on the establishment of reseeded species), the standard deviations (and therefore the models' deviances) were very high. This was due to the use of count data, zero inflation and overdispersion, and was corrected by using quasipoisson errors in the GLM's.

In chapter 3, the number of treatment replicates could be a limitation. At both experimental sites, size of suitable sites was a limiting factor. Only six replicates could be set up at De Denne, and eight replicates at Wolwekraal. At Wolwekraal, an effort was made to reduce pseudoreplication by constructing plots on four separate bare patches, though this could not be done at De Denne. Though the plots at Wolwekraal were clustered at each of the four plots (potentially leading to potential spatial pseudoreplication), the treatments were randomly assigned to their respective places in each plot, in an attempt to reduce pseudoreplication. Temporal pseudoreplication is also a potential concern with chapter 3, and further analyses should focus on taking this into account.

In chapter 4, variability in the soil preparations implemented was a limitation: even in cases where the same treatment was used, the density at which the treatment was implemented often differed between sites. The models developed did not consider treatment density. I also did not investigate the effect of livestock and game exclusion from rehabilitated sites. At sites near Loxton (sites DED and LAP), where livestock and larger game were excluded, heavy utilisation by rodents (particularly springhare) was still observed. So too, at the Wolwekraal and De Denne experimental sites, utilisation of reseeded plants by small and medium-sized herbivores was extensive, and to exclude all herbivores would be an impossible task. This aspect was therefore not investigated with this study.

My study did not include the effects of rainfall stochasticity in the models developed. Instead, I used the total initial rainfall amount and mean monthly rainfall in my analyses. Since the stochasticity of rainfall in semi-arid areas complicates rehabilitation efforts, a measure of this variable should be incorporated in future models.

5.5. FUTURE RESEARCH POSSIBILITIES

A number of potential research topics could stem from this dissertation. A negative relationship between pioneer plants and *O. sinuatum* abundance was observed at the experimental sites, but the cause was not investigated. Future research could investigate whether this was due to pioneer plants outcompeting *O. sinuatum*, or whether soil conditions at rehabilitation sites simply favour pioneer plants rather than *O. sinuatum*. Removal of pioneer plants may have an effect, for instance by increasing the establishment of reseeded species, and could be investigated. Another potential project is to develop ways to increase and promote the rate of succession. For example, research on forest restoration has shown great success in using alien plantation trees to catalyse succession to native forests (Geldenhuys 1997; Parotta *et al*. 1997). Plantations can facilitate forest succession in their understories through modification of both physical (e.g. light, temperature, moisture) and biological (e.g. transport of seed by wildlife) site conditions. Pioneer plants in the Karoo may aid succession in the same way by altering site conditions or providing later successional species with protection from grazers, and further research can investigate whether this is indeed the case.

This study did not focus on the influence of faunal species on rehabilitation success. It is plausible that predation on seeds by granivorous rodents and herbivory by small herbivores (both invertebrate and mammalian) could have a negative impact on rehabilitation, while the addition of seeds by frugivorous birds may have a positive one. Further studies could also investigate the significance of seed predation by granivorous rodents (and ants), herbivory by rodents and insects, how to minimise these negative impacts (if significant), and how to maximise the potential positive effects of frugivorous birds.

The spiny exotic Russian tumbleweed (*Salsola kali*) protected *Osteospermum sinuatum* seedlings against herbivory at the De Denne experimental site, but the competition between these two species has not been studied.

CHAPTER 6: REFERENCES

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APPENDIX 1: CHARACTERISTICS OF SITES SURVEYED

Site	Latitude	Longitude	Mean annual rainfall (mm)	Biome present	Soil types present
ADT	S33.00766°	E21.65827°	200	Nama Karoo	Sand; clay
BEF	S33.29285°	E20.71443°	170	Nama Karoo	Sand; clay
CPT	S33.10568°	E22.45708°	180	Nama Karoo	Gravel; clay
DED	S31.95408°	E22.39623°	340	Nama Karoo	Clay
GLD	S33.60642°	E22.04847°	260	Succulent Karoo	Clay
GLH	S32.54636°	E20.23404°	75	Succulent Karoo	Clay
HYD	S30.71521°	E24.08087°	250	Nama Karoo	Clay
JSV	S32.89800°	E24.72885°	320	Nama Karoo	Sand; clay; silt
KAP	S33.10849°	E20.00633°	140	Succulent Karoo	Clay
KKW	S31.19837°	E19.69333°	180	Succulent Karoo	Gravel; sand; clay
LAP	S31.89589°	E22.32096°	340	Nama Karoo	Clay
PCB	S32.51540°	E25.17264°	360	Nama Karoo	Clay
RFT	S32.90065°	E22.35771°	210	Nama Karoo	Sand
SFT	S32.76629°	E24.26870°	420	Nama Karoo	Clay
TBF	S31.71067°	E22.63711°	340	Nama Karoo	Clay
TKT	S33.75769°	E22.10582°	260	Succulent Karoo	Clay
WBD	S33.56506°	E21.96514°	260	Succulent Karoo	Clay
WKP	S33.70592°	E22.09383°	260	Succulent Karoo	Clay
WKS	S31.99544°	E22.78597°	325	Nama Karoo	Silt

APPENDIX 2: SUMMARY OF LONG-LIVED SHRUBS SOWED AND ESTABLISHED AT THE VARIOUS SITES

Site	Age (months)	Rain during first 3 months (mm)	Mean monthly rainfall (mm/month)	Soil preparation	Number of plots	Species sown	Number of plots present	Total number observed	Mean number observed (per ha)
ADT: Survey 1	6	35.900	18.650	Hollows	7	*Garuleum bipinnatum*	4	32	1828.571
						Osteospermum aghilliana	4	18	1028.571
				Ripping	2	*Garuleum bipinnatum*	1	2	800.000
						Osteospermum aghilliana	1	1	400.000
				Seeding only	1	*Garuleum bipinnatum*	0	0	0.000
ADT: Survey 2	24	35.900	17.292	Hollows	6	*Garuleum bipinnatum*	2	11	2037.037
						Osteospermum aghilliana	3	9	3333.333
				Ripping	2	*Garuleum bipinnatum*	1	1	555.556
						Osteospermum aghilliana	0	0	0.000
				Seeding only	1	*Garuleum bipinnatum*	0	0	0.000
CPT	54	94.300	15.874	Seeding only	9	*Osteospermum sinuatum*	1	1	138.889
DED	11	162.000	30.055	Hollows	5	*Tetragonia spicata*	1	2	444.444

Site	Age (months)	Rain during first 3 months (mm)	Mean monthly rainfall (mm/month)	Soil preparation	Number of plots	Species sown	Number of plots present	Total number observed	Mean number observed (per ha)
GLD	39	116.200	21.944	Hollows	6	*Tetragonia spicata*	2	4	634.921
GLH	49	26.400	6.131	Hollows	19	*Eriocephalus ericoides*	0	0	0.000
						Tetragonia spicata	0	0	0.000
						Osteospermum sinuatum	19	256	5676.275
				Ripping	5	*Eriocephalus ericoides*	0	0	0.000
						Tetragonia spicata	0	0	0.000
						Osteospermum sinuatum	3	6	480.000
				Seeding only	7	*Eriocephalus ericoides*	0	0	0.000
						Tetragonia spicata	0	0	0.000
						Osteospermum sinuatum	1	1	57.143
JSV1	12	44.400	25.300	Mulch	3	*Pentzia incana*	3	72	26667.667
JSV2	13	44.400	27.831	Hollows	11	*Eriocephalus ericoides*	3	6	606.061
						Pentzia incana	11	365	36868.687
				Mulch	6	*Eriocephalus ericoides*	0	0	0.000
						Pentzia incana	6	156	28888.889
KAP	27	10.400	9.489	Ripping	7	*Osteospermum sinuatum*	2	3	416.667

Site	Age (months)	Rain during first 3 months (mm)	Mean monthly rainfall (mm/month)	Soil preparation	Number of plots	Species sown	Number of plots present	Total number observed	Mean number observed (per ha)
KKW	30	23.000	15.467	Hollows	7	*Tetragonia spicata*	0	0	0.000
						Osteospermum sinuatum	5	24	3037.975
				Mulch	5	*Tetragonia spicata*	0	0	0.000
						Osteospermum sinuatum	2	27	4426.230
				Ripping	3	*Tetragonia spicata*	0	0	0.000
						Osteospermum sinuatum	0	0	0.000
				Seeding only	5	*Tetragonia spicata*	0	0	0.000
						Osteospermum sinuatum	0	0	0.000
LAP	11	162.000	30.055	Hollows	8	*Tetragonia spicata*	1	1	138.889
PCB	39	44.100	30.154	Mulch	17	*Eriocephalus ericoides*	2	11	718.954
				Ripping	4	*Eriocephalus ericoides*	0	0	0.000
TBF:Survey 1	6	89.000	47.000	Ripping	26	*Pentzia incana*	3	4	164.609
						Salsola calluna	6	9	370.370
						Tetragonia spicata	1	1	41.152
TBF: Survey 2	13	89.000	28.685	Ripping	12	*Pentzia incana*	0	0	0.000
						Salsola calluna	2	2	106.383

Site	Age (months)	Rain during first 3 months (mm)	Mean monthly rainfall (mm/month)	Soil preparation	Number of plots	Species sown	Number of plots present	Total number observed	Mean number observed (per ha)
						Tetragonia spicata	0	0	0.000
WBD	40	116.200	22.750	Hollows	3	*Tetragonia spicata*	0	0	0.000
						Osteospermum sinuatum	1	2	740.741
				Mulch	6	*Tetragonia spicata*	4	7	1111.111
						Osteospermum sinuatum	1	2	740.741
WKP	39	116.200	21.944	Hollows	8	*Osteospermum sinuatum*	5	8	1111.111
				Mulch	1	*Osteospermum sinuatum*	0	0	0.000

APPENDIX 3: SUMMARY OF SHORT-LIVED SHRUBS SOWED AND ESTABLISHED AT THE VARIOUS SITES

Site	Age (months)	Rain during first 3 months (mm)	Mean monthly rainfall (mm/month)	Soil preparation	Number of plots	Species sown	Number of plots present	Total number observed	Mean number observed (per ha)
CPT	54	94.300	15.874	Seeding only	9	*Lessertia annularis*	0	0	0.000
HYD	9	166.100	20.778	Ripping	10	*Lessertia annularis*	5	34	3777.778
JSV: Survey 1	12	44.400	25.300	Mulch	3	*Lessertia annularis*	1	1	370.370
KAP	13	10.400	9.489	Ripping	7	*Lessertia annularis*	0	0	0.000
KKW	30	23.000	15.467	Hollows	1	*Lessertia annularis*	0	0	0.000
					7	*Lessertia frutescens*	3	12	1714.286
				Ripping	3	*Lessertia annularis*		0	0.000
				Mulch	1	*Lessertia annularis*	0	0	0.000
					4	*Lessertia frutescens*	1	1	277.778
LAP	11	162.000	30.055	Hollows	8	*Lessertia microphylla*	3	11	1527.778
TBF:Survey 1	6	89.000	47.000	Ripping	26	*Lessertia annularis*	7	26	1111.111
TBF: Survey 2	13	89.000	28.685	Ripping	12	*Lessertia annularis*	1	1	53.191

Site	Age (months)	Rain during first 3 months (mm)	Mean monthly rainfall (mm/month)	Soil preparation	Number of plots	Species sown	Number of plots present	Total number observed	Mean number observed (per ha)
WBD	40	116.200	22.750	Hollows	3	*Lessertia annularis*	1	1	370.370
				Mulch	6	*Lessertia annularis*	1	4	740.741
WKS	46	109.900	27.154	Ripping	12	*Lessertia annularis*	0	0	0.000

APPENDIX 4: SUMMARY OF GRASSES SOWED AND ESTABLISHED AMONG THE VARIOUS SITES

Site	Age (months)	Rain during first 3 months (mm)	Mean monthly rainfall (mm/month)	Soil preparation	Number of plots	Species sown	Number of plots present	Total number observed	Mean number observed (per ha)
ADT: Survey 1	6	35.9	18.65	Hollows	7	*Fingerhuthia africana*	7	392	22400.000
						Stipagrostis obtusa	3	28	1600.000
				Ripping	2	*Fingerhuthia africana*	2	139	10002.780
						Stipagrostis obtusa	1	3	600.000
				Seeding only	1	*Fingerhuthia africana*	1	48	19200.000
						Stipagrostis obtusa	1	10	4000.000
ADT: Survey 2	24	35.9	17.292	Hollows	6	*Fingerhuthia africana*	5	86	15925.926
						Stipagrostis obtusa	3	16	2962.963
				Ripping	2	*Fingerhuthia africana*	2	15	8333.333
						Stipagrostis obtusa	1	4	2222.222
				Seeding only	1	*Fingerhuthia africana*	1	2	2222.222
						Stipagrostis obtusa	1	10	1111.111

Site	Age (months)	Rain during first 3 months (mm)	Mean monthly rainfall (mm/month)	Soil preparation	Number of plots	Species sown	Number of plots present	Total number observed	Mean number observed (per ha)
BEF	17	33.500	13.847	Mulch	11	*Fingerhuthia africana*	6	52	5252.525
CPT	54	94.300	15.874	Seeding only	9	*Fingerhuthia africana*	0	0	0.000
DED	11	162.000	30.055	Hollows	5	*Sporobolus iocladus*	5	104	23111.111
GLD	39	116.200	21.944	Hollows	6	*Fingerhuthia africana*	6	46	8518.519
HYD	9	166.100	20.778	Ripping	10	*Fingerhuthia africana*	0	0	0.000
JSV: Survey 1	12	44.400	25.300	Mulch	3	*Cynodon dactylon*	2	29	10740.741
						Digitaria eriantha	0	0	0.000
JSV: Survey 2	13	44.400	27.831	Hollows	11	*Cenchrus ciliaris*	9	103	10404.040
						Cynodon dactylon	9	144	14545.455
						Digitaria eriantha	3	20	2020.202
				Mulch	6	*Cenchrus ciliaris*	0	0	0.000
						Cynodon dactylon	0	0	0.000
						Digitaria eriantha	5	29	5370.370
KAP	27	10.400	9.489	Ripping	7	*Fingerhuthia africana*	0	0	0.000
LAP	11	162.000	30.055	Hollows	8	*Sporobolus iocladus*	8	29	4027.778
PCB	39	44.100	30.154	Mulch	17	*Cenchrus ciliaris*	11	51	3333.333

Site	Age (months)	Rain during first 3 months (mm)	Mean monthly rainfall (mm/month)	Soil preparation	Number of plots	Species sown	Number of plots present	Total number observed	Mean number observed (per ha)
						Fingerhuthia africana	7	56	3660.131
				Ripped	4	*Cenchrus ciliaris*	0	0	0.000
						Fingerhuthia africana	0	0	0.000
RFT	10	44.900	20.490	Ripped	10	*Cenchrus ciliaris*	5	70	777.778
						Cynodon dactylon	6	39	4333.333
						Fingerhuthia africana	4	56	6222.222
SFT	39	44.100	34.974	Mulch	7	*Cenchrus ciliaris*	7	241	38253.968
				Seeding only	9	*Cenchrus ciliaris*	9	127	15679.012
TBF: Survey 1	6	89.000	47.000	Ripping	26	*Stipagrostis obtusa*	0	0	0.000
TBF: Survey 2	13	89.000	28.685	Ripping	12	*Stipagrostis obtusa*	0	0	0.000
TKT	5	83.800	30.880	Ripping	12	*Cenchrus ciliaris*	10	54	5000.000
						Cynodon dactylon	12	141	13055.556
						Fingerhuthia africana	4	19	1759.259
WKP	39	116.200	21.944	Hollows	8	*Fingerhuthia africana*	6	27	3750.000
				Mulch	1	*Fingerhuthia africana*	0	0	0.000
WKS	46	109.900	27.154	Ripping	12	*Cenchrus ciliaris*	0	0	0.000
						Eragrostis curvula	10	62	5740.741

Site	Age (months)	Rain during first 3 months (mm)	Mean monthly rainfall (mm/month)	Soil preparation	Number of plots	Species sown	Number of plots present	Total number observed	Mean number observed (per ha)
WKS	46	109.900	27.154	Ripping	12	*Fingerhuthia africana*	5	10	925.926

APPENDIX 5: LIST OF PERSONS INVOLVED WITH THE STUDY

Arnhols, Stanley (JSV)

Barnard, Hennie (SFT)

Brazendale, John (BEF)

Dean, Richard (WWK)

Haw, Rick (TBF)

Hugo, Stef (GLH)

Jonker, Saag (GLD; WKP)

Keller, Johan (DD)

Lovemore, Steve (WKS)

Marais, Frik (GLD; WKP)

Milton-Dean, Sue (WWK)

Nortje, Adriaan (CPT)

Potgieter, Joey (WBD)

Reitz, Philip (KAP)

Schabort, Botha (RFT)

Scholtz, Clarke (KKW)

Tanner, Angus (POC)

Venter, Piet (HYD)

Schumann, Bonnie (DED; LAP)

Walters, Wally (ADT)