Drought stress responses in wild and cultivated *Aspalathus linearis* of the Suid Bokkeveld, Northern Cape Province of South Africa: linkages between local knowledge and empirical evidence

by

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DECLARATION

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ABSTRACT

The north-western region of the Western Cape forms part of the Fynbos biome and is home to the indigenous plant, *A. linearis* (rooibos). Rooibos cultivation is restricted to a small geographic area with wild rooibos plants being more at risk as a result of climate change. This research contributes to a growing body of evidence of the impacts observed and experienced by small-scale farmers, by adding much-needed analysis of empirical data on rooibos under low precipitation conditions to the body of science. The overall aim of this study was to examine the physiological response, using xylem hydraulic conductivity, to drought stress of wild and cultivated *A. linearis* plants in the Suid Bokkeveld and to determine the effects of organic mulch on cultivated rooibos' susceptibility to xylem cavitation in response to drought stress. The information was used to compare farmer perceptions of rooibos drought responses and to spotlight the variations and similarities between the two information systems (scientific and local ecological knowledge) with the hope of providing guidelines for effective climate change adaptation strategies. *A. linearis* appears to respond to soil moisture gradients but showed little differences within sites according to the reseeder-resprouter dichotomy. On the other hand, the use of mulch did not have an impact on the cultivated rooibos' hydraulic characteristics. Cultivated (reseeding) and wild (resprouting) rooibos ecotypes may differ in terms of their physiology, however, when the effects of drought exceed levels of tolerance in the two ecotypes, according to responses from the questionnaire survey, both may exhibit similar strategies (branch sacrifice and red leaf discoloration) to cope with prolonged precipitation deficits. The quarterly climate change workshops have proven to be a helpful tool when it comes to incorporating local climate issues with that of seasonal forecasts and ultimately provides a platform for adapting new methods in addressing the impacts of drought and climate change. Results from the traditional scientific methods and the survey questionnaire on local knowledge show that there may exist important disparities between these two methodologies, however, each prove invaluable for understanding certain phenomena exhibited, in this case, by wild and cultivated rooibos ecotypes. Local knowledge should be used to emphasize problem areas and detect possible solutions whereas conventional scientific methodologies may often assist in converting potential problems into a broader range of appropriate hypothesis testing.

OPSOMMING

Die noordwestelike streek van die Wes-Kaap vorm deel van die Fynbos-bioom en is die tuiste van die inheemse plant, *A. linearis* (rooibos). Rooibos produksie is beperk tot 'n klein geografiese area en klimaatsverandering hou 'n bedreiging in vir veld rooibos plante. Hierdie navorsing dra by tot die toenemende bewyse rakende die impak wat deur kleinboere waargeneem en ervaar word, deur die noodsaaklike analise van empiriese data aangaande rooibos, onder droogte toestande, by die liggaam van wetenskap te voeg. Die algehele doel van hierdie studie is om die verskillende fisiologiese reaksies op droogtestres van veld en mak *A. linearis* plante in die Suid-Bokkeveld te ondersoek, deur die gebruik van xileem hidrouliese geleidingsvermoë, en om die effekte van organiese deklaag op die mak rooibos se vatbaarheid tot xileem “kavitasie” in respons tot droogtestres, vas te stel. Die inligting was gebruik om die persepsies van boere aangaande die respons van rooibos plante teenoor droogtestres te vergelyk en om die verskille en ooreenkomste tussen die twee kennisstelsels (Wetenskaplike en Plaaslike Ekologiese Kennis) met die hoop om riglyne te vir effektiewe aanpassingsstrategieë ten opsigte van klimaatsverandering te verskaf. Dit blyk dat *A. linearis* plante op grondvog gradiënte reageer, maar het min verskille binne elk van die studie plase, volgens die hersaaier-herspruiter-digotomie, getoon. Aan die ander kant het die deklaagbewerking geen impak op die hidrouliese eienskappe gehad nie. Die mak (hersaaier)-, en veld (herspruiter) rooibos-ekotipes mag verskil op grond van hul fisiologie, maar wanneer die uitwerking van droogte egter die toleransievlakke in die twee ekotipes oorskry, mag beide van hierdie ekotipes soortgelyke fisiologiese veranderinge ondergaan, naamlik die verlies van takke en rooi blaarverkleuring (volgens die antwoorde soos gelys in die vraelys opname) ten einde by te hou met verlengde neerslae. Die kwartaallikse werkswinkels rakende klimaatsverandering het bewys dat dit ‘n nuttige hulpmiddel is met betrekking tot die inkorporering van plaaslike klimaatkwessies met dié van seisoenale voorspellings en bied 'n platform vir die aanpassing van nuwe strategieë om die impak van droogte en klimaatsverandering beter te hanteer. Resultate van die tradisionele wetenskaplike metodes en die vraelys-opname oor plaaslike kennis, toon dat daar belangrike verskille tussen hierdie twee metodieke mag bestaan, maar elkeen blyk waardevol te wees ten einde sekere verskynsels te verstaan, in hierdie geval deur veld- en mak rooibos-ekotipes. Plaaslike kennis moet benut word om probleemareas te beklemtoon en moontlike oplossings op te spoor terwyl konvensionele wetenskaplike metodieke kan dikwels bystand bied ten einde potensiële probleme om te skakel in 'n wyer reeks toepaslike hipotese toetsing.

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1.1. Introduction

1.1.1. Global climate change and the risk it poses to the Cape Floristic Region (CFR)

Climate change and habitat degradation are two enduring threats to the Fynbos Biome (Midgley *et al.,* 2002; Latimer *et al.,* 2004). According to Klasmeyer & Shaw (2009), the Mediterranean region is expected to become drier and will diminish in size by up to 7.2% as a result of the loss in precipitation expected in the winter months, thus making the region susceptible to the adverse effects of climate change. Along with these projections, the rooibos production area is expected to show reduced mean annual precipitation levels of up to 15% and an increase in temperatures of up to 2°C between the years 2040-2060. The Western Cape is expected to receive less annual rainfall (Malherbe *et al.*, 2013), along with temperature increases of 5°C between 2080-2100 (Engelbrecht *et al.,* 2009). Increases in extreme events have been shown by many authors (Hewitson *et al.,* 2005; Hewitson & Crane, 2006), which may contribute to increased intensity and frequency of drought episodes. The region already receives low rainfall and with the increase in temperature of 4°C, together with even less rainfall, this could negatively affect the climate and hydrological system of the region.

Analysis of rainfall data from the Western Cape shows that over the years, very few statistically significant trends in annual precipitation became evident. According to Midgley et al. (2005), the projected future impacts of global climate change will result in the rainy season arriving much later in the western region of the CFR, whereas Hewiston et al. (2005) found the exact opposite; the rainy season arrived earlier from March-May, whereas June-August displayed a drying trend. These predictions for the CFR poses a risk to rooibos production as the much-needed precipitation, according to these predictions, will arrive much later. *Aspalathus linearis* ecotypes will have to endure water-deficient conditions for a longer period of time, which could influence rooibos yield.

The Fynbos biome faces many challenges (Skelton, 2014) including limited crop production due to environmental factors. Rooibos production has also declined in the past few years with farmers suffering losses as a result of the reduced harvest from the 2016/2017 harvest season (Nieuwoudt, 2017). *Aspalathus linearis* belongs to the Fabaceae family and forms symbiotic relationships with rhizobial bacteria and arbuscular mycorrhizal fungi (Staphorst & Strijdom, 1975; Dakora, 1998). This species is adapted and grows in nutrient-poor, extremely acidic (pH 3-5.3), well-drained soils derived from sandstone of the surrounding mountainous region (Muofhe & Dakora, 2000). Despite these harsh soil conditions, *A. linearis* in conjunction with its symbiotic partners, have managed to set up an effective N_2-fixing symbiosis which is tolerable of the acidic and low nutrient soils by fixing high levels of nitrogen (1.5.0-128.0 kg nitrogen fixed per ha^1 annually) (Muofhe & Dakora, 1999). The activity and establishment of the symbiotic Rhizobium legume are found to be highly sensitive to drought stress (Sprent, 1972; Kirda *et al.,* 1989) and therefore, the plant plays an important nitrogen-fixing and ecological role as a pioneer plant within the post-fire surroundings.

Plant species used for herbal teas, traditional medicine and tonics have received major recognition worldwide due to their health-promoting properties, and their subsequent commercial value (Street & Prinsloo, 2013). Compared to other biomes in South Africa, the Cape Floristic Region (CFR), with its high levels of plant species endemicity and diversity, has few plant species which are used for medicinal purposes (Goldblatt & Manning, 2000). The most economically notable medicinal plant in South Africa is the Fynbos legume *Aspalathus linearis* (Burm. F) Dahlg., which forms the basis for the international multi-million rand rooibos industry and is endemic to the CFR (Dahlgren, 1968). The natural habitat for *A. linearis* includes the Cedarberg of the Western Cape and also the southernmost reaches of the Northern Cape Province – areas prone to seasonal summer drought. The plants have long histories of use as herbal teas amongst the local communities who reside in these areas (Boris & Van Wyk, 2017). Wild rooibos is still harvested in by local land users, primarily as a bulk product for tea production for niche markets locally and abroad. However, with the turn of the century, *Aspalathus linearis* went from being a wild resource harvested for household use to a cultivated crop of global renown (Van der Bank *et al.,* 1995). “Rooibos tea” is a herbal drink that is created from the leaves and twigs of wild or cultivated plants and is commercially valued for its health and medicinal properties (Baba *et al.,* 2009; Kawano *et al.,* 2009). Many cultivation experiments abroad have been unsuccessful due to its specific soil and climate conditions (Wynberg, 2017). Additionally, rooibos is the only source of aspalathin; the antioxidant with its antimutation activity is instrumental in the prevention and treatment of cancer and enhances the uniqueness of this beverage (Joubert & Schulz, 2006).

The rooibos production area used to be restricted to the rocky areas of the Fynbos biome, however, more and more production has recently spread into the low-lying regions of the south and western parts of the CFR where previously rooibos was not found. The mountainous area of the Cederberg is a semi-arid environment, with low rainfall, high levels of evapotranspiration, poor nutrient soils and where agricultural activity is limited (Cowling *et al.,* 1997; Goldblatt & Manning, 2000). The Atlantic Ocean lies to the west, to the east lies the Cederberg mountains o whilst the town of Nieuwoudtville forms the region’s northern border and the Berg River its southern border (Figure 1.1). The area falls within the Mediterranean climate region of South Africa, which is characterized by dry summer months (December-February) and cold, wet winters (June-August). However, due to the area having high levels of topographical diversity, the annual rainfall here can be as low as 150 mm near the coast and 1000 mm over the Cederberg mountains; the region is known for being prone to periodic dry spells (Rouault & Richard, 2003). Mediterranean-type ecosystems, like the CFR, are more susceptible to the effects of climate change according to a report released by the IPPC (2013). The potential negative effects of climate change will not solely have an affect on biodiversity in the region but also many rural areas that are heavily reliant on rain-fed crops, including rooibos tea.

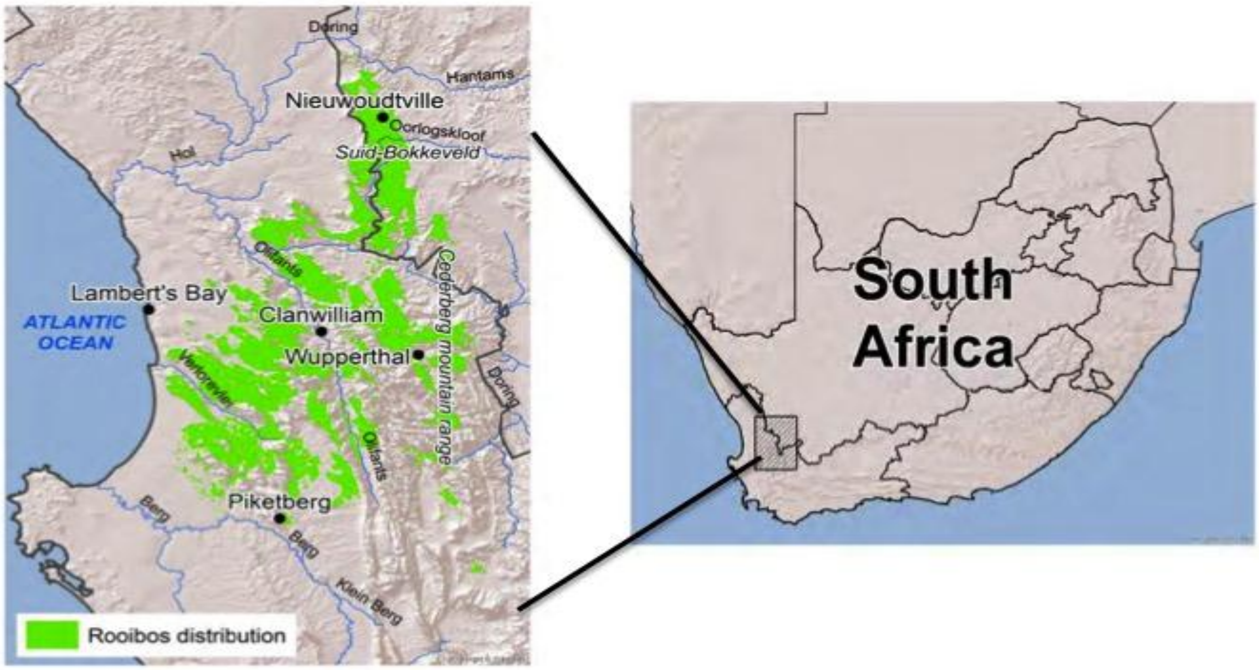

Figure 1.1-The northwestern part of the Western Cape showing the distribution of rooibos tea production (Lötter, 2015).

1.1.2. Influence of climate change on rooibos

The above-mentioned climate projections are very important as rooibos is a rain-fed crop and potential consequences will influence plant yield and performance. Local farmers knowledge was used by means of a participatory action research (PAR) approach to observe and record climate conditions and its effects on rooibos (Archer *et al.,* 2008). Findings of this study showed that late arrival of winter rainfall, increased occurrences of drought episodes and heat stress may decrease yield and overall quality of rooibos. This has prompted more investigation into climate scenarios in order to estimate the risk of surpassing important plant physiological boundaries under future climate predictions.

Gérard (2010) found that rooibos has rigorous habitat prerequisites and its distribution is principally driven by abiotic factors and especially, access to water. Because climate exerts a high degree of control over species distribution, Pearson & Dawson (2003) found that climate change may influence the geographic range of many species. Species that are endemic to a small range and limited ecological requirements are highly threatened by climate change and anthropogenic disturbances (Midgley *et al.,* 2003). The wild ecotype of *A. linearis* occurs in a slim geographic range and is limited to the Cederberg Mountain range at altitudes between 450 and 1000 meters above sea level. Distribution changes of species is unavoidable if the surrounding temperature and rainfall in a region shifts in such a way that it is far greater than a species' evolutionary adaptation potential and has already been seen where certain species have shifted their geographic distribution in response to recent warming (Hickling *et al.,* 2006; Chen *et al.,* 2011).

Environmental variables and species location information is used to identify species' niches and chart their respective geographic ranges i.e. species distribution model (SDM). The use of SDM in conjunction with climate scenarios can produce important information concerning future changes in the climate regime. According to SDM's, the dry and hot conditions experienced in the CFR will result in a reduction in the Fynbos biome of up to 65% (Midgley *et al.,* 2002). Many species belonging to the Proteaceae family will be forced to move into new novel environments in order to survive. The Department of Environmental Affairs released a report in 2013 that shows areas which are likely to undergo the most change include the northern and eastern regions of the Fynbos biome with these areas changing into Albany Thicket or Succulent Karoo. Due to some rooibos production being within the boundaries of the Fynbos and Succulent Karoo biomes in the north-eastern parts, the findings of the report may be of significance with regard to rooibos production and distribution. The work done by Lötter & Maitre (2014) found that should valuable rooibos production areas shrink in size, according to the species distribution model, it remains uncertain whether or not farmers will migrate to areas where *A.linearis* has colonized novel sites. This could result in additional pressure being placed on rooibos population harvesting and may promote the subsequent decrease of the species.

Confidence in the above-mentioned models can be gained by combining SDM's with experimental field studies. In order to obtain a thorough understanding of the plant's physiological response, one needs to look at both distribution models and experimental work which will enable better predictions for this endemic species to acclimatize to future climate change predictions.

1.2. Cultural and economic importance of rooibos tea

1.2.1. Cultural importance

Rooibos tea has been consumed for many generations, starting with the Khoi-San people who were herders in the Cederberg region since 1200 AD (Mountain, 2003) and was used as medicinal plants during the 17th and 18th centuries. There are a few literature studies, which suggests that local Khoi-San inhabitants often used the plant to attend to ailments during the 17-18th centuries. During the earlier 20th century, rooibos was documented as a South African remedial plant, however, no evidence of specific uses was presented in this study (Watt & Breyer-Brandwijk, 1932). This indicates that the utilization of rooibos as traditional medicine has long formed a part of South African traditional knowledge, whereas anecdotic confirmation of its medicative characteristics has become widespread since the late 1960's.

The current production of rooibos is primarily founded on the established methodology formulated by native inhabitants over many years. One such tradition is the collection of seeds by hand, which local inhabitants often take pride in. Even though commercial seed accumulation has become more advanced, the traditional gathering of seeds by hand is viewed as a pleasing act of labor and present the local community with a supplementary supply of financial gain (Leclercq *et al.,* 2009).

Today there are approximately 1000 Suid-Bokkeveld inhabitants comprising mostly of white and colored people, who are directly or indirectly involved in sustaining rooibos production and harvesting. Black African people are rarely seen in the community unless their work obligations bring them to the area i.e. road construction and seasonal farm workers. Despite living in a democratic country where many changes have occurred, colored farm workers still form the bulk of the labor on white-owned farms in the region (Koelle & Oettlé, 2003; Louw, 2006).

Limited funding, poor grades and the long distance that exist in order to get to a reputable tertiary institution, keep many scholars from continuing their education after leaving high school. Employment in Nieuwudtville, one of the larger towns in the region, remains limited to clerical work on local farms and businesses despite government's effort to promote employment amongst women and particularly the youth. Within the colored community, many of the small-scale rooibos farmers work for approximately six months on their own farm, i.e. working their land and harvesting their own tea, whilst spending the remainder of the year as laborers elsewhere (Oettlé, 2002).

1.2.2. Economic importance

Sheep, goat and tea production form the backbone of agricultural activities in the Nieuwoudtville area (Koelle *et al.*, 2003). Agricultural income is very low in the area and many residents are reliant on state child support grants and pensions. The nearest bank is 40 km away in the town of Nieuwoudtville, therefore the majority of transactions are done by bargaining goods amongst neighbors and family (Oettlé, 2002).

There exist many challenges for small-scale farmers wanting to earn a living, including poor infrastructure, bad roads, and limited market access. Since 1994, conditions have improved, however, these improvements have been very slow and still makes it difficult to sustain livelihoods. One of the biggest constraints on the development of small-scale farmers is the lack of available land in the Suid-Bokkeveld (Arendse & Oettlé, 2001).

Today there are approximately 550 rooibos tea farmers in South Africa, producing 12 000 tonnes of rooibos tea each year. It is a booming industry with both local and international export markets, of which Germany is the main export destination. The industry provides many employment opportunities to people from rural areas, as it is a labor-intensive process. This gives rise to the growing interest in rooibos production since most of the commodity is obtained from small-scale farmers in and around Nieuwoudtville (Nel *et al.,* 2007). Due to past racial inequalities, difficulties in getting access to land and low agriculture potential, the area has been economically marginalized. With scare and limited resources, these farmers are defenseless against the effects of climate change due to the delay in information getting to them. With the formation of the Heiveld cooperative, local farmers were able to have more bargaining power when it came to the prices of their produce, have access to information, and to share capital (Heiveld, 2008). The Heiveld cooperative uses production methods where local ecologcial knowledge has steadfastly been rooted in the cultivation and the processing of rooibos tea. The local ecologcial knowledge may also provide potential rooibos adaptation and management strategies within the face of a ever-changing climate.

1.3. Species ecology and natural distribution of *Aspalathus linearis*

Aspalathus linearis is one of 279 species belonging to the *Aspalathus* genus (Fabaceae, Tribe Crotalirieae) (Dahlgren, 1968). Van Heerden et al. (2003) described seven ecotypes of rooibos based on their chemical and morphological differences. Not only do they differ in terms of chemical composition and morphology, but also fire survival strategies, vegetative and generative morphology and flavonoid composition (Van der Bank *et al.,* 1995; Van der Bank *et al.,* 1999; Van Heerden *et al.,* 2003; Malgas *et al.,* 2010). *Aspalathus linearis* exhibits both seeder and sprouter life histories with ecotypes presenting either as reseeders or resprouters at the level of the population (Van der Bank *et al.,* 1999). Fire is a trigger mechanism which stimulates germination for both life histories i.e. seeders and sprouters (Brown *et al.,* 1993). In the post-fire environment, sprouters are able to survive and regrow by making use of soil-stored tubers whilst seeders can only regrow by making use of its seeds stored in the soil. Domination of seeder plant species in the Fynbos (Le Maitre & Midgley, 1992) is ascribed to the consistent rain received during the winter months (Ojeda, 1998; Midgley & Bond, 2001; Ojeda *et al.*, 2005. *Aspalathus linearis* resprouters in the wild have been reported by harvesters to be slower growing, less prolific at seed production, and more resistant to pests (Louw, 2006; Patrickson *et al.*, 2008).This is necessary and pertinent to this study because the regeneration technique could help in determining the degree to which proposed climate change will affect rooibos.

In the wild, *A. linearis* seeds form a mutualistic relationship with ants whereby seeds provide a food source for ants and the ants, in turn, disperse the seeds. After a fire and the first winter rains, the hard-shelled seeds start germinating. This process is simulated with seeds used for commercial purposes as they require smoke treatment, acid or manual scarification to soften or disrupt the seedcoat , and so, facilitate germination (Kelly & Van Staden, 1985). In cultivated environments, rooibos seedbeds are prepared during the late stages of summer i.e. February and March. This is the only stage of the rain-fed crop's lifecycle that seeds receive additional water. Seedlings tend to reach an average height of 10-20cm and during winter (June-August) and are replanted in cultivated fields; it is during these early life-stages that plants are particularly defenceless to harsh environmental conditions (Harper, 1977; Kitajima & Fenner, 2000) and within the Mediterranean region, seedling mortality is at its highest during the initial dry season of the plants' life cycle. Thus, adequate winter and spring precipitation is important in ensuring early seedling establishment in winter; this will increase the plant's survival of its first drought period (Richard & Lamont, 1996). Louw (2006) has shown that certain wild rooibos ecotypes ought be harvested only every 2nd year as they are relatively slow-growing plants.

A plant's ability to tolerate periodic drought has often been linked to the species vulnerability to xylem cavitation (Tyree & Zimmerman, 2002; Edwards & Diaz, 2006). Evidence suggests that there's a trade-off between hydraulic efficacy and cavitation resistance such that those plant species' who have larger vessels are prone to cavitation than those individuals with fuller walls and less lumen regions (Pockman & Sperry, 2000). According to Tyree & Sperry (1989), the method through which vulnerability to xylem cavitation influences the plant's ecological functioning is that it limits long-distance water transport. In essence, cavitation refers to the severity of water-stress that a particular plant can endure in any particular habitat.

1.4. Mitigation and adaptation

The literature highlights two approaches for managing the negative impacts that are expected to arise as a direct result of climate change: mitigation and adaptation strategies. The definition of "mitigation" is any activity that aid in the prevention or minimizes climate change. In accordance with Swart et al. (2003), mitigation tactics may be categorized into two groups: several delineates primarily scientific solutions; others include changes in the financial structures, organization of society or individual demeanor. Adaptation is those tactics used to empower individuals or a local community to deal and adapt to the effects of climate change in their local region(s). These tactics involve the better environmental resource management e.g. planting crops that mature early, planting hardier plant crops and specific livestock selection in areas where rainfall patterns are erratic or scarce. Adaptation tactics may also use technology, which will allow communities to operate in the "new" surroundings (Nyong *et al.*, 2007).

Before, adaptation and mitigation were considered as mutually exclusive tactics. Even so, there are sound connections between these tactics and today, it is accepted that the integration of these tactics may be an essential component for effectively approaching both issues. Klein et al. (2005) found that the integration of mitigation and adaptation strategies could provide assist in resource governance and management, conservation efforts and combating desertification. These two tactics should not just be about implementation possibilities; the success of implementation is also dependent on the accessibility of different resources to develop a setting permitting mitigation and adaptation, along with the necessary ability to adjust (Klein *et al*., 2003). The major obstacles to incorporating mitigation and adaptation in developing countries are because of poverty and restricted technical abilities, particularly in Africa (Michaelowa, 2001; Yohe, 2001; Wilbanks *et al.*, 2003).

1.5. Local Ecological Knowledge (LEK)

The challenges associated with global climate change have necessitated ecosystem management and its guiding policies to be directed by the most relevant knowledge systems available. Our knowledge of social and earth systems and their interactions can largely be attributed to knowledge generated in the fields of bio-physical and social sciences. Gaps in scientific knowledge, however, still lead to significant challenges in finding working solutions for ecosystem deterioration as a result of the current changes in climatic variables (Finucane, 2009). As such, indigenous (or traditional) knowledge is becoming particularly sought after as an important tool for climate change adaptation. The positive contributions of indigenous knowledge can be seen in various ecologically-inclined fields such as biodiversity conservation, agroforestry,sustainable development, applied anthropology, traditional medicine and natural resource management. Indigenous knowledge is thus likely to play an ever-increasing role in climate-related ecological studies and, when fully embraced, may greatly facilitate climate change adaptation strategies at various scales.

Local ecological knowledge (LEK) is a category of indigenous knowledge that can be defined as “a body of knowledge, belief, and practice, developed by means of adaptative processes and passed along from generation to generation”; this knowledge usually includes information on the connection amongst living organisms (humans included) and its environment (Berkes, 1999). LEK is often an important part of the local indigenous culture and environment and often encompasses management strategies, which are area appropriate. LEK may incorporate various descriptions or perceptions by the local community (Menzies & Butler, 2006). The latter may be able to provide various generational observations of a natural resource phenomenon.

There exist similarities and variations between science and LEK (Berkes, 1999; Ingold, 2000). The latest and increasing interest in LEK, from both academics and scientists, has produced a symbiotic relationship that promotes the combination of the two methodologies via dialogue (Alberts, 2001; Fox, 2003; Brewster, 2004). Even though the integration of LEKs with scientific evidence for the management of environmental resources is still new, nowadays there exist advantageous possibilities for scientific and local communities to join forces, particularly, when it comes to climate change.

Since the inception of the first international conference on desertification was held in 1977, science has played an important part in denoting land degradation along with responding to the problem of desertification and its extent (Corell, 1999). Techniques used to detect, evaluate and monitor land degradation include satellite remote sensing, ecological evaluation, soil property measurements, professional opinions and scientific discussions (Perkins & Thomas, 1993; Hill *et al.*, 1995; Klintenberg & Seely, 2004; Chasek *et al.*, 2011; Blaikie & Brookfield, 2015). Nevertheless, scientific methods can often be flawed and may not always afford a precise prognosis or resolution (Thomas & Middleton, 1994; Fairhead & Leach, 1996;

Wessels *et al.*, 2007; Vogt *et al.*, 2011). The earliest illustration of land degradation monitoring came from the work of Lamprey (1975) who deduced that the Sahara desert was growing approximately 5.5 km/y; this was done by using a single indicator i.e. desert margins. However, Hellden's (1988) remote sensing studies found erratic rainfall patterns may influence desert margins and therefore, science alone cannot be used to monitor land degradation over time. If Lamprey had done scientific research in conjunction with the participatory investigation, local knowledge may have been able to point out links amongst erratic rainfall patterns and desert margins, which may have been neglected.

Since then, a change has taken place whereby many scientists have recognized that even the most superior scientific methods have its limits (Forsyth, 2003). According to the United Nations Convention to Combat Desertification, local rangeland communities are increasingly recognized as holding a tremendous amount of knowledge, from which science could benefit e.g. indigenous ways of identifying, managing and adapting to land degradation (Reij & Waters-Bayer, 2001).

Information from both scientific methods and local ecological knowledge should be integrated to harness knowledge from between and within science and indigenous knowledge; this will allow local communities to recognize their capabilities to better oversee and respond adequately to land degradation challenges (Stringer & Reed, 2007). The combined "knowledge" (Forsyth, 1996; Nygren, 1999) ought to be used by scientists and local stakeholders to generate better decisions regarding policy-making (Robbins *et al.*, 2002). The co-operation of both these methodologies could reduce conflicts between and amongst environmental management concerns and commercial and ecological values (Daniels & Walker, 1996). However, there still does not exist an approach, agreed on by all, to integrate local and scientific knowledge (Abelson *et al.*, 2003), let alone the incorporation of different opinions into policies and effective land management (Folke *et al.*, 2002; Dougill *et al.*, 2006). This approach is advocated for by many academics, however, there are a meager number of studies using this approach (Thomas & Twyman, 2004) and the necessary tools, which will allow integration, are often limited. Therefore, there is a need for researchers to examine and improve participatory action, which can assist in decision-making by various stakeholders.

1.6. Climate change: incorporating local knowledge with mitigation and adaptation tactics

The African Sahel is one example where local ecological knowledge has been incorporated with scientific evidence to reduce carbon emissions, carbon sequestration, and substitution. In the Sahel, local ecological knowledge has been used as an adaptation strategy through its application to weather predictions, assessing region vulnerability and the carrying out of adaptation strategies.

Farmers in the Sahel are known for conserving carbon in the soil by making use of no-tilling in cultivation, organic mulch (Chapter 2 of this thesis will further discuss the use of mulch as a water stress management technique in rooibos) and many other soil management tactics (Osunade, 1994; Takimoto *et al.*, 2008; Takimoto *et al*., 2009). The work of Archer et al. (2008) better explains the use of local management techniques by rooibos farmers in the Suid Bokkeveld to adapt to a changing climate. Using organic mulch moderates the temperature of the soil controls the outbreak of pests and conserves moisture. Before chemical composting methods, farmers were highly dependent on organic farming; the latter may be used to reduce greenhouse gas emissions as few or even no chemical fertilizers are used, hence chemical fertilizer production may be reduced resulting in less greenhouse gas emissions (Brown *et al*., 2004; Burkhard *et al.*, 2009).

Biodiversity conservation, which may be used as a mitigation strategy, is heavily dependent on local ecological knowledge. The World Bank has established gene banks to conserve genetic information of endemic species. The stored genetic information and their accompanying cultivation practices could be beneficial e.g. breeding programs could result in plants becoming more resistant to pests and diseases or be able to endure harsher climate conditions (McCouch *et al.*, 2013). However, this initiative does possess the disadvantage in that the plant's genetic make-up is stored and preserved devoid of information of their husbandry; this may present the complication of seeds reserved in seed banks not possessing the necessary information on how to cultivate and grow the seeds (Briggs, 2005). Therefore, it is of paramount importance that gene banks should work in collaboration with local farmers and communities, who grow local varieties of these plants; this will allow the preservation of vital knowledge and skills in situ.

Based on farmer's inherent knowledge on managing climate risk, preserving water and soil and biodiversity conservation, farmers initiated extended adaptation strategies following the dry spell period of 2005 in the Suid Bokkeveld. Strategies included the planting of windbreaks (this prevents tea loss because of strong winds) utilizing indigenous vegetation planted at an angle in the direction of the predominant wind (Archer *et al.*, 2008). To promote water conservation, alien vegetation was removed. Wind erosion deterrence was produced by farmers i.e. retaining indigenous plant strips in-between stands of cultivated rooibos tea. However, to date, scientific evidence in the form of rooibos' physiological response to the imminent effects of climate change and local climate adaptation strategies has not yet been incorporated; incorporation of these two systems will provide farmers with a better understanding of what is actually happening "inside" the plant and this may provide answers as to rooibos' morphological response to drought stress. One adaptation strategy, currently used by local rooibos farmers, is the addition of organic mulch to stands of cultivated rooibos tea to prevent increased soil moisture loss when precipitation levels are very low. The reasoning behind the trials is to determine whether or not organic mulch may aid cultivated rooibos to retain more moisture during the drier parts of the year and if in so doing, promote growth and produce adequate yields even with reduced rainfall. The testing of mulching techniques as a possible adaptation to drought stress has already been implemented in the Suid Bokkeveld rooibos region. This strategy was also recommended by the Western Cape government to the agricultural community at large as a potential climate change mitigation strategy (Western Cape Climate Strategy, 2014). This strategy is one of many to be implemented by Western Cape government in the face of a changing climate.

1.7. The role of mulching: possible adaptation strategy

The Western Cape Province is characterized by a service-based economy however; the province's coastal vulnerability is seen as a major threat to coastal properties, tourism and infrastructure. The Western Cape's agricultural is responsible for approximately 60% of South

Africa's agricultural exports and contributes up to 20% of the country's agricultural production. Soil conservation techniques are increasingly practiced in the Western Cape, particularly agricultural regions such as the Cederberg, Ceres and the surrounding winelands. A report by Western Cape government (Western Cape Climate Strategy, 2004) suggest that local farmers conserve carbon in soils through the employment of no tilling practices in agricultural cultivation, as seen in the Suid Bokkeveld, organic mulching and other soil management strategies.

Organic mulches mitigate soil temperatures and control diseases and malignant pests. One of these management techniques, the use of mulch, is presently being used by rooibos farmers to conserve much-needed soil moisture in the arid and drought-prone Suid Bokkeveld.

One of the biggest advantages of using mulching as a farming practice is the preservation of soil moisture (Mulumba & Lal, 2008). Apart from tillage, research has found that soil moisture was greatly amplified after using maize mulch in loamy soils (Sharma *et al.*, 1990). One of the biggest agricultural problems in the Mediterranean region is soil erosion which is attributed to the arid conditions and concentration of rainfall (Lal, 1999; Western Cape Climate Strategy, 2014). The soil particles found in cultivated soils are highly susceptible to becoming detached and being swept away by erosive agents and this, in turn, leads to soil loss **(**Boardman, 1990**)**.

One of the key factors influencing soil quality in semiarid regions is soil organic matter. Unlike many other land uses, soil which has been cultivated tend to have very low levels of soil organic matter (Masciandaro *et al.*, 1998). The reduced level of organic matter can attributed to the continued intensive use of land over many years, which evidently lead to soil quality being greatly reduced (Reicosky *et al.*, 1995). According to Celiki (1987), cultivated soils in the Mediterranean region exhibit satiated hydraulic conductivities which are much lower than that of forest soils. He found that soils are more predisposed to erosion due to cultivation practices degrading soil physical properties. However, soil quality and productivity of cultivated soil can be greatly improved through the addition of crop residues which has been shown to have a positive effect on soil characteristics (Lal & Stewart, 1995; Mulumba & Lal, 2008). With the addition of crop residue mulch, soil organic matter content of cultivated soils tend to increase (Duiker & Lal, 1999; Saroa & Lal, 2003). The use of “no tilling” can very often be seen in a significant amount of crop residue on the soil surface, this, in turn, leads to higher organic matter, improved chemical and physical fertility along with better soil erosion control (Mulumba & Lal, 2008).

1.8. Xylem cavitation vulnerability

The Mediterranean region is characterized by hot summers with very little precipitation; this could affect the plant’s ability to access adequate water since there remains so very little in their natural environment (Ladjal *et al.*, 2005). During a drought period, water is transported at a much slower rate and this results in the increase of water tension in the xylem and thus increases the likelihood of embolism formation and system malfunction (Crombie *et al.*, 1985; Sobrado, 1997). Some plants may exhibit changes in hydraulic traits when experiencing drought conditions and this enables them to sustain a positive water balance (Tyree & Ewers, 1991). According to Hacke et al. (2000), an increase in stem conductivity (K_s) can be positively related to an increase in leaf specific conductivity (K_1) when soil experiences prolonged drying. The soil-to-leaf pressure gradient is greatly reduced when K_1 is increased (Tyree & Ewers, 1991; Mencuccini & Grace, 1995), resulting in in the risk of xylem embolism being reduced. Studies show that in several plant species there exist a relationship between xylem vulnerability and habitat preference (Brodribb & Hill, 1999; Tissier *et al.*, 2004). The resilient response of stem hydraulic conductivity and vascular tissue vulnerability to prolonged drought conditions are not often understood, particularly in rooibos.

Another trait plants exhibit during drought periods is the synchronisation of the closing of the stomata and reduced hydraulic conductivity. Several studies show that there are many plant species where stomatal closure is correlated with a significant loss in leaf hydraulic conductivity (Cochard, 2002; Nardini *et al.*, 2003). This ensures that species with reduced susceptibility to the formation of xylem embolisms, the assimilation of CO_2 is preserved for as long as possible during a drought period (Tyree & Sperry, 1988). However, plant species experiencing stable water supply and early stomatal closure provides greater protection against the formation of embolisms (Pockman & Sperry, 2000). A plant's safety margin (P_{50} – minimum stem water potential) can be used to determine whether or not a plant is operating near its threshold value and ultimately determine susceptibility to xylem embolism formation. If the safety margin < stem water potential then the plant is less likely to form embolisms. Should the safety margin > stem water potential, the plant is operating above its threshold value and therefore xylem embolism is more likely to occur.

Using a plants' vulnerability to cavitation in conjunction with the plants' water stress levels can often be used to measure drought tolerance in plant species (Pockman & Sperry, 2000; Mahareli *et al.*, 2004). Cavitation tends to occur when the xylem pressure in the stem is so low that it causes the adhesion capillary forces to be overwhelmed, allowing air into the vessel, forming an embolism and consequently, blocking the transport of water (Jarbeau *et al.*, 1995; Hacke & Sperry, 2001). Research has shown that xylem vessels with thick walls and less lumen show greater resistance to cavitation, however, increasing xylem wall areas, at the cost of the lumen, may result in a decline in xylem conducting areas (Pockman & Sperry, 2000).

1.9. Problem statement

A. linearis is endemic to the Cederberg fynbos region and is harvested and produced from the leaves and shoots of wild and cultivated rooibos. The biggest threats to both wild and cultivated rooibos tea is the predicted effect of climate change. Many of the small-scale farmers in the Suid Bokkeveld are financially dependent on their rooibos crop and any change in climate, with adverse effects, may hamper production and ultimately influence livelihoods. Hydraulic dysfunction has been used to determine whether or not plant species are susceptible to cavitation and which plant or tree species experience difficulties in transporting water (Pammenter & Vander Willigen, 1998; Skelton, 2014). This is very important as restrictions on water movement could lead to the plant not receiving adequate amounts of water and could eventually lead to the plants' death. However, hydraulic dysfunction has not yet been tested in rooibos tea and results from this study will enable researchers to determine the cavitation susceptibility of both wild and cultivated rooibos. Land-users receive premium prices for small quantities of wild-harvested biomass supplied to niche overseas markets in the organic and fair-trade sectors. Land-users thus have a vested interest in ensuring the well-being of plants in the wild. These plants are also known to deliver ecosystem services through root adaptation and nutrient cycling capacities (Hawkins *et al.*, 2009; Muofhe & Dakora, 2000). This research will determine which of the two, wild or cultivated, is more prone to cavitation and ultimately determine the one most likely to perish first. This knowledge is cardinal for the sustainable management and production of wild-harvested *A. linearis* plants.

1.10. Study aims

The overall aim of this study is to investigate the different physiological responses, by means of xylem hydraulic conductivity, to drought stress of cultivated reseeder and wild resprouter *A. linearis* plants in the Suid Bokkeveld and compare this information to farmer perceptions of drought stress responses. Along with the aforementioned aim, this study will be used to determine if the use of scientific methodologies and local ecological knowledge can lead to drought adaptation strategies of *A. linearis* species in the Suid Bokkeveld. Secondary to this, the aim of this study is to establish if the use of organic mulch can be used to reduce water loss under drought conditions.

1.11. Study objectives

Within this overall aim, the objectives of the research are to:

i. Investigate local farmers' perception regarding drought stress and climate change.

ii. Examine various physiological adaptation strategies in cultivated (reseeder) and wild (resprouter) *A. linearis* to drought stress.

iii. Establish whether there is a link between farmers perception on drought stress and the physiological responses of *A. linearis*.

iv. Establish whether there is a link between mulching techniques and cavitation risk in cultivated (reseeder) *A. linearis*

The general approach used to achieve the above-mentioned objectives was, firstly, to conduct interviews with local farmers in the Suid Bokkeveld with regards to their perception of recent drought periods (2003 – 2006) and (2015 – 2016) and their views on climate change. In order to investigate the physiological differences between the wild and cultivated rooibos tea, the researcher made use of both field and laboratory experimentation. Field experimentation involved measuring the water potential of wild and cultivated rooibos at various sites along a north-south rainfall gradient (350mm – 100mm) at different times of the day, whilst laboratory experimentation involved sampling of both wild and cultivated rooibos in order to measure their respective xylem hydraulic traits and if they show signs of xylem cavitation. Mulching techniques were used at the four different sites in order to determine the cavitation risk of cultivated rooibos plants.

1.12. Key Questions

1. What are the physiological effects of drought stress on wild and cultivated rooibos in the Suid Bokkeveld?

2. What are the perceptions of local rooibos farmers of the effect of drought stress on wild and cultivated rooibos?

3. How do farmer perceptions and empirical data contribute to local adaptation strategies?

4. Does management intervention (mulching) affect cavitation risk in cultivated *A. linearis* plants?

1.13. Expected outcomes

The expected outcome is that the wild *A. linearis* ecotype will show greater resistance to xylem cavitation than the cultivated ecotype. A second expected outcome is that the use of mulch, as drought adaptation strategy, will reduce the risk of xylem cavitation and the formation of embolisms in cultivated *A. linearis* ecotypes. We also expect that the use of both scientific methodologies and local ecological knowledge may lead to better drought adaptation strategies in the Suid Bokkeveld.

1.14. Outline of thesis

Chapter 1 exhibits a literature review centered on climate change model predictions for the Cape Floristic Region and the potential adverse effects it may have on the Fynbos biome, and then rooibos in particular. The literature includes a descriptive and historical background of rooibos and rooibos tea cultivation, local ecological knowledge about the species, and the value of LEK and science in addressing risks of climate change to wild and cultivated rooibos. Chapter 2 focuses on rooibos' response (both wild and cultivated ecotypes) to drought stress and its vulnerability to xylem embolism formation by means of hydraulic conductivity experiments and the use of organic mulch as a potential drought adaptation management technique. Chapter 3 explores, by means of a survey questionnaire, local rooibos farmers perceptions of rooibos' response to drought stress and climate change. the perceptions of the local rooibos tea farmers. Questions included, which ecotype responds first to drought stress, the way the latter responds to drought stress and perceived reasons for the current erratic weather patterns in the Suid Bokkeveld. In chapter 4, comparisons are drawn between the perceptions of local rooibos farmers about drought response in rooibos, and empirical data from field experiments to test the species vulnerability to cavitation. Results from the two knowledge sources are correlated to present-day trends in research and theory and are applied to topical questions about rooibos production and cultivation in the face of a changing climate. Incorporating local knowledge into climate change adaptation strategies for the Fynbos biome and rooibos production may prove invaluable in informing future research directions and continued sustainability of one of South Africa's most prized Fynbos species.

1.15. 1.15. References

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Chapter 2

Drought-tolerance traits of cultivated and wild *Aspalathus linearis* and the use of organic mulch as a possible drought adaptation technique in the Suid Bokkeveld, South Africa

2.1. Introduction

One of the leading causes for concern in agriculture today is global climate change and the accompanying threat it poses for agricultural production. According to a report published by the IPCC (2007), climate change is alleged to be one of the foremost threats facing the Earth's ecosystem. Future climate change projections show an increase in mean temperature and areas experiencing seasonal droughts are expected to become arider; rainfall patterns are also expected to become more variable and erratic (IPCC, 2014).

The Cape Floristic Region is world-renowned for its plant biodiversity and is regarded as a biodiversity hotspot, based on its high levels of plant endemism and species richness endemism. The most distinctive vegetation type in the CFR is Fynbos, which stretches for 200 km along the coast from Clanwilliam in the west, all the way to Port Elizabeth in the east (Low & Rebelo, 1996; Ojeda *et al.*, 2001). According to climate modeling projections (Midgley *et al*., 2003; Hannah *et al.*, 2005), the Fynbos biome is apt to be heavily impacted by climate change and the expected changes may have severe impacts on plant species in this biome (Rutherford *et al.*, 1999). Climate projections for the western part of the Fynbos biome include drier conditions and increase rainfall intensity (Engelbrecht *et al.*, 2008). Due to the expected drier conditions, the Fynbos biome will likely lose large areas of its natural vegetation in the northern parts of the biome. In the next 50 years (Botes *et al.*, 2006), the Fynbos biome will likely be substituted with different, unidentified vegetation types (Midgley *et al*., 2002).

The Mediterranean region of South Africa is home to the endemic *Aspalathus linearis* (rooibos) (Dahlgren, 1968; Hawkins *et al.*, 2011). This shrub is well-adapted to deep, oligotrophic, acidic, well-drained soil (Muofhe & Dakora, 2000). Survival of this shrub, after the onset of a fire, is either done by re-seeding or re-sprouting (Van der Bank *et al.*, 1999), and the species has been subdivided into a number of ecotypes, among others, differing in regeneration strategy (some are resprouters and some re-seeders) (Hawkins *et al.*, 2011). The species as a whole plays a crucial role as a pioneer species by fixing nitrogen (N_2) in its surrounding ecosystem (Cocks & Stock, 1997). This fynbos shrub has both medicinal and economic value and contributes considerably to the heritage of various human communities; today, it is one of South Africa's chief indigenous commercially cultivated crops (Hawkins *et al.*, 2011). Farming of this native shrub is limited to a very small area with a distinct micro-climate and cultivation efforts elsewhere in the country and abroad has to date been unsuccessful. Both wild and cultivated rooibos relies on annual rainfall, rather than manual irrigation; water deficits experienced in the summer season **(**Boyer, 1982**)** may lead to reduced plant performance and yield.

The prevalence of frequent and intense periodic drought in the area where this study was conducted, had significant repercussions for the production of various crops where farmers have raised concerns regarding annual winter rains arriving later in the season as well as ongoing heat stress, which have caused a reduction in rooibos yield and quality (Archer *et al.*, 2008). Species distribution modeling done by Lötter & Le Maitre (2014), suggest possible grave consequences due to range shifts of *A. linearis* under a changing climate. Under the the A2 emissions projection suggested by Nakicenovic et al. (2000), global climate change models suggest that of suitable land for the cultivation of rooibos tea, up to 57% may be gone as a direct result of climate change. According to the distribution model, suitable land for the farming of cultivated rooibos tea is limited by rains received during winter, while winter and summer temperatures restrict areas which are climatically suitable for crop production.

The Mediterranean climate is characterized by lengthy summer droughts, ultimately affecting the transport of water in plant species (Daget, 1977). Increased water tension in the xylem during drought results from transpiration and loss of water (Crombie *et al.*, 1985) and increases the risk of embolism (also called cavitation) and malfunction of the conducting system (Sperry & Tyree, 1988). By changing their hydraulic traits to sustain a positive water balance (Tyree & Ewers, 1991), plants are able to respond adequately to seasonal drought. Cavitation occurs when the root xylem water pressure decreases so much that the capillary forces, which is essential for the xylem water to adhere to wall of the vessel, are disrupted. Air is then allowed into the column resulting in the formation of an embolism, which limits water transportation (Jarbeau *et al.*, 1995; Hacke & Sperry, 2001). Research shows that the walls of xylem vessels which are more compact and contains a reduced lumen area, have more resistance to cavitation. However, a lower lumen to wall ratio could result in the xylem conducting area becoming smaller (Pockman & Sperry, 2000; Hacke *et al*., 2001; Hacke & Sperry, 2001). Slower-growing species tend to have higher resistance to embolism, and faster growth may come with the trade-off of higher sensitivity to drought. Therefore, resistance to cavitation may aid in determining the amount of water-stress a plant can tolerate in a particular habitat. The combination of vulnerability to cavitation, along with measuring the plants' water stress levels in the field, may thus be beneficial when determining plants' tolerance to drought stress (Pockman & Sperry, 2000; Mahareli *et al.*, 2004).

Several methods have been suggested to counter the worst ramifications of climate change-induced drought, and among the most widely touted is mulching and assisted ground cover techniques. The use of mulch in the Mediterranean region is not widespread (Western Cape Climate Change Response Strategy, 2014), especially when it comes to the rooibos tea production areas. The use of organic mulch in agriculture has been approved and recommended by the Western Cape government as a potential drought adaptation strategy. According to a report published by the Western Cape government (Western Cape Climate Change Response Strategy, 2014), the use of organic mulch could reduce soil surface water evaporation especially in drought-prone regions such as the Suid Bokkeveld. Cultivated soils which are not tilled tend to show high levels of mulching residue left behind on the surface of the soil and this has favorable effects on SOM, physical properties and chemical fertility of the soil as well as showing resistance to soil erosion (Mulumba & Lal, 2008). According to Mulumba & Lal (2008), the effect that crop residue will have on SOM is positively correlated to the amount of residue applied and to a lesser extent the type of crop residue used. One of the significant benefits of employing mulch on crop farming is its ability to conserve soil water (Mulumba & Lal, 2008). The addition of maize mulch to loamy soils often results in soil moisture being greatly increased (Sharma *et al.*, 1990). Given the potential for altered soil moisture regimes in plants subjected to mulching treatments, such plants may show adaptation of their hydraulic traits and ability to withstand drought.

In this study, the relationship between water-stress-induced xylem cavitation resistance in two rooibos ecotypes was investigated. To date, little is understood concerning the vulnerability of *A. linearis* to xylem cavitation and the effects of organic mulching on rooibos' susceptibility to xylem cavitation. The overarching aim of this study was to examine the physiological response, using xylem hydraulic conductivity, to drought stress of wild and cultivated *A. linearis* plants in the Suid Bokkeveld and to determine the effects of organic mulch on cultivated rooibos' susceptibility to xylem cavitation under drought conditions. Vulnerability to cavitation was examined in two ecotypes of *A. linearis*: one cultivated and one wild rooibos ecotype growing in the same landscape on three different farms in the Suid Bokkeveld; the wild ecotype is a re-seeder whereas the cultivated ecotype is a resprouter. Due to proven hydraulic variations amongst fynbos reseeders and resprouters (Pratt *et al*., 2012) and other similar ecosystems (Pratt *et al.*, 2008; Pivovaroff *et al.*, 2016), as well as more generally (Zeppel *et al.,* 2014), we theorized that the two ecotypes would show differences in their resistance to cavitation. The cultivated rooibos ecotype is fast-growing and produces a higher yield but is more susceptible to pests and less drought tolerant than the wild ecotype (Environmental Monitoring Group, 2017). Therefore, we expect the wild ecotype to show greater resistance to xylem cavitation across the three potential farm sites and may maintain lower midday water potentials than that of the cultivated ecotype. Furthermore, we expected the mulched plants to show less resistance to cavitation as it can be expected that these plants will have greater access to water. Results will potentially enable rooibos farmers to improve their approaches for coping with drought stress and reducing the loss of rooibos production in the face of a changing climate.

2.2. Methods

2.2.1. Study site

Three study sites (Table 2.1) were identified according to the age of the cultivated rooibos populations. Melkkraal, a 1,300-ha farm, is home to 30 households who farm with sheep and rooibos tea and is situated 20 km outside Nieuwoudtville in the Northern Cape. Melkkraal (780 m above sea level) receives approximately 350-380 mm rainfall per annum. The 2750 ha Blomfontein farm is situated on the Bokkeveld escarpment, 45 km south of Nieuwoudtville. It receives good rains (>300 mm), being at a relatively high altitude (740 m) area. The farms Landskloof and Matarakopje are situated a further 25 km from Blomfontein at an altitude of 470 m and 480 m, respectively, above sea level. These farms are the aridest of the three study sites receiving less than 150 mm per annum. For the mulching trial results, cultivated rooibos used for experimental purposes originated from Melkkraal, Blomfontein and Matarakopje farm.

Table 2.1- Geographical and climatology information of the sites used in the study. Three study sites were used for each part of the study, but only two were common.

SITE	GPS CO-ORDINATES	ALTITUDE (M)	AVERAGE RAINFALL (MM/Y)	STUDY USED FOR
MELKKRAAL	31.379435° S, 19.217834° E	780	380	Xylem embolism sensitivity and organic mulch study.
BLOMFONTEIN	31.73700° S, 19.13594° E	740	300	Xylem embolism sensitivity and organic mulch study.
LANDSKLOOF	31.86021° S, 19.08089° E	470	150	Xylem embolism sensitivity and organic mulch study.
MATARAKOPJE	31.94056° S, 19.1123° E	480	150	Organic mulch study.

At Melkkraal, Landskloof and Matarakopje farm, soils retain less water and tend to be deep and sandy. However, cultivated rooibos plantations at Melkkraal are planted quite close to a river running through the low-lying areas of the farm and these plants may have access to underground water sources, which cultivated rooibos plants at Landskloof and Matarakopje may not have. The soil surface area at Blomfontein is characterized by a layer of weathered shale. Both ecotypes, cultivated (Figure 2.1) and wild (Figure 2.2) of rooibos can be found at each of the four farming sites. The cultivated rooibos stands used in this study were all three-year-old populations, whilst the wild populations varied between 7-10 years (except

Landskloof). The Fynbos biome is a fire prone-area, especially during the hot summer season (Hope *et al.,* 2012; van Wilgen *et al.,* 2012). The farm of Landskloof experienced a veld fire in 2013 and destroyed much of the wild rooibos populations on the farm. Hence, the wild rooibos sampled on Landskloof was 3 years old, whereas the wild rooibos sampled on Melkkraal and Blomfontein farm were 7 years or older.

Figure 2.1. Cultivated rooibos, Suid Bokkeveld, Northern Cape (Rafferty, 2016).

Figure 2.2. Wild rooibos ecotype, Suid Bokkeveld, Northern Cape (Rafferty, 2016).

2.2.2. Sampling

Resistance to cavitation was evaluated in wild and cultivated *A. linearis* ecotypes at each of the three farms in the Suid Bokkeveld. This resistance to xylem cavitation was also examined in cultivated *A. linearis* rooibos where the organic mulch was applied by farmers and these results were then compared with vulnerability to cavitation in cultivated rooibos stands without the addition of mulch. The use of mulch was suggested by members of the Heiveld Co-op as a possible drought adaptation technique. Farmers were concerned with the ongoing drought and the possible effect lack of precipitation could have on cultivated rooibos yield. At the

Heiveld's quarterly climate change workshop during 2015-2016, farmers decided to use organic mulch as protection against excess water evaporation. In so doing, what little rainfall the region may receive, the mulch layer will soak up more moisture and provide much-needed water during the hottest part of the day.

For the vulnerability to cavitation experiment, five stems were randomly sampled from each ecotype per farm, giving a total of ten samples per farm. For determination of both pre-dawn and midday stem water potential, five stems were sampled from each ecotype per farm; this was done for both pre-dawn and midday sampling giving a total of twenty samples per farm; these sample sizes were repeated for the mulching trial analyses as well. Criteria for sample selection was based on the conditions that the plants were healthy and growing actively. The small-scale rooibos farmers, residing at the three study sites, are dependent on revenue received per ton for their harvested rooibos and therefore a smaller sample size was opted for so as not to influence their income.

Three different mulching treatments were applied during this experiment. Melkkraal farm saw the addition of wheat straw mulch (Figure 2.3) applied on cultivated rooibos tea stands. The straw mulch was applied in such a way as to form a thick layer on top of the soil; there was no specific quantity added to the soil. Blomfontein farm (Figure 2.4) employed compost and manure, along with dried twigs and branches, as its mulching treatment; here, the compost was worked into the soil and formed part of the top layer of the soil. Wood chippings and shavings were applied to the selected cultivated rooibos stand on Matarakopje farm (Figure 2.5). The experimental plot sizes were 2 m x 3 m and were duplicated three times conforming to the randomized block design; the control treatment had a smaller plot size of 1 m x 2 m. Manual weeding was used to remove weeds when necessary. At the time of the sampling, the mulching experiment had been ongoing for 6-7 months.

Figure 2.3. Wheat straw mulch treatment used on Melkkraal's experimental plot (Rafferty, 2017).

Figure 2.4. Organic compost and dried twigs form part of the mulch heap at Blomfontein farm (Rafferty, 2017).

Figure 2.5. Woody shavings forming the experimental mulch on Matarakopje farm (Rafferty, 2017).

2.2.3. Stem water potential (Ψ_x)

During summer, the xylem water potential of stems was measured (November 2016-May 2017). Pre-dawn stem water potentials (Ψ_{PD}) were measured between 04h30-05h30 at each of the farm sites between November 2016 and May 2017 (n = 5 samples per ecotype); water potential measurements were obtained by making use of a PMS Model 600 Pressure Chamber Instrument (PMS Instrument, Oregon, USA). The stem of the plant was used to determine pre-dawn and midday water potential, and each sampled stem was cut with a sharp blade. The above-mentioned experiment was repeated between 12h00-13h00 to measure midday water potential (Ψ_{MD}) for each ecotype at the three farms; the plant individuals used for water potential measurements were also used to obtain vulnerability to cavitation measurements and in so doing, produce vulnerability curves. Because there are three sites, three days were set aside for Ψ measurements; one day per farm. Ψ_{PD} and Ψ_{MD} measurements were taken from the same individual rooibos shrub (both wild and cultivated) and for the mulching trials, using both control and treatment at each sampling period. Sealable bags were used, throughout the measurement process, to store samples and reduce water loss during measurement.

2.2.4. Vulnerability to embolism

For each of the measurements, five to eight samples of each ecotype were selected; these samples were collected at the same rooibos shrubs where samples were collected for Ψ_x measurements. Each sample was cut at the base of the shrub and the latter was cut again whilst submerged in water. Once the re-cutting took place under water, handling of the plant sample continued underwater. Each of the five stems was exactly 21 cm in length.

A cylindrical pressure chamber was used to insert the stems, which had an orifice at the end on both sides. The chamber, containing the stem, was then tightly sealed whilst the ends of the stem protruded 15 mm at each end of the chamber. A weak solution of $CaCl_2$ is pushed through the stem for 2 minutes; this will give the hydraulic conductance lost at zero pressure. The initial conductivity measurement (K_h) was made, as explained above, at a pressure of 0.05 MPa; this prohibits the escape of H_20 (water) via the stems. The conductivity measured at 0.05 MPa also gives us the value for maximum conductivity (K_{hmax}). Once the initial conductivity measurements were obtained, samples were subsequently exposed to an increase in air pressure (i.e. 10 MPa). After samples were subjected to each increase in pressure for approximately 10 minutes the pressure was discharged for 2 minutes whilst the $CaCl_2$ moved through the stem; hydraulic conductivity was then calculated in accordance to a pressure of 0.05 MPa. The aforementioned procedure was also repeated for the cultivated rooibos used in the mulching trials. Percent loss in hydraulic conductivity (PLC) was computed as:

$$\mathbf{PLC}_{\boldsymbol{i}} = 100\ (1- \frac{\boldsymbol{K_{hi}}}{\boldsymbol{K_{hmax}}})$$

where PLC_i refers to the loss of conductivity percentage at a set pressure *i*, K_{hmax} is highest conductivity reached at 0.05 MPa and K_{hi} refers to conductivity calculated at a set pressure, *i.*

2.2.5. Safety margins

Calculating a plant's safety margin can often be used to determine whether or not a plant is operating near its threshold value (P_{50}) and may ultimately determine susceptibility to xylem embolism formation under field conditions (Nardini *et al.,* 2014). The safety margin was computed as the difference between average P_{50} and the average midday water potential for each group (the cultivated group and the wild group for each farm) and for each mulching treatment and for each farm.

2.2.6. Statistical analyses

Data ware tested for normality and homogeneity of variance, ($P < 0.05$) (Statistica Release 8, StaSoft Inc); data was found to be normally distributed. A factorial ANOVA was applied to determine if there were significant interactions for the pre-dawn and midday water potential results across the three farms. The Fisher LSD posthoc test for means separations was utilized to test for significant differences. Three different mulch material combinations were used for each of the three farms, therefore, a t-test was used to establish differences within each site (pre-dawn and midday) and ecotype.

2.3. Results

2.3.1. Wild vs. cultivated

For the wild ecotype, P_{50} values ranged from -1.31 to -6.52 MPa; the cultivated ecotypes P_{50} values ranged from -1.46 to -4.56 MPa. The mean P_{50} values for the wild and cultivated ecotypes did not differ significantly ($F_{2,2} = 10.41$, $P > 0.05$). However, overall, Landskloof showed the lowest average P_{50} value (-4.20 MPa), which was significantly lower than at the two other farms (Table 2.2).

At Melkkraal and Blomfontein the wild ecotype reached P_{50} earlier (less negative pressure) and was not significantly different ($P = 0.10$) compared to Landskloof, which reached P_{50} at -4.71 MPa and differed significantly from both Melkkraal ($P = 0.02$) and Blomfontein's ($P = 0.00$) wild ecotype (Table 2.2). The cultivated ecotype of Blomfontein and Landskloof reached P_{50} at -2.93 MPa and -3.58 MPa respectively; Melkkraal's cultivated ecotype reached P_{50} at only -2.63 MPa. In the case of Melkkraal and Blomfontein's cultivated ecotype, there were no significant differences ($P = 0.60$). There were no significant differences between Landskloof's and Melkkraal's cultivated ecotype ($P = 0.18$) as well as no significant difference between

Blomfontein's and Landskloof's cultivated ecotype ($P = 0.13$). Only Blomfontein farm had significant differences between the wild and cultivated ecotype ($P < 0.05$). There were no significant differences between the wild ecotypes ($P > 0.05$) across sites, however, Melkkraal ($P = 0.02$) and Blomfontein's ($P < 0.05$) wild ecotype differed significantly from Landskloof farm.

Table 2.2. Mean values for P_{50} across ecotypes. Values are in MPa, and standard deviations are displayed in brackets (n=5). A factorial ANOVA was carried out to compare the wild and cultivated ecotypes across sites. Small letters denote significant differences within sites, whereas capital letters indicate significant differences across sites (P < 0.05).

SITE	ALL DATA	WILD ECOTYPE	CULTIVATED ECOTYPE
MELKKRAAL	-2.65 (±0.94)^{A}	-2.68 (±0.95)^{A}	-2.63 (±1.07)
BLOMFONTEIN	-2.29 (±0.75)^{A}	-1.65 (±0.44)^{Aa}	-2.93 (±0.15)^{b}
LANDSKLOOF	-4.20 (±1.05)^{B}	-4.70 (±1.09)^{B}	-3.58 (±0.65)

Figures 2.6 and 2.7 show the average water potential measured at pre-dawn (Ψ_{PD}) and midday (Ψ_{MD}), respectively, of the wild and cultivated ecotypes between and across farms.

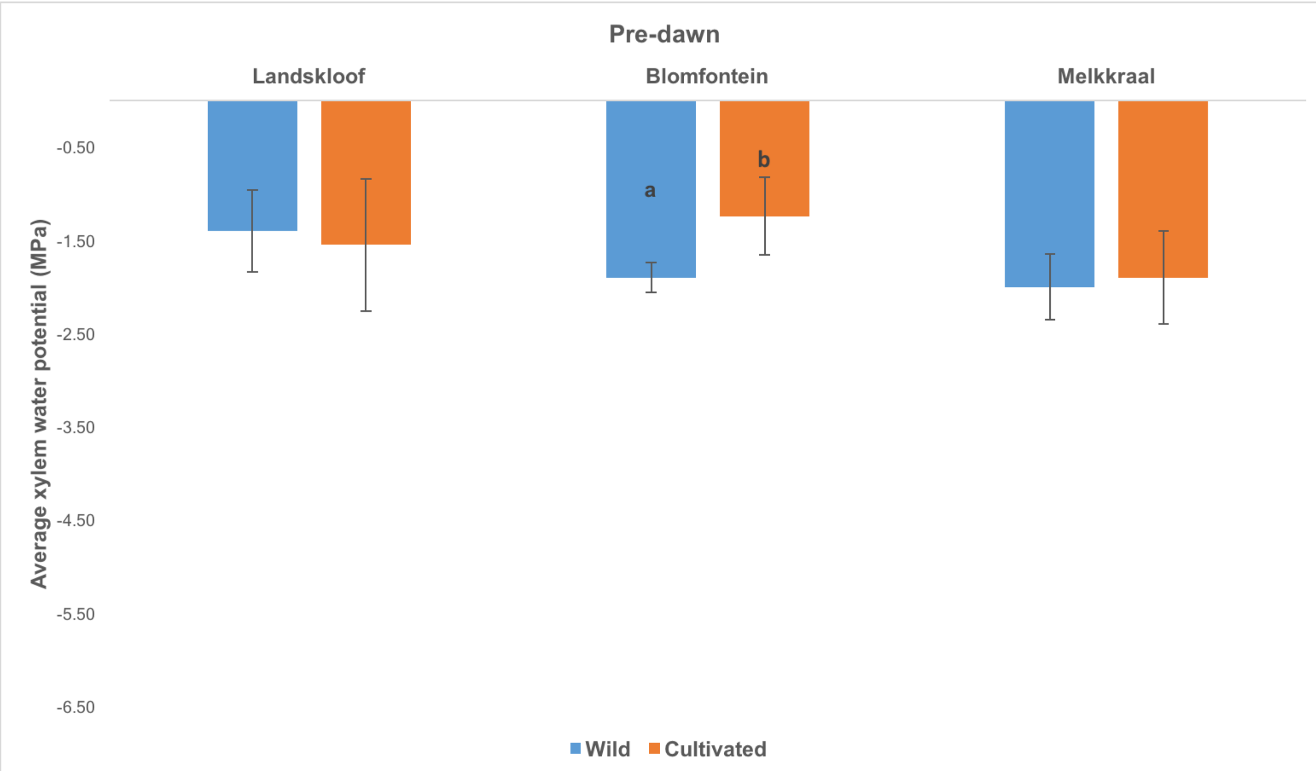

Figure 2.6. Water potential measured at pre-dawn (Ψ_{PD}) for all farms. Bars represent ± one standard deviation of the mean (n=5). Small letters denote significant differences within sites, whereas capital letters indicate significant differences across sites ($P < 0.05$); there were significant differences within and across sites.

Melkkraal farm (Figure 2.6) showed the lowest mean Ψ_{PD} for both wild and cultivated ecotypes, approximately -2.00 and -1.90 MPa respectively. However, there were no significant differences between the wild and cultivated ecotypes on Melkkraal farm ($P = 1.00$). The cultivated and wild ecotype sampled at Landskloof had an average Ψ_{PD} of -1.55 MPa and -1.40 MPa respectively, and again, no significant difference was observed. Blomfontein's cultivated ecotype had the highest average Ψ_{PD} of -1.24 MPa whereas the wild ecotype had a Ψ_{PD} of -1.90 MPa ($P = 0.01$). The wild ecotype sampled at Melkkraal ($P = 0.08$) and Blomfontein had the lowest Ψ of all the wild ecotypes sampled at pre-dawn; Blomfontein's wild ecotype differed significantly from Blomfontein's cultivated ecotype ($P = 0.01$). A two-way

ANOVA revealed no significant differences for average Ψ_{PD} among farms and between wild and cultivated ($F_{2,2}$ = 1.47, $P > 0.05$).

Midday Ψ ranged from -1.50 to -5.90 MPa and were lower than the Ψ_{PD} in all cases. At midday (Figure 2.7), the wild and cultivated ecotype sampled at Landskloof showed the highest Ψ_{MD} of all three farms; approximately -3.30 MPa and -1.90 MPa respectively.

Average midday water potential values of ecotypes measured at Blomfontein were not that far apart; the wild ecotype had an average Ψ_{MD} of -4.18 MPa and the cultivated ecotype had an average Ψ_{MD} of -3.28 MPa. Melkkraal's wild ecotype had the lowest Ψ_{MD} (-4.54 MPa) out of all three farms. A factorial ANOVA for average Ψ_{MD} measured at midday (regardless of ecotype) across all three farms was not significant ($F_{2,2}$ = 2.12, $P > 0.05$). There was, however, a significant difference between the means of the wild and cultivated ecotype sampled at Landskloof (P = 0.00) and a significant difference between the wild and cultivated ecotypes sampled at Melkkraal farm (P = 0.02).

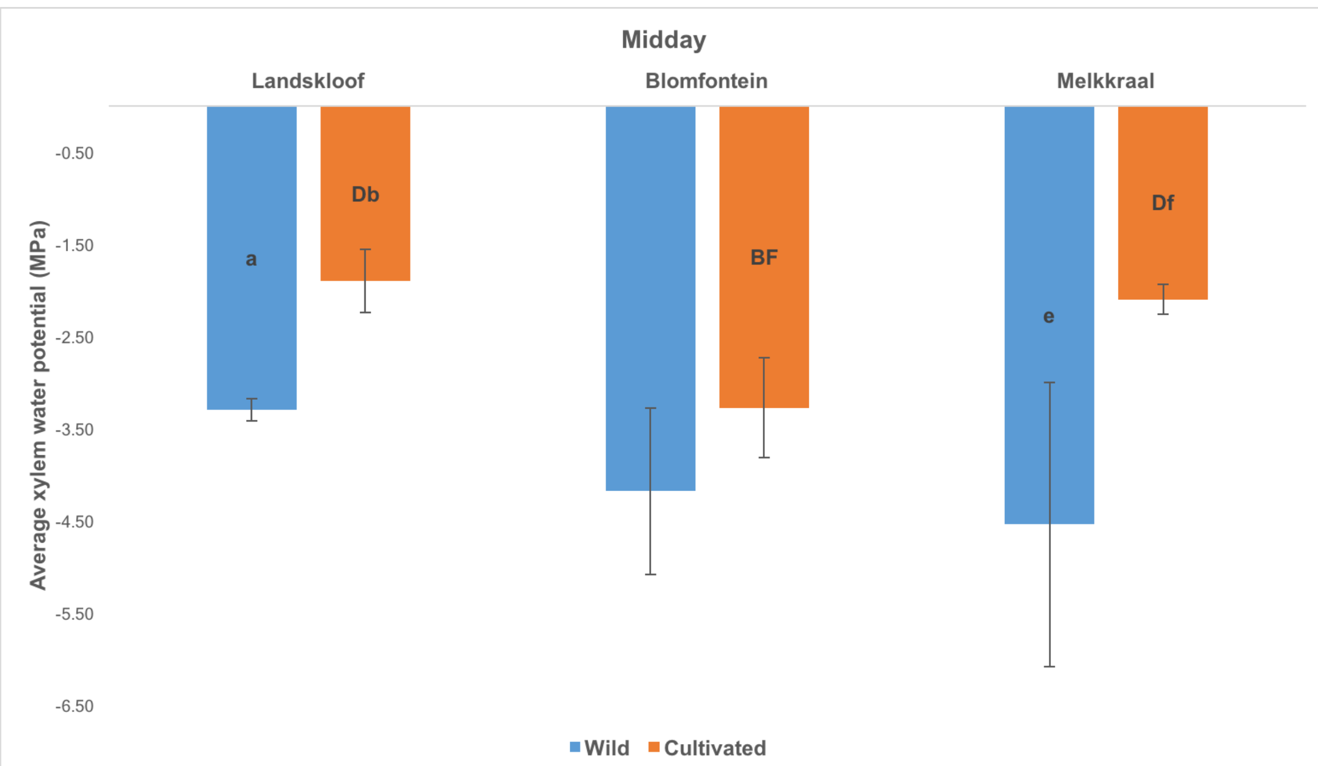

Figure 2.7. Water potential measured at midday (Ψ_{MD}) for all farms. Bars represent ± one standard deviation of the mean (n=5). Small letters denote significant differences within sites, whereas capital

letters indicate significant differences across sites ($P < 0.05$); there were significant differences within and across sites.

The safety margin (Table 2.3) was calculated as the difference between the P_{50} values and the Ψ_{MD}.

Table 2.3. P_{50} safety margin calculations for Ψ_{MD} for wild and cultivated *A. linearis*; values are in MPa (n=5) The values in bold are where the P_{50} values were exceeded.

SITES	WILD	CULTIVATED
MELKKRAAL	**1.87**	0.53
BLOMFONTEIN	**2.53**	**0.34**
LANDSKLOOF	1.40	1.68

Melkkraal's wild rooibos was operating above its threshold value (1.87 MPa). Melkkraal's cultivated rooibos is unlikely to form runaway xylem embolisms as its stem water potential (Ψ_{MD}) is less than the P_{50} value (0.53 MPa). In the case of the Blomfontein's ecotypes, in both cases, the P_{50} values are exceeded, and in the case of the wild ecotype, by a substantial margin. Only at Landskloof farm both the wild as well as the cultivated ecotype operated below their P_{50} values.

2.3.2. Mulch vs. control

Since three different mulch treatments were used on three different farms, a factorial ANOVA was not used for statistical analyses, however, a one-way ANOVA was used to distinguish statistically between the mulch and non-mulch trials within each farm.

P_{50} values for the mulching treatment ranged from -1.40 to -4.50 MPa. Both Melkkraal's mulch and control treatment (Table 2.4), reached P_{50} at a lower pressure than treatments at Blomfontein and Matarakopje farm. The latter farms, saw their treatments reach P_{50} at -3.00 MPa and lower. There was no significant difference between the mulch and control treatment within sites ($P < 0.05$).

Table 2.4. Mean values for P_{50} for the mulch and control treatments. Values are in MPa, and standard deviations are displayed in brackets (n=5). A t-test was carried out to compare the mulch and control treatments within each site. No significant differences were found.

SITE	ALL DATA	MULCH	CONTROL
MELKKRAAL	-2.86 (±0.98)	-3.10 (±0.96)	-2.63 (±1.07)
BLOMFONTEIN	-3.31 (±0.59)	-3.62 (±0.71)	-3.00 (±0.21)
MATARAKOPJE	-3.28 (±0.58)	-3.04 (±0.43)	-3.58 (±1.09)

Figures 2.8 and 2.9 show the average water potential measured at pre-dawn and midday, respectively, for the mulch and control treatments within farms.

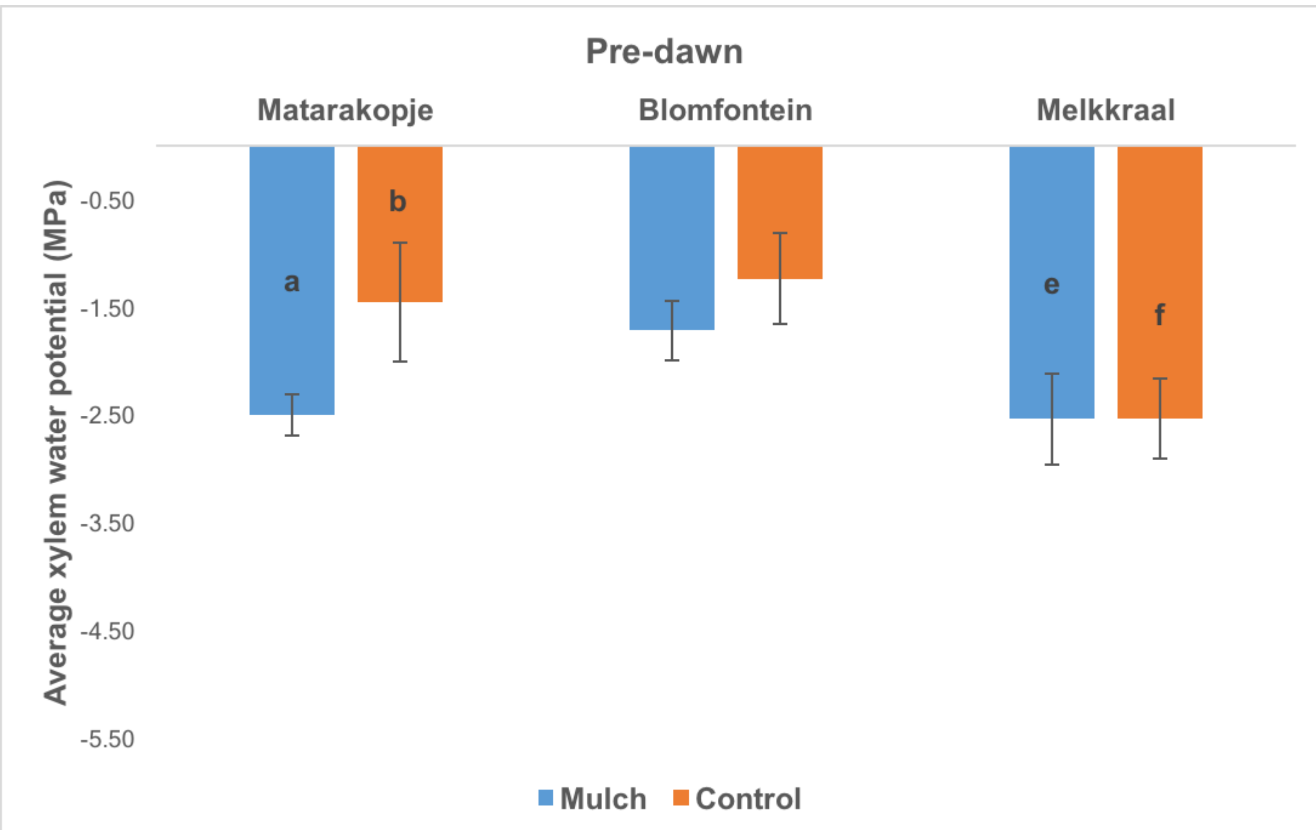

Figure 2.8. Water potential measured at midday (Ψ_{PD}) for all farms and all treatments (mulch and control). Bars represent ± one standard deviation of the mean (n=5). Small letters denote significant differences within sites (P < 0.05).

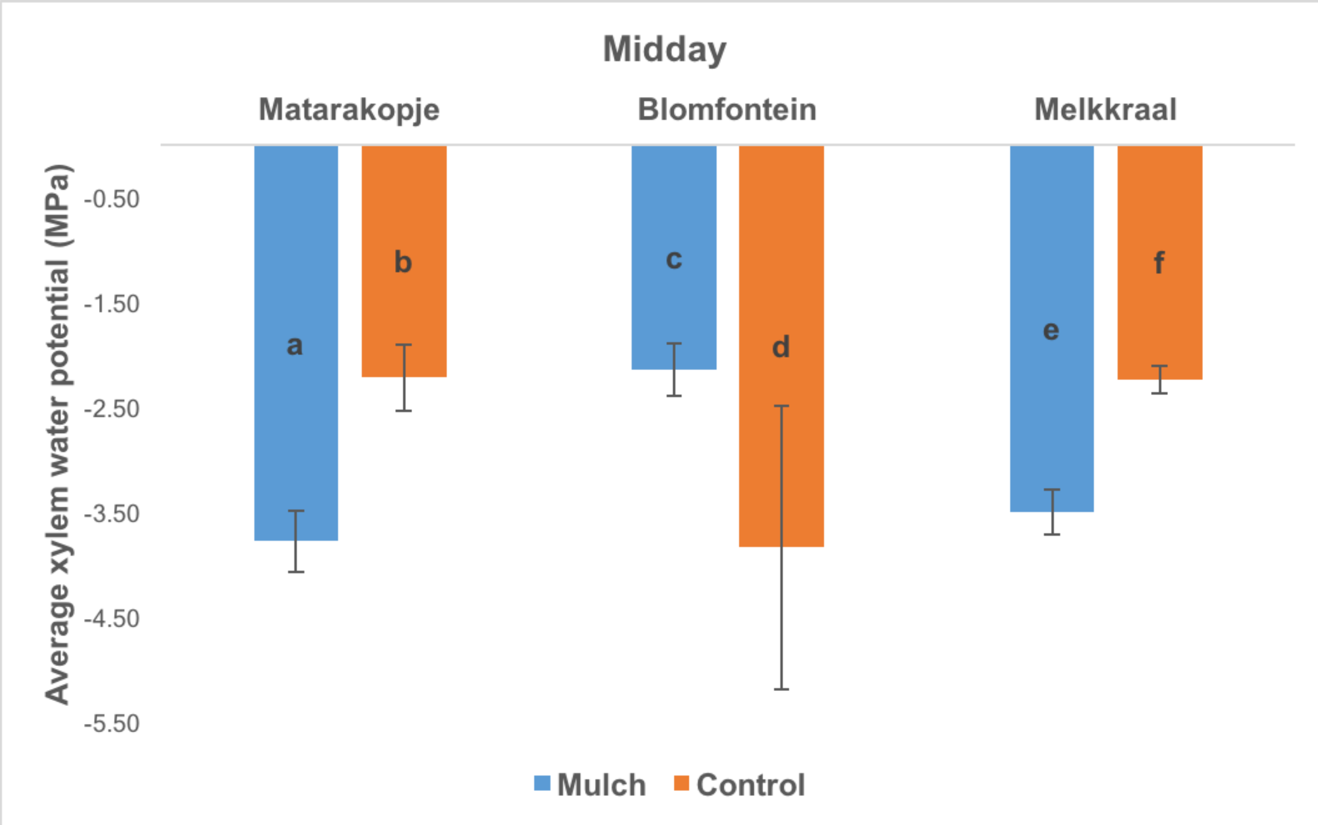

Figure 2.9. Water potential measured at midday (Ψ_{MD}) for all farms and all treatments (mulch and control). Bars represent ± one standard deviation of the mean (n=5). Small letters denote significant differences within sites (P < 0.05).

Blomfontein farm (Figure 2.8) showed the highest Ψ_{PD} for both the mulch (-1.72 MPa) and control (-1.24 MPa) treatments. The mulch treatment at Matarakopje farm measured the lowest Ψ_{PD} of -2.50 MPa followed by the mulch treatment of Melkkraal (-2.54 MPa). Blomfontein's control treatment (non-mulch) measured the lowest Ψ_{PD} of approximately -1.24 MPa. A t-test showed a significant difference between treatment means α = 0.05 and there is a significant difference between the mulch and control treatment means sampled at Melkkraal (P = 0.02) and Matarakopje farm (P = 0.01).

The lowest midday Ψ_{MD} (Figure 2.9), for both mulch and non-mulch (control) treatments, was measured at Blomfontein farm (-3.84 MPa), followed by Melkkraal's mulch treatment (-3.34 MPa). Matarakopje's control treatment measured the highest Ψ_{MD} of approximately -1.90 MPa. A t-test showed a significant difference (α = 0.05) between the mulch and control treatments sampled at Melkkraal (P = 0.00), Blomfontein (P = 0.02) and Matarakopje farm (P = 0.00).

The safety margin (Table 2.5) generally showed a lower differential. In most cases, the plants operated within their safety margins, with the exception of the mulch treatment at Matarakopje. The widest margins were found at the mulching treatment of Blomfontein 1.48 MPa and the control of Matarakopje (1.36 MPa), however, both are well below their P_{50} values. This is in contrast with the wild ecotype, where the P_{50} values were sometimes exceeded by wide margins.

Table 2.5. P_{50} safety margin calculations for Ψ_{MD} for the cultivated *A. linearis* used for the mulch and control treatments; values are in MPa (n=5). The values in bold are where the P_{50} values were exceeded.

SITES	MULCH	CONTROL
MELKKRAAL	0.60	0.39
BLOMFONTEIN	1.48	0.16
MATARAKOPJE	**0.74**	1.36

2.4. Discussion

2.4.1. Wild versus cultivated

Resprouting and reseeding after the onset of fire (Bond & Van Wilgen, 1996) are common life history strategies of plants in Mediterranean ecosystems (Power *et al.,* 2011). Resprouters possess underground stems and/or organs, which allow such taxa to resprout after fire (Clarke *et al.,* 2013). Seeder plant species die after a fire; however, their released seeds are able to germinate (Pratt *et al.,* 2012). These two regeneration strategies also differ in terms of resource allocation. Resprouters develop underground buds where they store their resources. Seeders, on the other hand, do not form these underground organs and redirect their resources to the above-ground plant parts (Midgley 1996). Zeppel et al. (2014) and Pausas et al. (2015) suggested that differential resource allocation also play out at the level of hydraulic characteristics, with seeders (non-sprouters) typically showing more sensitivity to drought (higher P_{50} values).

In this study, the hypothesis was that the wild (resprouter) ecotype would show a higher resistance to xylem cavitation than the cultivated (reseeder) ecotype since many farmers believe the wild ecotype tend to show greater drought resistance capabilities than the cultivated ecotype (Archer *et al.*, 2008, Malgas *et al.,* 2010). This is also in line with the work of Zeppel et al. (2014), as stated. No consistent differences between a wild ecotype (seeder) and the cultivated ecotype (sprouter) were apparent in this study. However, the mean P_{50} of -3.09 MPa, taken across farms and life history type or domestication status falls squarely within the range suggested by Nardini et al. (2014) for Californian and Mediterranean plant species and Zeppel et al. (2014) for angiosperm resprouters and seeders.

The wild ecotype showed very variable P_{50} values, ranging from -1.30 to -6.5 MPa, while the cultivated plants were varied in a narrower range, from 1.50 to 4.5 MPa. Factors such as fire may have played a role in the ability of the wild ecotype to resist cavitation, for instance, older plants may exhibit greater resistance to cavitation than younger plants (Pausas *et al.,* 2015). These authors found that *Heteromeles arbutifolia* seedlings reached P_{50} at -2.0 and adult plants were able to resist 50% cavitation until approximately -5.50 MPa. The trend showed here is the opposite: the farm of Landskloof experienced a veld fire three years ago, however, the wild ecotype at Landskloof farm showed greater resistance to xylem cavitation than the wild ecotypes at either Melkkraal or Blomfontein. These results may instead be related to differences in precipitation as Blomfontein receives more rain annually than Landskloof farm situated further south. In literature, it is clear that precipitation can influence P_{50} values, with drier sites generally showing lower P_{50} values. This was evident in Pratt et al. (2012) in terrestrial fynbos as well as in riparian sites in fynbos areas (Crous *et al.,* 2012) where sites with higher streamflow showed higher P_{50} values (less drought resistant). In the case of Pratt et al. (2012), lower P_{50} and P_{75} values were found at a drier site compared to a wet site (i.e. more resistant to embolism at the drier site) for three fynbos species. None of these species were leguminous, nonetheless showed this trend consistently, which was in line with the results found with *A. linearis* in the current study. The P_{50} values are thus consistent with the decreasing rainfall gradient, the highest P_{50} values were found at Melkkraal farm (a relatively wetter site) for both the cultivated hydraulic conductivity experiment and the mulching trials.

Some minor and inconsistent differences appeared when comparing within and between farms and ecotypes. Findings of this study showed different trends for the farms, with the wild ecotype at Blomfontein significantly lower P_{50} values, while no differences between the ecotypes evident for the other farms. At both Melkkraal and Landskloof, the wild ecotype reached saturation at a lower pressure than that of the cultivated ecotype, and there were significant differences between the wild ecotype of Landskloof farm and the wild ecotype sampled at Melkkraal and Blomfontein; this indicates that there exist differences the wild ecotype's drought resistance capabilities across the three farms. At Blomfontein farm, the wild populations have not been harvested for more than a decade. These wild populations have become moribund, however, show a trend that is the opposite of what was expected namely greater resistance with age (e.g. Pausas *et al.,* 2015). This is, however, consistent with an expectation of higher resistance to cavitation in sprouting plants; in this case, the sprouter (cultivated) had greater resistance to cavitation. Nonetheless, this can only be confirmed with trials where seeders and sprouters of the same age are planted in a garden experiment, which was not possible given the timelines for this study.

The Ψ_{PD} of the cultivated ecotype on Landskloof and Melkkraal was the lowest, with Blomfontein's cultivated ecotype showing the highest Ψ_{PD} of all the cultivated ecotypes measured at pre-dawn. Variations in Ψ_{PD} may be ascribed to rooting depth disparities across the three sites (Breshears *et al.,* 2009; Moriana *et al.,* 2012). This could be an indication that the cultivated population's rooting system at Blomfontein could have access to more moisture than Melkkraal and Landskloof.

Midday water potential (Ψ_{MD}) is important in plant-water relations because it denotes the minimum amount of water a plant can bear to remain active (Bhaskar & Ackerly, 2006). The study results suggested that there were notable differences in water potentials within and between the three sites, measured at midday. Research done by Bhaskar et al. (2007) suggested a relationship between Ψ_{MD} and xylem structure; plants with lower water potentials tend to have more drought-resistant xylem. According to this paradigm, Melkkraal's wild ecotype should be the most drought-resistant ecotype since its Ψ_{MD} is the lowest of all the ecotypes across all three sites. This is in contrast with the findings that showed Landskloof was, in fact, the most drought resistant, at least measured using P_{50} as a benchmark.

At all the sites, the Ψ_{PD} was relatively low; it could be expected that water potentials should equilibrate closer to zero when considering the work of Bhaskar et al. (2007) and Bhaskar and Ackerly (2006). However, this may be another indication of the drought, where all individuals are stressed, regardless of life history or the rainfall gradient. This may also explain the lack of difference between life history types – the prevailing paradigm is that non-sprouters should be more sensitive to drought (higher P_{50} values) (Zeppel *et al.*, 2014). This is clearly not the case, but as stems harvested are quite young, they may reflect the prevailing drought conditions, regardless of category.

Individuals at Landskloof also kept a wide safety margin when considering both P_{50} values and the midday water potential. At the two other farms, Melkkraal and Blomfontein, during late summer, when the measurements were taken, the P_{50} values were exceeded in the wild ecotype. While the plants were visually stressed (personal observation), no deaths were evident at these farms. However, the region is in the throes of a multi-year drought, and this may mean that the wild populations at the two more mesic farms, Melkkraal and Blomfontein are, in fact, more at risk of hydraulic failure in the wild populations. The wild population of Landskloof may be better pre-adapted to multi-year drought, and may survive drought periods more readily, when considering that these plants kept a wider safety margin, and Ψ_{MD} was well lower than the 50% embolism suggested by the P_{50} values, doing this perhaps through stomatal control.

When the results were compared to another legume genus (*Cyclopia*) (Malgas *et al.,* Unpublished), *A. linearis'* wild and cultivated ecotypes had a lower P_{50} value than the species *Cyclopia maculata* but was more drought sensitive than the other three species combined. Thus, it appears that overall, *A. linearis* ecotypes were somewhat more drought sensitive than most *Cyclopia* spp., however, with the exception of *Cyclopia maculata*, a species known to occur in riparian zones and wetland areas.

Table 2.6. Average P_{50} values of legume species of studies done in the Western Cape. The honeybush study was done in Genadendal in the Overberg; values are in MPa.

STUDY	P_{50}			
CURRENT STUDY	***A. linearis* Wild**	***A. linearis* Cultivated**		
	-3.01	-2.26		
HONEYBUSH STUDY	***Cyclopia genistoides***	***Cyclopia maculata***	***Cyclopia sessiliflora***	***Cyclopia subternata***
	-4.45	-1.30	-4.03	-5.05

Findings from the Landskloof farm are consistent with the hypothesis that the wild ecotype of *A. linearis* is better adapted to limited water supply and more drought resistant than the cultivated ecotype. No differences between the wild and cultivated ecotype were evident, most likely a result of a multi-year drought that gripped the Cederberg during the time of the study. However, Landskloof, the driest site, had the most resistant xylem, which is consistent with the expectation, based upon available literature (Brodersen *et al.,* 2010; Crous *et al.,* 2012, Pratt *et al.,* 2012; Vilagrosa *et al.,* 2012).

2.4.2. Mulching

It was expected that plants subjected to the mulching treatments would be less resistant to xylem cavitation and that they would be more likely to form embolisms and restrict water movement. When looking at treatment differences across farming sites, the same pattern could be seen and there were no significant differences either within or between farms. All three farming sites showed varied responses to induced drought as both the wild and cultivated ecotypes functioned within the same P_{50} range before reaching the saturation point where the risk of xylem cavitation increases. This may also be a response to the current drought conditions leading to the mulching treatment not showing the expected hydraulic response, perhaps due to the overall lack of soil moisture, regardless of mulching treatment. Alternatively, the period that the mulching treatment commenced to sampling for hydraulic properties was to short to show a significant response. However, as was the case with the wild versus cultivated comparison, the P_{50} values were well within the range of what was expected from fynbos plants, and somewhat higher than other legumes e.g. *Cyclopia* spp.

2.5. Conclusion

In conclusion, *A. linearis* appears to respond to soil moisture gradients but showed little differences within sites according to the reseeder-resprouter dichotomy (Zeppel *et al.,* 2014). At the drier end of the spectrum, plants with more resistance to cavitation could be found, which is consistent with other studies, including in the fynbos biome showing hydraulic adaptation in response to drought. On the other hand, mulching did not have an impact on hydraulic characteristics, however, there should be studies over a longer period of time rather than the short-term study presented here.

2.6. References

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Chapter 3

Local small-scale farmers' perceptions of drought-stress in wild resprouting and cultivated reseeding ecotypes of rooibos (*Aspalathus linearis*).

3.1. Introduction

Local ecological knowledge (LEK) is increasingly recognized as a valuable resource in the management of natural resources and sustainable agricultural production (Burkes *et al.,* 2000; Agrawal, 2014). Drought-prone South Africa provides scores of natural products to international markets from its local stock of endemic species distributed across the Cape Floristic Region (CFR). Some of these species, like rooibos (*Aspalathus linearis*), are both wild harvested, and cultivated, and are well adapted to local natural conditions. Local knowledge from land-users in the Cedarberg and Suid Bokkeveld have provided crucial complementary information to previously published ecological research (Van der Bank *et al.,* 1995; Van der Bank *et al.,* 1999; van Heerden *et al.,* 2003). Incorporating LEK into ecological research led to the differentiation of ecotypes of rooibos based on local nomenclature and morphological features of the species (Malgas *et al.,* 2010, Hawkins *et al.,* 2011), and, in turn, has informed farming practices in those regions. The melding of experiential farmer knowledge with empirical ecological investigation thus offers land-users and scientists joint insights that could lead to improved management and innovative practices that may not have been achieved by relying on only one knowledge system. Moreover, complimentary use of scientific data and farmer knowledge could be especially helpful when addressing the uncertainties that come with climate change and its effects on indigenous crop species, such as rooibos (Archer *et al.,* 2008; Lötter & Maitre, 2014).

Aspalathus linearis (Burm. f) (rooibos) belongs to the Fabaceae family and is endemic to the Mediterranean region of South Africa (Dahlgren, 1968). Wild populations of *A. linearis* are limited to the southwestern, mountainous areas of the Northern Cape Province (Suid Bokkeveld) and the Cederberg mountains. Rooibos grows naturally in nutrient deficient soils that are low in pH and well-drained, derived from Table Mountain sandstone (Muofhe & Dakora, 2000; Louw, 2006, Lötter & Maitre, 2014). The climatic distribution of rooibos is influenced by winter rainfall (100-350 mm) and hot dry summers (35-40°C) (Dahlgren, 1968; Bradley *et al.,* 2012; Joubert & Schultz, 2012). Though described as a single species, several ecotypes of rooibos have been identified, some of which are reseeders, and others of which are resprouters. Cultivated rooibos and its wild relative are seeders – fast-growing plants, usually tall and slender (approximately 1-1.8m), and prolific seed producers (Malgas *et al.*, 2010). By comparison, resprouting ecotypes are slower growing, have prostrate growth forms, possess the ability to resprout after fire from an underground storage organ, and produce fewer seeds.

Farmers in the Suid Bokkeveld rely on rooibos harvesting for a significant portion of their livelihoods**.** Due to increasing demands from international markets, the rooibos industry has seen an extraordinary growth in the past few years. Small-scale farmers, along with well-known commercial farmers, play an important role in ensuring the social and economic stability of formerly abandoned farming communities in the dry Suid Bokkeveld region. Wild and cultivated rooibos is marketed by small-scale farmers as a fair trade and organic endorsed product for markets abroad (Louw, 2006; Malgas, 2010). The small-scale rooibos farming communities in the Suid Bokkeveld are therefore dependent on *A. linearis* for their livelihoods.

Local land-user perceptions and knowledge are increasingly valued in research on natural phenomena, such as climate change and drought stress. Global changes in earth temperature, sea level rise, and high GHG emissions have acute impacts on agricultural sectors across the world (Nyong *et al.,* 2007). While mitigation and adaptation have been conceptualized as the main responses to climate change (UNFCCC, 1992), small-scale farmers have few resources with which to buffer extreme changes in climate and weather. To reduce the vulnerability linked with the predicted adverse effects of climate change, adaptation is deemed necessary to reduce this potential risk (Cohen *et al.,* 1998). The use of both mitigation and adaptation strategies is increasingly recognized as yielding better results when used to complement one another (Robinson & Herbert, 2001; Collins *et al.,* 2013). The incorporation of small-scale farmer knowledge in the Suid Bokkeveld to understand and respond to climate change in that region may aid farmers in developing improved drought adaptation techniques.

The incorporation of local ecological knowledge (LEK) into climate change mitigation policies could lead to farming methods that are more sustainable and cost-effective (Hunn, 1993; Robinson *et al.*, 2001). However, the incorporation of LEK into official climate change adaptation strategies is not often seen (Swart *et al.*, 2003; Nyong *et al.*, 2007; Green & Raygorodetsky, 2010). The latter, however, should not be done to the detriment of evidence obtained via scientific research. Knowledge based on scientific experiments and research, along with LEK that has been passed down from one generation to the next should not be in competition with one another but rather complementary. Research on the use of local ecological knowledge in rangeland management of the Kalahari, Botswana (Reed *et al.,* 2007), and communal grazing systems in Namaqualand, South Africa (Snyman, 2010) offer several insights into the value of complementary LEK and scientific investigation. Reed et al. (2007) drew on scientific and local ecological via a process where potential management alternatives were determined by means of interviews with local farmers and literature review and then assessed in community groups and officials from the agricultural sector. The aforementioned process recognized various applicable and novel approaches that could be utilized by many local communities to acclimate to land degradation. Snyman (2010) found that adhering to traditional and conservative strategies may not always be advantageous when it comes to managing rangelands effectively. The author suggests that a more flexible strategy is required, which will allow the continuation of traditional subsistence living without negatively influencing biodiversity conservation. Similarly, the Heiveld Co-operative has been drawing on the local knowledge of their own members, combining it with research outcomes and weather forecasts to respond to local climate change phenomena, such as drought (Archer *et al.,* 2008).

The winter rainfall region of the Fynbos biome is expected to receive reduced and unpredictable rainfall as well as an increase in daily maximum temperatures due to climate change (IPCC, 2007). These climatic changes have direct implications for rooibos production since the areas affected fall within the current production area. Indeed, rooibos producers have been experiencing prolonged dry spells between 2003 and 2007 (Archer *et al.,* 2008), and again from 2013 (Lötter & Maitre, 2014), with negative implications for small-scale farmers with regard to crop failure and loss of agricultural productivity. The impacts of drought are evident in agriculture through reduced soil moisture levels and an increase in evapotranspiration (Sonmez *et al.*, 2005), conditions that would be detrimental even for a well-adapted Fynbos species such as rooibos if drought conditions persisted. Rural economies associated with rooibos are highly dependent on agriculture, which in turn is heavily dependent on precipitation. The effects of drought on the rooibos production area could have an adverse impact on the yield and production of small-scale rooibos farmers in the drought-prone Suid Bokkeveld.

Local communities, such as found in the Suid Bokkeveld, are reporting the effects of variations in climate in their region and they are reacting to the new conditions as best they can e.g. change soil preparation timeframes for crops, implement wind erosion prevention methods and water conservation strategies (Archer *et al.*, 2008). These adaptation strategies have allowed farmers to uncover differences and similarities from their respective approaches and aid in developing and improving their own adaptation strategies. However, insufficient resources is a limiting factor and in 2005, farmer participants of the quarterly climate change workshop made the decision to elicit the help from external agencies to implement some of their adaptation strategies (Archer *et al.*, 2008). With initial funding from the Worldwide Fund for Nature (WWF), and then the Global Environmental Facility (GEF) Small Grants Programme, members of the Heiveld Co-operative were able to plan and implement climate change adaptation practices themselves. Implementation of strategies are guided by two mentor farmers democratically appointed from amongst the members, and with institutional support from local NGOs such as the Environmental Monitoring Group (EMG) and Indigo Development & Change. Implementation of the programme is guided by two members of the community who were selected to aid farmers in assessing environmental difficulties pertaining to the loss of soil and water and determine a suitable approach that can be used to mend the situation (Archer *et al.*, 2008).

There is, however, a notable gap in adaptation support by the Department of Agriculture of the Northern Cape. This contradicts the substantial activity by the same department where in February 2006 the Directorate of Agricultural Risk Management of the Department of Agriculture hosted a workshop on global climate change management in the agricultural sector, and these workshops have been hosted by the department ever since. An extension officer in the Suid Bokkeveld region is lacking and therefore much of the aid and assistance provided to farmers is as a result of the involvement of non-governmental agencies. The latter has played an important role in providing adaptation supporting roles to farmers by combining local adaptation knowledge with external knowledge (Archer *et al.*, 2008; Bynum *et al.*, 2008). Promising discussions have occurred with the provincial Department of Agriculture, however, frailties in government aid that might make adaptation possible, in light of the potential effects of climate change, are of great concern. Regrettably, this predicament is not exclusive to the Suid Bokkeveld region (Vogel *et al.*, 2005; Akpalu, 2006; Brown *et al.*, 2007).

It is, therefore, important to study farmers perception and understanding of drought stress and the effect it may have on rooibos plants in the Suid Bokkeveld. The study complements previous studies on the value of local knowledge in rooibos management (Louw, 2006), landscape-level implications of climate change on rooibos production (Lötter & Maitre, 2014), local adaptations in the Suid Bokkeveld under drought conditions (Archer *et al.*, 2008) and more recently, research by Koelle et al. (2012) on livestock monitoring in response to drought amongst women in the Suid Bokkeveld. The main objective is to assess farmers' perception and comprehension of drought stress with the awareness of prior drought experiences, the level of understanding and knowledge of climate change.

3.2. Methods

3.2.1. Study area

The Suid Bokkeveld is located on dolerite soils in the Northern Cape and characterized by succulent Karoo vegetation. To the west and south, Table Mountain Sandstone forms the geological substrate and the prominent vegetation here is fynbos. Succulent Karoo and Fynbos vegetation are the two dominant vegetation types of the Suid Bokkeveld with remnant patches of Renosterveld vegetation occurring in some areas; these patches have been ploughed over to make way for monocultural wheat and rooibos tea production during the 20th century (Oettlé, 2002; Koelle *et al.*, 2003). Due to the quality of the soils, current agricultural practices are limited to rooibos tea production, sheep farming and, to a lesser extent, cereal production.

In the 18th century, white farmers and settlers displaced and mixed with native Khoi and San people living in Nieuwoudtville (Koelle *et al.*, 2003). Today, the Suid Bokkeveld populations comprise of largely white and colored people whereas black seasonal workers only ever occur as part of contract work (construction of roads). The colored community makes up the majority of labor on many white-owned farms. Due to lack of funds and low academic achievement, largely due to the institutional neglect of racialized education and rural decline (Louw, 2006), many school leavers in the Suid Bokkeveld do not continue onto tertiary education. The costs to get to a reputable tertiary institution is also very high as the nearest institution is more than 100 km away. Employment opportunities in the Suid Bokkeveld are confined to secretarial work with local businesses in Nieuwoudtville and farm work on the neighboring farms (Louw, 2006).

The main sources of income for small-scale rooibos farmers include rooibos tea and livestock farming i.e. sheep and goats. The Suid Bokkeveld is situated on the border between the Succulent Karoo and Fynbos biomes. The Fynbos biome comprises approximately 71 337km^2 and coincides with the CFR, the latter known as one of the world's most significant floral kingdoms (Cowling *et al.*, 1997). The Fynbos biome has over 7300 species with over 70% of plant species being endemic to the region. The Succulent Karoo biome also contains a diverse range of species (~5000) of which about 50% are endemic (Mucina *et al.*, 2006; Hoffman *et al.*, 2009). At the transition zone between the aforementioned biomes, the Suid Bokkeveld predominantly receives winter rainfall of 150-300mm per annum. Rainfall for the region during the drought of 2016-2017 has been as low as 300 mm.

More than a fifth of South Africa's rooibos comes from the Suid Bokkeveld region. Members of the Heiveld Co-operative, which was founded in 2001, pick and sell their organic rooibos to the co-operative and from there it is exported to niche markets mainly in Europe, but also to

North America. Approximately 200 tons are transported to Cape Town harbour annually for export, raking in R4-million in 2014; the latter is distributed amongst the 73 farmers who are liable for staff and productions costs (Louw, 2006; Archer *et al*., 2008).

3.2.2. Questionnaire survey

Due to the severe drought between 2003 and 2007, many farmers of the Suid Bokkeveld will perceive or classify drought because of their previous experiences; all farmers interviewed experienced the devastating drought which lasted from 2003-2007. Because of the drought of the latter, farmers made use of a climate calendars to track rainfall data for 18 months (January 2003-June 2004). All respondents observed the harsh effects of drought for the May-July 2003 period. Drought stress observations in farmers tea crops mainly in the form of reduced production yields (Archer *et al.*, 2008).

A questionnaire survey was conducted between November 2016 and May 2017 to document local perceptions of climate change according to local rooibos tea farmers in the Suid-Bokkeveld. Participation was limited to persons who had experience (>5 years) farming with rooibos tea. All respondents were small-scale rooibos farmers and are members of the Heiveld Cooperative, a rooibos producer organization established in 2001 (Malgas *et al.,* 2011). Experiential knowledge discussed during interviews was based on the individual's personal experience gained whilst farming rooibos. Members of the Heiveld were approached for participation, regardless how long they had been involved with rooibos production. The choice was governed by the fact that a) 100% of the resident members of the Heiveld have had more than 10 years experience with rooibos tea production, b) the number of participants with knowledge of wild rooibos is limited, and further restrictions would have made the pool smaller. The potential trade-off between less restrictive selection criteria and the relevance of knowledge of inexperienced knowledge holders (b) was mitigated by the fact that by default, all farmers were eligible by virtue of (a). This specialized knowledge is passed down from parents and grandparents.

Prior to the survey period, potential interviewees were approached through the Heiveld Co-operative's research review processing, during which time the research and researcher were introduced to interviewees. Introductions were made with the help of a researcher already known to the interviewees as a result of their previous work and research in the community. With the conclusion of the introductions, participants were made aware of the nature of the interviews and permission to participate in the interview was requested. As expected, rooibos knowledge is restricted to a small number of active producers in that population.

Only 6 of the 53 (11%) of the Heiveld membership of 53 were eligible to participate in the study, according to the criteria set for their selection. The criteria were: knowledge on wild and cultivated rooibos production, members of the Heiveld Co-op, rooibos farming experience, and rooibos' drought responses. Since information on rooibos production and rooibos ecotypes is not widely known, only a small number of people possess this knowledge, hence the small sample size. Of these, four were full-time rooibos tea farmers, and two also generated incomes from administrative work; all respondents also worked on an *ad hoc* basis during the rooibos harvest season as farm laborers on other farms in the region. The remaining two farmers were both rooibos tea and livestock farmers and had considerable experience in herding, as well as rooibos tea production. The questionnaire dispensed was intended to elicit how rooibos farmers perceived rooibos' response to drought stress and perceived reasons for the changes in climate. Apart from the demographics and social characteristics of respondents, questions were designed to address the following:

1. Observed incidence of wild and cultivated rooibos ecotype mortality i.e. which ecotype experiences mortality first
2. Observable responses to drought stress in rooibos i.e. leaf growth, wilting, leaf yellowing etc.
3. Observed post-drought response
4. Perceptions of climate change amongst small-scale rooibos farmers

A semi-structured questionnaire was utilized to collect data from respondents. Information gathered during interviews was based on respondents personal experience and knowledge. Thus, opinions presented here of respondents personal perspective of the topic. The survey questionnaire consisted of four parts. The first part focused on the socio-demographic background and status of the participants. The second part contained questions pertaining to initial drought responses in wild or cultivated rooibos. The third part of the questionnaire focuses on respondents' perception of the post-drought response of rooibos. The last part included questions underlining farmers' insight and understanding of the changing climate such as temperature and precipitation trends over the past 6-10 years and perceived reasons for the weather patterns they are currently experiencing. The semi-structured outline also provided a platform for respondents to elaborate on specific themes/questions, permitting a broader perception of respondents' perspectives.

One hundred and sixty minutes of the survey questionnaires were recorded. The interviews lasted between fifteen and twenty minutes. The timespan of the interviews was dependent on the interviewees' readiness to share information and the amount of time they were willing to spend complete the survey questionnaire.

3.2.3. Ethical considerations

The study was conceptualized and conducted in accordance with Stellenbosch University's criterions on ethical research. As per the criteria, any research, as pertaining to ethics, should ideally protect the respondent, the investigator and the research itself. Therefore, research is dependent on willful participation, informed consent, anonymity, and in confidence. According to the criteria, respondents have the right to informed consent and confidentiality. Accordingly, respondents were advised of the nature of the study, the option to participate in the study or not was made available, and their consent sought. The assurance was given to respondents that there would be no adverse outcomes or compensation if they participated. Involvement in the study depended on free will, rather than enforcement.

The face-to-face interviews hindered complete anonymity, however, respondents were given the guarantee that all information would be handled with the utmost regard to discretion and confidentiality.

3.3. Results

3.3.1. Demographic status of respondents

Of the six respondents, three were male and three were female. Two of the respondents have been residing in the Suid Bokkeveld for up to 10 years whereas the remaining four has lived in the Suid Bokkeveld for more than 10 years. Sources of knowledge were reported to be from parents and grandparents. In terms of age structure, four respondents were above 35 years of age and two respondents were 50 years and older.

The residents, who are experienced in rooibos farming, have been living in the Suid Bokkeveld for more than 10 years. There are no new and emerging rooibos farmers coming into the Suid Bokkeveld region. The younger generation of the community has always been there, and they are more likely to take over the production of rooibos from their parents. The younger generation of rooibos farmers have not been members of the Heiveld Co-op for more than 5 years, however, their experience in rooibos cultivation and farming has been ever-growing for many years. The interviewees have been residing in the Suid Bokkeveld for many years and their knowledge on rooibos production is extensive.

The Heiveld Co-op has many training opportunities so even if new rooibos farmers were to arrive on the scene, the Heiveld's business is so connected to the ecology of the species and conservation orientated, there would be many opportunities for newcomers to learn more about the production and cultivation of rooibos.

3.3.2. Impact of drought

When asked which ecotype responds first to drought stress, all respondents stated that, compared with wild rooibos, cultivated rooibos is the first to respond to drought stress, and that this is evident in the plants' morphology. Morphological responses to drought includes slower plant growth when compared to the wild ecotype, which are of the same age as the cultivated ecotype. Respondents observed that the cultivated ecotype's leaves become desiccated and wilts during reduced precipitation conditions. Another drought response observed by farmers is the red discoloration of the leaves and leaf dropping of the red leaves.

Figure 3.1- Cultivated rooibos stands with distinct red discoloration as a sign of water stress, Melkkraal farm (Rafferty, 2017).

Three respondents observed loss of branches occurring in cultivated rooibos as a drought response; loss of branches was reported to occur on the side of the rooibos shrub where leaf wilting and red discoloration has started to occur. Respondents reported that when precipitation eventually arrives, it may be able to save the rooibos shrub and prevent branch loss. The remaining three respondents have not experienced loss of rooibos shrub branches, as a response to drought stress, on their farms. Of the three respondents, two respondents stated that only leaf wilting and discoloration occurs on the affected ecotype and this occurs mainly in winter because of frost.

In terms of drought responses of seedlings compared to adult cultivated rooibos, four respondents reported that seedlings respond to drought stress first, before adult plants, since their root system is not yet fully developed. However, one respondent believed that sufficient care and tillage of the soil may aid the seedling plants to withstand drought stress and flourish under adverse conditions. The last respondent believed that the adult cultivated plants respond first to drought stress since it is more susceptible to drought stress.

3.3.3. Post-drought response

Respondents reported that both wild and cultivated ecotypes respond positively after a good bout of rain (n=5). They also indicated that after a month of receiving good rains, both ecotypes show improvement in terms of their morphology i.e. reduced leaf wilting and accelerated growth. One respondent remarked that the cultivated ecotype shows the first signs of improvement after a drought and a period of good precipitation.

In terms of the first emergence of cultivated plants, all respondents indicated that emergence of seedlings usually occurs 7-14 days after seed planting. The emergence of seedlings is heavily dependent on adequate precipitation, and according to climate change forecast models, rain bearing mid-latitude cyclones are expected to shift northwards in the coming future, which could influence plant emergence even further i.e. if the rains do not arrive or inadequate amounts is experienced, seedling emergence could be delayed, and this could influence production yield. It should be noted that the wild ecotype is not as closely monitored in terms of first seedling emergence due to logistical difficulties i.e. wild rooibos sites are not always easy to access, which makes monitoring very difficult. The latter, according to respondents, usually occurs in January and soil preparation occurs the previous December; the Heiveld Cooperative provides their members with cultivated seeds. All respondents indicated that harvesting occurs from February to March, however, wild rooibos is not harvested every year as in the case of cultivated rooibos. Four respondents indicated that the cultivated rooibos stands are pruned in April whereas the remaining two indicated that they prune the rooibos stands only in August; again, this varies from farm to farm. However, what is interpreted as pruning may refer to the topping of tea – a practice of removing the tall apical stem to allow more voluminous lateral growth. All respondents believed that flowering of cultivated and wild rooibos depends on the rainfall, however, should they receive steady and consistent rainfall, flowering tends to occur in September; two of the six respondents believe the wild rooibos ecotype does not flower every year.

3.3.4. Awareness of climate issues

Regarding the local climate, all respondents perceived that the local is not what it used to be and is changing. A followup question, "How is the local climate changing?" yielded diverse responses (Table 3.1). For the most part, the change was apparent in terms of daily maximum temperatures have increased significantly when compared to previous years (5), reduced number of rain days in the rainy season (4) and reduced rainfall amounts (3).

Table 3.1- Public perception of local climate conditions; (n=6).

PERCEPTION	AGREE	DISAGREE	UNDECIDED
TEMP. GETTING WARMER (SUMMER)	5	1	0
TEMP. GETTING COOLER (WINTER)	2	4	0
LESS RAINFALL	6	0	0
REDUCED RAINFALL DAYS	6	0	0
INCREASE IN RAINFALL DAYS	0	5	1

3.3.5. Respondent's perceived reasons for a changing climate

Answers to the question “Why do you think the climate is changing?” were varied. A considerable proportion (4 respondents) explained climate change in terms of the observed climate experiences in their local environment. One respondent believed that the changing climate is due to natural forces i.e. “climatic elements naturally vary over time”. The remaining respondent attributed local changing climate to man-made activities including deforestation.

In terms of participants public perception of climate change, two categories were consistent throughout the interviews: human factors and natural phenomena. Four participants attributed the reason for climate change due to human influence such as deforestation and man-made activities. The remaining 2 participants observed that the reason for the climate changing is “climatic events naturally vary over time”, “ozone depletion” and changes in the environment”.

3.4. Discussion

Respondents observed that the cultivated ecotype responds first to drought stress whereas the wild ecotype seems to be “stronger” and “better adapted to drought conditions”. According to respondents, slower plant growth was observed in the cultivated ecotype, which in the case of rooibos, is a reseeder. West et al. (2012) found the same phenomena when looking at other reseeder species in the Fynbos region such as *Erica pyxidiflora, Erica ericoides* and *Erica subcapitata* and the proteoid species *Leucadendron laureolum.* Research done by Lötter et al. (2014) reported that drought stress can lead to a reduction in photosynthesis since the closure of the plant’s stomata leads to a decrease in stomatal conductance. Similar to Louw (2006), wild resprouters are reported to be more resilient to drought stress and post-harvest disturbances, thus we expect that their drought responses will be similar.

Seedling survival is crucial in a harsh environment such as the Suid Bokkeveld and since cultivated rooibos are obligate reseeders, erratic and harsh environment conditions may hamper survival (Hawkins *et al.,* 2009). The Suid Bokkeveld is a drought-prone region and what little precipitation it receives, during winter, could influence cultivated rooibos seedling establishment and survival (Moles & Westoby, 2004). With the onset of drought conditions, slowed plant growth may enable the survival of cultivated rooibos until the arrival of the rainy season. It does result in lower biomass productivity, with dire implications for farmers who derive their livelihoods from the production of rooibos, as was the case in the 2003 – 2007 dry spell (Malgas *et al.,* 2011). The survival of seedlings is also dependent on strong root development in the early stages of establishment. *A. linearis* has a range of root adaptations that aid its survival in the wild and in cultivated fields. These include symbiotic Rhizobium for nitrogen fixation (Andrews & Andrews, 2017), mutualistic relationship with mycorrhiza for nutrient acquisition (Allsopp & Stock, 1992); and cluster roots that help with the uptake of phosphorous (Lambers *et al.*, 2006). However, in the time it takes for young seedlings to develop root systems with these adaptive functions, rainfall is essential for the transport of available nutrients. Seedling protection is thus a key management intervention during times of drought. Wild rooibos has a higher survival rate than cultivated rooibos since it not only survives through seed production but also its underground vegetative storage reserves. The cultivated rooibos is the main export of many small-scale rooibos farmers and any seed mortality will have negative impacts on rooibos production and export.

Aspalathus linearis exhibits both reseeding and resprouting capabilities and both life histories are adapted to nutrient-poor soil conditions (Muofhe & Dakora, 2000). The two ecotypes (wild and cultivated) possess different life histories and therefore they differ in terms of drought responses. Zeppel et al. (2014) did a study on drought responses in reseeders (*Aspalathus hirta*) and resprouters (*Diospiros glabra*) in the Fynbos region and found that resprouters tend to be more sensitive to drought (higher P_{50}) than reseeders. In Chapter 2 of this thesis, the reseeder cultivated ecotype showed higher P_{50} values than the wild resprouter ecotype, showing similar results for *A. linearis*.

Leaf drop, and senescence were also reported by interviewees as drought responses in rooibos. Reduced precipitation leads to transpiration and little to no photosynthesis occurring. Photosynthesis is important for plant and leaf growth and without photosynthesis providing energy for the plant, the plant eventually loses it leaves so as to prevent further use of its energy reserves (Miyashita *et al.,* 2005). Reduced photosynthesis could have influenced the observed “branch die-back” exhibited by some of the cultivated rooibos stands. The loss of cultivated rooibos branches could possibly have been as a result of reduced photosynthesis, brought on by reduced precipitation, rather than as a result of xylem cavitation. A similar reduction in transpiration, as a result of drought, has been reported in reseeding *Protea susanne* and *Protea compacta* in the Mediterranean region (Richards *et al.,* 1995), two focal Fynbos species used in the cut flower industry. In a comparison phenology between wild and cultivated rooibos, Louw (2006) reported that wild resprouters retain their leaves longer and drop fewer leaves than cultivated plants. It could be that during times of drought stress, the same principle applies, and that wild plants are able to retain more of their leaves for long periods of time. As with slowed growth, pre-harvest leaf drop and senescence, whether in cultivated or wild harvested plants, result in reduced harvestable biomass, to detriment of farmers’ livelihoods.

Red discoloration of cultivated *A. linearis* was also reported as a drought response. Respondents perceive that the red discoloration is a result of reduced precipitation which eventually leads to these “red leaves” dropping and the plant dying. Leaf yellowing is the first visible indication of leaf senescence (Biswal,1995; Borrell *et al.,* 2000). This is due to chlorophyll degeneration in the senescing leaves, which exposes the presence of carotenoids. In the case of cultivated rooibos plants, the red discoloration in leaves is as a result of the build-up of anthocyanins (Neil & Gould, 2003). Although senescence is known to occur in rooibos in after summer (Louw, 2006), Fynbos species are known to “draw back” reserves in their leaves in an attempt to retain precious nutrients (Oettlé, 2010). This discoloration of leaves is thus a result of this survival strategy. Discoloration in rooibos can also be attributed to insect damage, a process in some ways facilitated by drought, as plants give off stress signals making them more susceptible to insect pests.

Farmers are quite aware of changes – probably due to input and exposure to climate change preparedness workshops. All are in agreement about certain points: precipitation days are shorter, summer is hotter and drier, winters are milder, less rainfall and arrives later. Perceived causes for climate change were diverse amongst the small sample interviewees, but given the limited sample size, and the limited scope of the study, it is difficult to ascribe the reasons for the diverse responses to any particular factor. However, one respondent mentioned broader connections between their local experience of climate change and larger global phenomena that are anthropogenic in nature, e.g. deforestation, greenhouse gas emissions (GHG) etc. This particular account demonstrates the value of local science communication around climate change and offering farmers information that otherwise would be inaccessible to them. Not only does local knowledge add value to science, but the scientific information could add value in how people interpret their own observations and experiences with rooibos production.

3.5. Conclusion

Reseeding cultivated, and resprouting wild rooibos ecotypes may differ in terms of their physiology, however, when the effects of drought exceed levels of tolerance in the two ecotypes, both may exhibit similar strategies (branch sacrifice and red leaf discoloration) to cope with prolonged precipitation deficits. It also appears that the cultivated rooibos has a lower tolerance to drought stress than that of the wild ecotype; the cultivated ecotype is the first to show signs of drought stress i.e. branch sacrifice. The wild ecotype does show greater resistance to xylem cavitation, which could lead to better drought adaptation capabilities (Chapter 2), and the observations of the farmers corroborate these findings. However, age may be a factor when considering the latter since the older wild ecotypes on Melkkraal and Blomfontein did not show great resistance to cavitation compared with Landskloof farm where the wild ecotype was much younger. This further discussed in Chapter 2.

Local knowledge from six participants supported much of what has been reported elsewhere, both for rooibos in the Suid Bokkeveld (Louw, 2006, Lötter *et al.,* 2014), but also for other species with similar life history traits. Linkages between interview data and reports from literature offer opportunities to explore mechanisms for observed drought stress responses in wild and cultivated plants. Generally, drought stress leads to loss of harvestable biomass, ultimately affecting the livelihood opportunities associated with rooibos production. Management interventions should be aimed at lower risks of indirect and direct effects of global climate change on rooibos production, such as the selection of genetic material, seedling production, retention of soil moisture, and general plant maintenance.

In this study, I have analysed the perception of climate change effects and rooibos' response to drought stress by local Suid Bokkeveld rooibos farmers, by making use of a survey questionnaire. The results indicate that farmers are aware of the different responses of wild and cultivated rooibos to drought stress, and that perceived reasons for the change are informed by their own experiences as farmers, but also strongly influenced by knowledge and interactions on the topic as they are presented at regular climate change workshops. Due to improved technology and the inception of the quarterly climate change workshops, held by the Heiveld Co-op, farmers are also more aware of weather patterns and the influence it has on rooibos cultivation and production, particularly for the cultivated rooibos ecotype since it is widely exported. The quarterly climate change workshops have proven to be a helpful tool when it comes to incorporating local climate issues with that of seasonal forecasts and ultimately provides a platform for adapting new strategies in coping with the potential effects of drought and climate change.

Drawing on local ecological knowledge amongst small-scale rooibos farmers has added to growing knowledge of wild and cultivated rooibos and their responses to drought. Understanding the ecological and physiological principles that govern growth and production of rooibos under drought conditions informs the worthwhile pursuit of climate change adaptation amongst producers. A thorough understanding of the physiological responses and the agro-ecological context of rooibos production is thus crucial for improved decision-making and management of this endemic Fynbos species. The study also demonstrates that as much as local knowledge can contribute to scientific insights, a scientific investigation can also offer local rooibos producers a lens through which to interpret and incorporate their own observations of natural phenomena.

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Chapter 4

The value of incorporating land-user perceptions and scientific surveys to advise drought adaptation tactics of *Aspalathus linearis* in the Suid Bokkeveld, South Africa.

4.1. Introduction

Several authors (e.g. Parry *et al.*, 1999; Fischer *et al.*, 2002; Jones & Thornton, 2003; Aggarwal *et al.*, 2004; Antle *et al.*, 2004; Easterling *et al.*, 2004; Parry *et al*., 2004; Parry *et al*., 2005; Thomas *et al*, 2005; Reid & Vogel, 2006; Easterling & Aggarwal, 2007; Seo & Mendelsohn, 2007) have documented substantial and disturbing effects of climate variability on the agricultural sector. A recent report by the IPCC suggests that crop yields are likely to decrease, particularly in locales where food security is already vulnerable and challenged (Boko *et al.*, 2007; Easterling & Aggarwal, 2007). Southern Africa is recognized as an area where crop yield is likely to be affected, and this has led to increased activity at the level of policy, of late, to adapt the agricultural sector to the new reality (Nhemachena *et al.,* 2007; Stringer *et al.,* 2009). In South Africa, policy development has been rendered in a top-down manner, which limits stakeholders (Easterling & Aggarwal, 2007; Archer *et al.*, 2008).

This chapter will look at the scientific results (vulnerability to cavitation) and the answers from the survey questionnaire and will seek to relate these two methodologies with the eye to find a common approach to incorporate these two methodologies; incorporation of the different methodologies may provide insight into improved climate change adaptation and mitigation strategies.

4.2. Integration of scientific and local knowledge to enhance adaptation to drought

Based on farmer's indigenous knowledge on climate risk management, biodiversity conservation and preserving water and soil, farmers initiated extended adaptation strategies following multi-year drought period of 2003-2005. Strategies included the planting of windbreaks (this prevents rooibos loss because of strong winds) utilizing indigenous vegetation planted at an angle in the direction of the predominant wind (Archer *et al*., 2008). To promote water conservation, alien vegetation was removed. Wind erosion deterrence was initiated by farmers e.g. retaining indigenous plant strips in-between stands of cultivated rooibos. However, to date, scientific evidence in the form of rooibos' physiological response to a changing climate and local adaptation strategies has not yet been incorporated; incorporation of these two systems will provide farmers with a better understanding of what is actually happening internally to the plant and this may provide answers as to rooibos' morphological response to drought stress.

One adaptation strategy, currently used by local rooibos farmers, is the addition of organic mulch to stands of cultivated rooibos tea to prevent increased soil moisture loss when precipitation levels are very low. These mulching trials are currently underway on three farms in the Suid Bokkeveld: Melkkraal, Blomfontein, and Matarakopje. The reasoning behind the trials is to determine whether or not organic mulch may aid cultivated rooibos to retain more moisture during the drier parts of the year and if in so doing, promote growth and produce adequate yields even with reduced rainfall.

To integrate local ecological knowledge (LEK) and climate change adaptation strategies, certain protocols need to be followed. Firstly, one has to recognize that LEK has equipped communities with the ability to adapt and survive past and present climatic vulnerabilities. Secondly, one has to adopt a bottom-up participatory approach as this will lead to the highest level of community interaction. Third, the local community should have an equal partnership stake throughout the development process. For example, local community members should take the lead while external partners provide outside assistance. Fourth, the acknowledgment of local practices are important, however, one should not develop these practices at the cost of modern techniques; the two should complement one another to produce the best possible outcome for adaptation and mitigation (Adugna, 1996; Nyong *et al*., 2007). Nontheless, it is imperative to realise that not all local practices are advantageous to the sustainable development of the community and not all LEK can provide solutions to a particular problem.

For this reason, before intergrating or adopting LEK into mitigation strategies, local practices need to be examined to determine if they are appropriate.

4.3. The need to understand wild versus cultivated *A. linearis'* response to drought stress

Rooibos displays both seedlings (cultivated) and sprouting (wild) traits (Louw, 2006) and both ecotypes can be found growing and being cultivated in the Suid Bokkeveld. Wild rooibos is more resilient to pathogens and pests as well as current drought conditions than the cultivated rooibos. This implies that the cultivation of the wild rooibos may be used as a possible adaptative tactic in the setting of climate change. The wild rooibos, of the Suid Bokkeveld, has an advantage over the cultivated rooibos as the latter does not possess carbohydrate reserves stored below-ground to provide resilience against adverse climate conditions (Louw, 2006).

To better understand the drought responses of the aforementioned ecotypes under climate change conditions, we need to incorporate both indigenous and scientific knowledge into an consolidated scheme that will be able to afford better guidance (Bosch *et al.*, 1997) during execution of adaptation and mitigation strategies for the sustainable production of rooibos under changing climate conditions. This study combined an experimental study on the susceptibility of rooibos ecotypes to xylem cavitation under a changing climate with a survey of local rooibos farmers' knowledge and their perceptions of climate change and drought responses exhibited by wild and cultivated rooibos. Results, from the latter, of the standard scientific methodologies were compared with those from the survey questionnaire to establish whether there exist any similarities between the two knowledge systems, moreover, how these two systems supplement one another in acquiring a more comprehensive understanding of rooibos' drought responses and adapting current climate change adaptation strategies.

4.4. Findings in relation to climate change

There were no indications from the physiological measurements that there were substantial differences in the ecotypes with regard to their responses to drought, with the exception of one farm. In contrast, most farmers suggested that the wild ecotype is more drought resistant. The effect of the multi-year drought could have played out at the level of hydraulic architecture, which may have affected how plants respond. Further, the visual response in terms of branch dieback (sacrifice) has been reported, more so in the cultivated type, however, no direct physiological response could be linked to this observation. However, it is clear that the aridity gradient played a role (lower P_{50} values at the lower end of the rainfall gradient, Landskloof), though this could not be drawn out from the questionnaires as most farmers were more familiar with their own farms and immediate broader environment. The contrasting findings from the questionnaires and the physiological measurements warrant a more comprehensive investigation, perhaps during a wetter period when physiological responses may be less affected by the overriding effect of prolonged lack of moisture and the implications for growth.

No differences were evident in between the mulching and the control treatments in the response of the hydraulic properties of the conducting tissue. This could be due to generally dry conditions, with a lack of moisture resulting in little difference in soil moisture levels regardless of ground cover, or, alternatively, could be due to the short period of the trial before measurements took place. It should be noted that the mulching trials, at the time of this study, had only been running for 8 months and therefore more time should pass in order to test for any significant changes in cultivated rooibos' response to water stress. Further research may be needed to determine if age has an influence on rooibos' susceptibility to xylem embolisms.

4.5. Conclusion

Results from the traditional scientific methods and the survey questionnaire on local knowledge show that there may exist important disparities between these two methodologies, however, each proves invaluable for understanding certain phenomena exhibited, in this case, by wild and cultivated rooibos ecotypes. On the other hand, the various approaches that these methodologies use can often generate complications when interpreting results. Local knowledge should be used to emphasize problem areas and detect possible solutions. Conventional scientific methodologies may often assist in converting potential problems into a broader range of appropriate hypothesis testing.

On a final note, it is imperative to know and understand that in-field experiences offer important information that is worthwhile to comprehending the complications of climate variations, therefore these “in-field” experiences are useful when assessing and identifying if problems and its context are suitable for addressing issues currently discussed at many multinational negotiation panels. Well thought-out, inclusive, case studies should be submitted to policy-makers and academic communities to illustrate how linkages between themes and or concerns can be used to improve communities’ resiliency to a changing climate. Therefore, one of the biggest challenges facing community-based organizations (CBOs) and NGOs, is to convince decision-makers the importance of field experience tactics to surmount a broad scope of environmental problems, along with adaption to catastrophes associated with climate change.

4.6. Future direction in integrating local and scientific knowledge

The effects and variations in climate has already been observed by local communities in their regions and this is testing the ability of communities and institutions to adapt to these new conditions. in order to adapt to altered climatic conditions, it was suggested that local communities should be involved in important policy-decision making, particularly when it comes to climate change (UNFCCC, 2002). Local communities should not only be educated regarding the implications of climatic variations, but they are also competent enough to create favourable outcomes that are more likely to work in their areas (Gupta & Hisschemöller, 1997). Local organizations face the complex and often complicated task of predicting, with accuracy, the future implications of climatic variability. Much research on climate change implications has been done, however, this information is often available in a format or language that common audiences do not have access to **(**Jasanoff, 1997**)**. Thus, a need exist to generate information in a user-friendly manner and in doing so, local communities in vulnerable regions will have the opportunity to access this valuable information; the latter will result in better adaptation to forthcoming conditions.

Apart from this, the academics need to be more conscious of local knowledge and experiences. Many researchers have the inclination to overlook local knowledge generated from practical experience **(**Jasanoff, 1997**)**. Consequently, essential intelligence on field experiences might not be taken into consideration; the latter may result in local contributions being absent from the development of policy-making, or implemention of plans to be unsuccessful.

Although the severity and extent of adverse climatic events are likely to increase, the singular way local communities can adapt to the expected variations is via the reinforcement of adaptation activities already underway (Reed *et al.*, 2006). Therefore, it could be translated that adaptation is a response to enhance the resilience of local livelihoods. The latter can only be accomplished through information-sharing, by practice, and by testing the limitations of present-day projects. Adoption new ways in which to interpret and to incorporate uncertainty in the context of anticipated effects of climate change remains a key driver for adaptation. Without suitable linkages between academic knowledge and local experiences, practitioners, CBOs and NGOs may find it that much harder to design appropriate responses to increased climate variations. The capacity of academic researchers to incorporate experiential knowledge with results generated from scientific inquiry ought to afford academia invaluable input in research and policy consulting work relevant to societies facing dramatic climatic changes.

To cement the importance of indigenous knowledge and experiences and to reinforce aid for local endeavours, CBOs should commence three forms of action **(**Rojas Blanco, 2006**)**. Number one would be to undertake “no regrets” projects such as management techniques to adapt to climate variability e.g. the mulching trials mentioned in this chapter and study. Secondly, circulate knowledge created by these endeavours amongst various organizations and regions and in so doing, dispense knowledge on the challenges and advantages that current environmental projects are facing owing to climate variability. Lastly, it is of utmost importance to link CBOs and the academic community to lead to improved and accurate information being used to determine fittingly designed development and environmental projects.

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Appendix

Interview Protocol

Greeting and introductions

Reminder to interviewee of purpose of research

Repeated reassurance of privacy and confidentiality

Repeated request to conduct and record interview

Biographical information

Gender

Age

Occupation

The observed incidence of plant mortality of wild and cultivated ecotypes i.e. which ecotype experiences mortality first?

Seedling vs. adult A. linearis response to drought stress

Occurrence of branch sacrifice

Harvesting

Observed post-drought response of *A. linearis*

First seedling emergence

Soil preparation

Harvesting

Flowering

Respondents perception of local climate conditions

Perception	Agree	Disagree	Undecided
Temp. getting warmer (Summer)			
Temp. getting cooler (Winter)			
Reduced rainfall			
Rain days have reduced			
Rain days have increased			

Respondent's preceived reasons for a changing climate

Perception	Agree	Disagree	Undecided
Climatic elements naturally vary over time Changes in the environment			
Deforestation Man’s activities			
Fossil fuel burning			
Ozone depletion			