Water use productivity of the rooibos tea crop in the winter rainfall region, Western Cape, South Africa

By

Wasanga Mkhanzi

Master of Science

In

Environmental and Water Science

Department of Earth Sciences, Faculty of Natural Sciences, University of the Western Cape

Supervisor: Prof. D Mazvimavi

Co-Supervisor: Dr D Lötter

August 2023

Declaration

I Wasanga Mkhanzi, declare that the thesis entitled **Water use productivity of the rooibos tea crop in the winter rainfall region, Western Cape, South Africa** is my own work, that it has not been submitted for any degree or examination in any other University, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Full name.: Wasanga Mkhanzi

Date: August 30, 2023

Signed: 

Dedication

To my late father, T.A Mkhanzi, you might not be here, but your words carry me through everything. Thank you for instilling the importance of education in me. I am forever grateful Tata.

Acknowledgements

Firstly, I extend my gratitude to the CSIR and WRC for providing me with the opportunity to be part of their project as well as providing me with funding. To my Supervisor, Prof D Mazvimavi, thank you for allowing me to do master's with the UWC institution. Your input and directions in my research writing are highly appreciated. To My Co-Supervisors, Dr D. Lotter, I am very honoured to have worked with you on this project. I greatly admire your knowledge regarding this topic and working with you shed light on my work. To Dr S. Dzikiti, thank you for always being available to assist me. I have acquired a lot of knowledge in terms of installing equipment and have a greater understanding of my research due to your patience and willingness to help. I am also grateful to Prof. Dube for remembering my name when it was most vital to do so. I would also like to extend my gratitude to my colleague Y. Mkunyana, thank you so much for the free consultations and for being patient with me, I appreciate it. To my husband (Mr. Mpkairi), without your love and support this journey would have been unbearable, thank you. I would not have made it without the support of my friends and family, thank you, for being my rock. Finally, I would like to thank God for his provisions throughout this journey.

ABSTRACT

Aspalathus linearis, commonly known as rooibos or red tea, is one of the well-known herbal tea beverages in South Africa. *A. linearis* is known for its medicinal, economic, traditional and ecological values. This leguminous shrub is endemic to the greater Cederberg Region of the Western Cape Province, South Africa. The area receives winter rainfall. With the Western Cape Province predicted to get drier in future with increasing temperatures and heat waves, the sustainability of range restricted species like *A. linearis* may be negatively affected by climate change. Given the value of the rooibos crop, there is a need to establish the sustainability of rooibos production to mediate the effects of climate change. Henceforth, this study seeks to determine the water use and yield patterns of rain-fed rooibos crops. In addition, the study sought to test how environmental conditions affect rooibos production and estimate the water use efficiency of *A. linearis* under present-day (May 2019-June 2020) conditions in a prime rooibos growing area in Porterville in the Western Cape Province. The study's objectives were achieved by determining the micro-climate, soil physical properties, plant attributes and the water use dynamics of cultivated *A.linearis.* Weather data were obtained from an automatic weather station (AWS). The field leaf area index (LAI) was measured using a LAI-2000 leaf area meter. Plant growth was determined by measuring plant height, width and breath. Soil samples were collected to determine the type and physical properties of the soil at the rooibos field, while soil moisture content was determined in the field using soil moisture probes at 20, 40, 60, 80 and 100 cm depths. Water use of the rooibos crop was quantified using various methods such as micro-stem heat balance sap flow sensors, Penman Montheith equation, open path eddy covariance, FruitLook and the soil water balance method. Lastly, to assess the potential impact of climate change on the rooibos crop, ETo was estimated using two Shared Socioeconomic Pathways (SSPs): SSP1-2.6 and SSP5-8.5.

The results show that the study area is dominated by sandy soils, characterised by a low water holding capacity. The rooibos crop's average growth ranged from 1.0 cm in winter to 12cm in spring. LAI increased steadily from 0.28 in June and reached its peak at 1.56 in December. Declining soil moisture content (SMC) in spring and summer was observed at all depths suggesting that plant water uptake occurs up to at least 100 cm depth for the rooibos crop. Daily transpiration rates peaked in October, reaching 2.0 mm/day. The maximum recorded actual evapotranspiration (ETa) was 2.93 mm/day in September (SWB), 4.52 mm/day in October (EC method) and 21.27 mm/week in October (Fruitlook). When comparing transpiration, reference evapotranspiration (ETo) and actual evapotranspiration results suggest that water at the rooibos field is used mostly by weeds during the early growing season (winter and early spring).

Climatic factors such as vapor pressure deficit of the air and solar radiation were the strongest drivers of transpiration, ETo and ETa (Fruitlook). In contrast, the soil water deficit had a weak influence which was unexpected. Additionally, during the dry season, water use of the rooibos crop is more than the rainfall received at the rooibos farm. Moreover, as soil water deficit (SWD) increased during the dry season, rooibos crop growth increased, reaching a maximum height in January. The observed increase in growth and water use of the rooibos crop whilst SWD increases further suggests that rooibos has external water sources besides the SWC within the 100 cm depth. Moreover, water productivity was calculated as the ratio of yield to the annual ET and was about 0.24 kg of rooibos per m3 of water consumed. Finally, climate change projections from SSP5- 8.5 (between 2019-2040) suggest that if no GHG policies are implemented, the will be an increase in evaporative demand in the rooibos growing region of Porterville.

This study suggests that greater water productivity can be potentially achieved by removing weeds early in the growing season to preserve the residual moisture from the winter rains stored in the soil profile. This information can provide baseline information for developing climate change adaptation strategies in the future.

Key words: Rooibos, Climate-change, Evapotranspiration, Water use efficiency, Soil moisture content, Weeds.

Table of Contents

List of Figures

List of Tables

ABREVIATIONS

E - Evaporation

EC- Eddy Covariance

ET- Evapotranspiration

ETo- Reference evapotranspiration

ETa- Actual evapotranspiration

T- Transpiration

FC-Field Capacity

LAI- Leaf Area Index

VPD- Vapour Pressure Deficit

SR-Surface renewal

SWC- Soil Water Content

SWD- Soil Water Deficit

WUE-Water Use Efficiency

SSP- Shared Socioeconomic Pathways

1: INTRODUCTION

Globally, consumer awareness relating to the benefits of nutrition, health, quality of life, and disease prevention has increased (Joubert and de Beer., 2017). This has been one of the key factors influencing consumers' purchasing decisions for specific foods and beverages. Herbal tea is one such food supplement that has seen rapid growth in the global market due to the growing scientific evidence relating to the health benefits of herbal teas.

For an extended period, numerous plants have been used as 'tea' in South Africa (Watt and BreyerBrandwijk, 1932). However, the most popular herbal teas in the country are rooibos (*Aspalathus linearis*), honeybush (*Cyclopia intermedia*) and bush tea (*Athrixia phylicoides*) (Joubert et al., 2008). Rooibos and honeybush are mainly produced for the global herbal tea market, while bush tea has the potential to have a global demand as it is currently sold informally.

Marnewick (2011) mentions that rooibos and honeybush teas offer a natural, rich source of compounds beneficial to one's health and advises that people should incorporate these herbal teas into their diet to improve their health. Besides health benefits, the rooibos crop has become a beverage of preference as it contains no colorants, additives or preservatives and is free of caffeine. As a result, there has been an increased demand for rooibos plants in both local and international markets. However, rooibos production is likely to be affected by changing climatic patterns, especially recurring droughts (MacAlister et al., 2020). It is with this background that this study seeks to investigate the water use productivity of rooibos plants in South Africa.

The rooibos plant forms part of the Fynbos Biome found in the Cape Floristic Region (CFR), South Africa (see figure 1.1). The CFR is widely recognized as a biodiversity hotspot. Rooibos or *Aspalathus linearis* (also known *as A.contaminata, A.corymbosus, Borbonia pinifolia or Psoralea linaeris*) is a leguminous shrub endemic to the Cederberg Mountains of the Western Cape Province in South Africa. Rooibos is also found as far as Nieuwoudtville in the Northern Cape Province, specifically on the Bokkeveld plateau on the border with the Western Cape. However, most rooibos production is centred in the Clanwilliam and Citrusdal areas (Jourbert et al., 2016). The genus name *Aspalathus* is taken from the Greek word *aspolathos* (a name of a fragrant bush that grew in Greece). The epithet *linearis* originates from a Latin word for linear which refers to the form of the leaves (South African National Biodiversity Institute (SANBI), 2019).

The rooibos shrub has been used as a herbal beverage by indigenous Khoi people since the late 1700's (Joubert and de Beer, 2011). According to Gadow et al. (1997), the Khoisan tribe was the first to establish that one can use rooibos leaves as medicine or to make a tasty tea. The Khoisans used simple processing methods to extract tea from the rooibos leaves. This involved cutting and bruising the rooibos leaves and stems, then the "sweating" of the tea heaps and finally drying tea in the sun. According to Louw (2006), the commercial value of rooibos was not realised until 1904, when one of the locals of Clanwilliam, Benjamin Ginsberg, exported the first packages of rooibos to Europe. During the 20th century, rooibos began to be commercially cultivated for the local and international markets. Rooibos is currently the most important commercially cultivated indigenous crop in South Africa (Hawkins et al., 2011).

1.1.1 Contribution of rooibos to the economic sector of South Africa

Rooibos is exported to approximately 60 countries. Germany, Netherlands, United Kingdom, Japan and the United States of America (USA) are the leading importers of rooibos (DAFF, 2014). At a local level, the rooibos tea industry has contributed to poverty alleviation in the Greater Cedarberg region, where several previously disadvantaged communities have been receiving income from the harvesting and production of this tea (Nel et al., 2007). Statistics from the South African Rooibos Council (2020) show that the rooibos industry provides employment to more than 5000 people in South Africa. Additional employment is created in downstream activities such as processing, packaging and retailing of the plant. The rooibos industry generates approximately R500 million per annum (DAFF, 2013). According to the Rooibos Council, the total rooibos sales in 2019 were equal to just more than 6 billion cups of tea which translates into one cup per human on earth. Production of rooibos does not only contribute to the well-being of locals (people of the Western Cape) but to South Africa as a whole since its export contributes to the country's Gross Domestic Product. Furthermore, rooibos's contribution to the economy has been increasing as consumer demand has been on the rise since trade sanctions were lifted against South Africa in the 1990's. Recently the rooibos sector has been attracting other producers, such as grain farmers, who would like to diversify their crops and take advantage of the easier growing conditions of rooibos.

Rooibos is not only enjoyed as herbal tea but is also used as an ingredient in cosmetics, in slimming products, as a flavoring agent in baking, cooking and cocktails (SANBI, 2019). A report conducted by the Swiss Business Hub in South Africa suggested that globally, rooibos tea seems to be the second most consumed beverage after ordinary tea (*Camellia sinensis*) (Joubert and de Beer, 2011). The increasing global demand for rooibos has led to an increase in sales and production.

For instance, in 1996, only 8.6 tonnes of rooibos were exported, whilst this figure increased to 3300 tonnes by 2000 (Arendse, 2001) and in 2003 to 10400 tonnes (Trade and Investment South Africa,

2004) (Figure 1.1). In the past decade, production has varied between 10 000 and 18 000 tons per year. By the year 2018, rooibos's global consumption reached more than 14 000 tons, as shown in Figure 1.2.

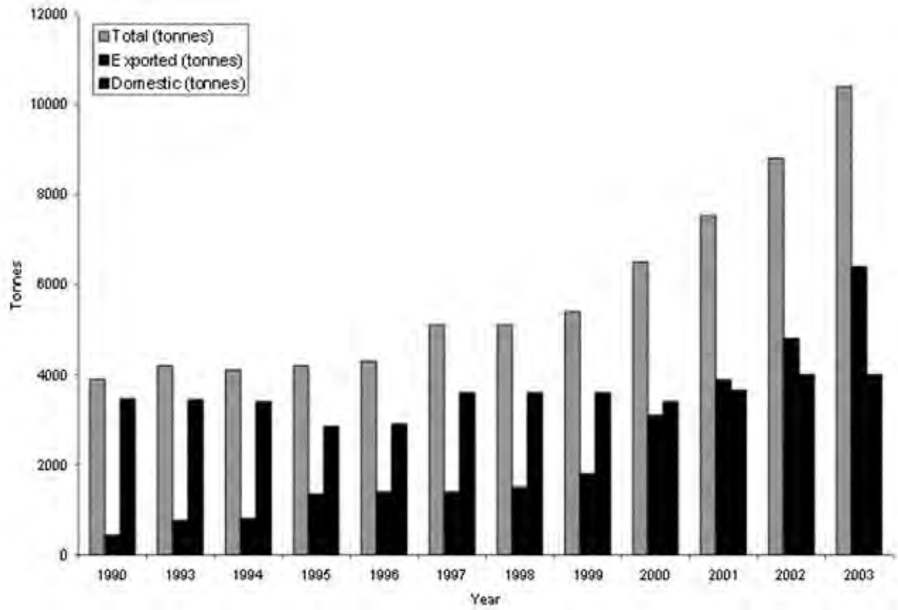

Figure 1.1: Rooibos tea sales figures (tonnes.yr--1) from 1990–2003 (Department of Trade and Industry Rooibos Sector Report, 2004). Information compiled by Willem Engelbrecht from PPECB statistics and other industry sources.

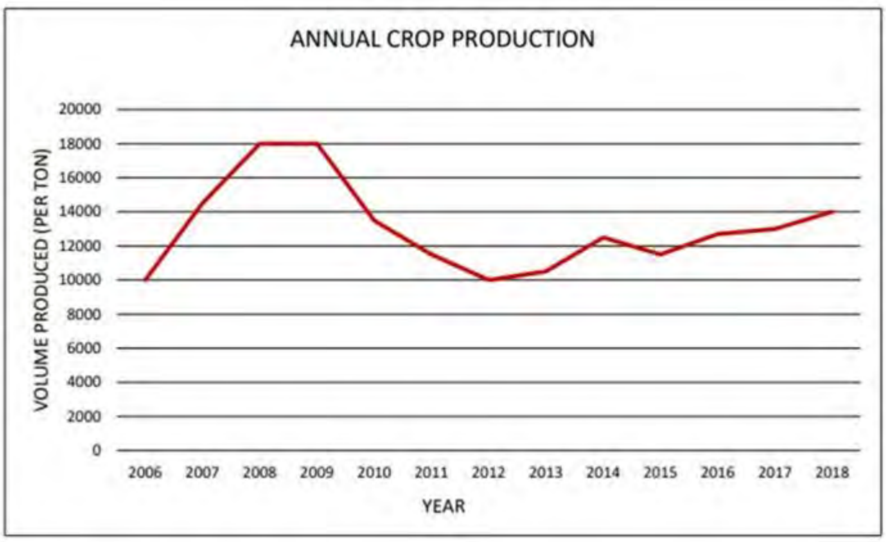

Figure 1.2: Annual crop production of the rooibos crop (Rooibos Council, 2019).

1.1.2 Climatic and soil conditions suitable for rooibos tea crop growth

The rooibos tea crop thrives under very specific climatic and soil conditions hence, this crop is only grown in the region around the Western Coast of South Africa and nowhere else in the world (Lötter, 2015). The Mediterranean climate, characterized by long dry summers and cool, wet winters, is essential for the successful growth of rooibos. Annual precipitation suitable for the growth of rooibos varies between 200-450 mm/yr in winter, with occasional showers during the early and late summer periods. The rooibos crop is sensitive to frost and snow during the early developmental stages. However, the rooibos crop adapts to cold winters and warm summers as it matures. Hence the rooibos crop is adapted to thrive in temperatures ranging from 0◦C- 45◦C. Additionally, the rooibos crop is well adapted to extreme weather conditions such as drought without being severely affected like other rain-fed crops.

Rooibos grows at altitudes ranging from 200-1000 meters above sea level and is adapted to nutrient-poor, well-drained and acidic sandy soils with pH ranging between 3.0 and 5.3 (Muofhe & Dakora, 2000) and where the clay layer is at least one meter below the surface. Rooibos has three specialized mechanisms for the uptake of nutrients, namely cluster roots (Hawkins et al. 2011), mycorrhizal roots for the enhanced acquisition of phosphorus (P) (Lambers et al. 2006) and a well- nodulated root system, which allows efficient fixing of nitrogen (Morton, 1983). However, rooibos's ability to fix nitrogen and the establishment of the symbiotic Rhizobium legume are found to be highly sensitive to drought stress (Sprent, 1972; Kirda et al., 1989).

Figure 1.3: Cultivated rooibos at the selected study area in Porterville (2020/05/23).

1.1.3 Water use patterns of plants

Water plays a significant role in the growth cycle of a plant. Kramer and Boyer (1995) showed that crop yields depend more on an adequate water supply than on any other single environmental factor. Water accounts for more than 70 % of the weight of non-woody plant tissues (Angrish, & Rani, 2007). The water content of plants is in a continual state of flux. According to Ruggiero et al. (2017) the constant flow of water through plants is a matter of considerable significance to their growth and survival. During the process of photosynthesis, plants take up carbon dioxide from the atmosphere. However, this action also exposes plants to water loss through the stomata. To prevent leaf dryness or loss of turgor pressure, water must be absorbed by the roots and transported to other parts of the plants (Angrish, & Rani, 2007; Hopkins, 2008). Maintaining a balance between uptake, transport and water loss is a significant challenge for plants. Although plants tend to use a lot of water, only a small part of the water remains in the plant since 97% of the water taken up by plants is evaporated back into the atmosphere (Hopkins, 2008). Only 2% of the remaining water is used for cell expansion and 1% goes to metabolic processes, predominantly photosynthesis (Ruggiero et al., 2017).

Water plays a significant role in the growth cycle of a plant. Kramer and Plant growth and geographic distribution are greatly affected by environmental conditions. Different environmental factors such as temperature, sunlight, humidity, rainfall and carbon dioxide regulate the number of stomata in developing leaves. This adaptation allows plants to control water relations, minimizing water loss through the process of transpiration and optimizing carbon dioxide fixation (during photosynthesis), therefore increasing water use efficiency. However, if the environmental conditions are not ideal, this will limit the plant's growth and distribution. For example, poor environmental conditions, such as reduced water availability, can cause a plant to wilt and die or make a plant more susceptible to disease or insect attack. Understanding how environmental factors affect plant growth and production helps to meet plant's needs to optimize yield. By recognizing the roles of these factors, one may be able to diagnose plant problems caused by environmental stress.

Water use of plants is primarily influenced by changes in climatic conditions such as increased temperature, variations of precipitation, humidity and the concentration of carbon dioxide. Furthermore, climate change will increase the water demand of crops as well as limit soil water availability as a result of increased variation in precipitation during the growing season (Trenbreth, 2011; Collins et al., 2013).

Climate change is a reality in the rooibos growing region; hence it is vital to determine the water requirements of the rooibos crop to ensure sustainable productivity and conservation of this endemic species. During the year 2015, the Western Cape Province recorded the lowest annual rainfall since 1904 (Botai, 2017). Additionally, SmartAgric (2015) projected that the Western Cape Province is expected to get warmer in future. The Intergovernmental Panel on Climate Change's (IPCC) 4 th assessment report shows that annual rainfall will be reduced by 15-20% and temperatures will increase by 1-2 ^{o}C from 2040-2060 and by 5 ^{o}C from 2080-2100 (Malherbe et al., 2013), in the rooibos growing region. Since the rooibos growing region receives a limited supply of water, high temperatures ranging between 2- 4 ^{o}C in conjunction with further negative changes could significantly affect the hydrological and climate regime of the region. The Rooibos Council (2019) mentions that the rooibos crop's production is highly dependent on the quantity and distribution of rainfall received (since it is a rain-fed crop), hence, the projected climatic condition poses significant threats to plant development and yield. Therefore, this study attempts to assess the environmental factors that influence the water use patterns of rooibos plants in the Western Cape Province of South Africa.

1.2 Problem statement and Justification

Currently, there is a limited understanding of the water requirements for rooibos crop production and the environmental factors influencing the growth and productivity of rooibos. Most studies related to rooibos focus on the medicinal properties, chemical composition and processing of the plant. For instance, Diane and Blumberg (2007) and Joubert and de Beer (2011) review numerous studies on the medicinal properties, composition and processing of the rooibos crop. In addition, Louws (2006) mentions that most of the attention has been given to the biochemical and antioxidant activity of *Asphalathus linearis*. Other areas of research that receive significant attention on rooibos are pest and disease control, fertilizer type and application levels as well as microbial diversity. van Schalkwyk (2018) investigated the effects of soil depth and fertilization on soil water balance, root development and water-use efficiency biomass (WUEB) of rooibos. Nonetheless, the study focused on soil-water interaction rather than water uptake of the rooibos plant. Previous studies regarding rooibos productivity and water use were mainly based on either climate envelope modelling (Lotter, 2015), or experimental control of moisture conditions under glasshouse (Lotter et al., 2014). These did not account for field observations and measurements of actual water use by the plants over complete growing cycles. Hence further work needs to be done to provide insight on the actual water requirements and water use efficiency of rooibos.

Although the rooibos crop is adapted to harsh climatic conditions, extreme droughts and high temperatures have placed pressure on the yield of the rooibos crop. As a result, farmers have reported that rooibos production has declined whilst demand is increasing (van Schalkwyk, 2018). Evidently, the rooibos industry reported large-scale losses from 2003 to 2012 (SARC, 2019). Nieuwoudt (2017) also reported a decline in yield production during 2016 and 2017 when the Western Cape Province was experiencing a severe drought.

According to Archer et al. (2009), climate change will place significant additional pressure on rooibos production in areas where rainfall is already low and variable. Hence, knowledge of the water requirements of the rooibos crop and how that correlates to yield will help in determine how climate change may impact rooibos production. This will assist farmers in deciding on the viability of rooibos cultivation in specific geographic areas in future and also initiate research on adaptation responses to optimize water use efficiency. Such knowledge will guide the formulation of relevant policies on adapting to climate change and improving farm management practices to produce high yields of good quality tea.

1.3 Research questions

1. What are the diurnal and seasonal water use patterns of the rooibos crop?
2. How does rooibos transpiration rates respond to changes in climatic and soil moisture conditions?
3. How is evapotranspiration in rooibos fields partitioned into plant transpiration and soil evaporation and how is this influenced by rainfall events?
4. How does the water status of rooibos crops vary with environmental conditions?
5. What is the water use efficiency of the rooibos crop (i.e. the amount of tea produced per m^3 of water used) under present-day conditions?

1.4 Aim

The current study aims to investigate the water use patterns of rooibos crops and determine the environmental factors that affect rooibos growth under present-day growing conditions at Porterville in the Western Cape Province.

1.5 Objectives

1. To quantify the diurnal and seasonal variations of water use of rooibos.

2. To establish environmental conditions affecting the water use rates, plant water status, growth, and yield of rooibos.
3. To quantify the water use efficiency of rooibos under the current climatic conditions.

1.6 Study hypothesis

1. Rooibos water use is strongly affected by both climatic and soil factors;
2. Increasing water stress in the root zone increases the water use efficiency of the rooibos crop.

1.7 Significance of the Study

The endemic rooibos crop has particular soil and climatic needs. For example, *A.Linearis* requires soils similar to the Fynbos biome in pH, moisture content, microorganisms, nutrient concentration and a Mediterranean climate to grow effectively (Pretorius et al., 2011). Rooibos Being a range-restricted species, climate change may have a negative impact on the sustainability of the rooibos industry. According to Lotter (2015), analysis of climatic parameters vital for rooibos production (such as rainfall frequency and intensity, temperature extremes and wind speed) show that in the next coming decades, the rooibos crop will experience a shorter period of water availability during winter and prolonged exposure to high temperatures and water stress during summer. In addition, climate change modelling suggests that wild and cultivated rooibos types are at risk of losing between 49.8% and 88.7% in the extent of the bio-climatically suitable areas, most notably along the western and northern side of the rooibos production area by 2070 as indigenous ecosystems are shifting southwards (Lotter, 2015).

The indigenous rooibos crop is of great value in historical, cultural, economic, biodiversity and health terms; hence, sustainability of the rooibos crop is crucial. This study will contribute to improving knowledge of water use status and the impact of environmental factors on rooibos growth and production. This information will help in distinguishing how much water the rooibos crop needs throughout its growing cycle, the season in which it uses more water, and how different climatic conditions (such as temperature, humidity, wind speed and rainfall) affect rooibos production. In addition, this will assist farmers in enhancing yield as they will better understand how environmental factors influence rooibos growth and yield. By recognizing the roles of these factors, farmers will be able to better diagnose plant problems caused by environmental stress or changes in climate conditions. Thereby improving farm management and conservation of the rooibos crop.

1.7 Thesis outline

Chapter 1 provides background and introduction of the study. It also covers the problem statement, research questions, study hypothesis, aim and objective of the thesis. Chapter 2 of the study reviews the relevant literature connected to the current study. This covers information on the rooibos crop, climate change and how it has affected the rooibos crop growing region, environmental factors affecting water uptake of plants and how water uptake can be quantified to achieve the research objectives. Chapter 3 discusses details of the selected study area in-depth as well as the experimental setup in the field. Chapter 4 is composed of results and a discussion of the study. Chapter 5 covers the conclusion as well as recommendations deduced from the results of the study.

2: LITERATURE REVIEW

2.1 Consumption of herbal teas in South Africa.

Herbal teas are derived from plants or parts of plants, usually leaves, roots, flowers or fruits. The use of plants as medicine is common amongst the indigenous population of South Africa due to the variety of vegetal species. The well-known Cape flora comprises close to 9000 species of seed plants (Manning and Goldblatt, 2012), of which more than 60% are endemic. Several plant species in the Cape Floral region have been used as medicine. Nonetheless, over time few have evolved to become commercial herbal teas and functional foods. Examples of these plants include rooibos tea (*Aspalathus linearis*), honeybush tea (*Cyclopia genistoides*), buchu (*Agathosma betulina* and *A. crenata*), hoodia (*Hoodia gordonii*), cancer bush (*Lessertia frutescens*) and kougoed (*Mesembryanthemum tortuosum*) (Van Wyk and Wink, 2015). Amongst the many herbal teas in South Africa, rooibos (*Aspalathus linearis*) is the most well-known followed by honeybush tea (*Cyclopia species*) which has most recently gained commercial success, and lastly bush tea (*Athrixia phylicoides*) which has shown potential commercial success (Joubert et al., 2011). Reichelt et al. (2012) and Lerotholi et al. (2017) mentioned that combining rich ethnobotanical heritage with scientific research, this has led to the sustainable commercialization of indigenous herbal teas in South Africa.

2.1.1 Rooibos ecotypes

Studies by Malgas et al. (2010); Hawkins et al. (2011) have distinguished several ecotypes (wild types) of the rooibos crop. van Heerden et al. (2006) differentiated rooibos tea 'types' based on distinct morphological and chemical differences. According to Morton (1983), rooibos occurs naturally in four forms: Rooi Tea, Vaal Tea, Swart Tea and Rooibruin Tea. Rooi Tea is further subdivided into two types, namely Nortier (this is the one that is commercially cultivated by producers) and Cederberg type, which, whilst alike, grows in the wild in the Cederberg Mountains around Clanwilliam and is broader and coarser than the Nortier type. Vaal Tea, Swart Tea and Rooibruin Tea were harvested before 1966, but due to their poor quality, their harvesting was seized. The rooibos crop can be harvested in the wild, but 99% is cultivated (Waarts, 2008). This study focused on the rooibos tea crop that is commercially cultivated (Notier type) and is the most widely cultivated (Joubert and Schultz, 2006).).

Cultivated rooibos

A study conducted by Cheney and Scholtz (1963) described the Nortier type *A.linearis* as an upright, thin-stemmed shrub that reaches up to 1.35 to 2 m in height with a taproot system that is 2 meters deep. The rooibos crop is closely related to other South African low-bushy legumes of the genera *Lebeckia* and *Cyclopia.* Moreover, the Nortier type has long, fragile red-brown branches (approximately 60 cm long) with 2-6 cm long linear needle-like leaves. According to the South African Rooibos Council (SARC) (2016), the long needle-like leaves reduce the surface area, thereby limiting moisture loss on hot days. In spring and early summer, dense yellow flowers appear at the tips of the branches. The fruit is a small lance-shaped pod usually containing one or two hard seeds (SANBI, 2019). *A. linearis* (Nortier type) is commercially cultivated in Piketberg, Clanwilliam, Vanrhynsdorp, Wuppertal and Nieuwoudtville.

Figure 2.1: Cultivate rooibos (Nortier type) at the selected study area in Porteville.

2.2 Effects of climate change in South Africa

Global climate is changing radically due to greenhouse gas emissions in the post-industrialisation era. Van Der Merwe (2005) mentioned that scientific evidence collected from ecologists, climatologists, geomorphologists, and hydrologists suggests that climate change is occurring in South Africa. The observed evidence shows that there is a likelihood of a significant increase in air temperature, decrease in regional rainfall and ecosystem changes. Moreover, continued climate change may result in a widespread increase in evaporation and further drying over southern Africa's western regions, including the Western Cape and Northern Cape Province of South Africa.

Kruger and Seleke (2012) found warm extremes to have increased while cold extremes decreased in South Africa during the 1962-2009 period. The western half and parts of the northeast of South Africa experienced stronger warm extremes and a decrease in cold extremes compared to other parts of the country. South Africa is expected to have increased variation in rainfall. The summer rainfall region is expected to be wetter, whilst the winter rainfall region will experience drier conditions (DEA, 2013). Hewitson and Crane (2006) made similar conclusions. Climate change, therefore, poses a critical threat to the region's water resources, agriculture, health, infrastructure, ecosystem services and biodiversity, amongst other sectors.

2.3 Climate change in the Western Cape Province

The Western Cape Province experiences a Mediterranean climate, characterised by cool, wet winters and warm to hot, dry summers. Tyson et al. (2002) suggest that the Mediterranean climate may now be changing, as temperatures have been increasing and rainfall decreasing, mainly in the winter season. Similar conclusions were made by Lötter and Maitre (2014) about climate change in the rooibos growing region. A review of climate change in the Western Cape (Smart-Agric, 2016) indicates increased temperature in the future, with more significant increase inland and a lower increase along the coast. The following changes are thus expected, higher mean annual temperatures, higher maximum temperatures, more hot days and more heat waves, higher minimum temperatures, fewer cold days and frost days. However, analysis of rainfall data from the Western Cape over the years shows that there have been statistically few significant changes in annual precipitation. However, results from a study conducted by Midgley et al. (2005) suggest that the projected future impacts of global climate change will result in the rainy season arriving much later in the Cape Floral Region, whilst Hewiston et al. (2005) suggested that the rainy season arrived earlier from March-May whereas June-August displayed a drying trend.

2.4 Climate change and Rooibos

Plants have preferences for certain climatic conditions, such as combinations of temperatures, rainfall (SANBI, 2007) and soil type. Rooibos is a good example of such species, which is only adapted to grow within a certain range of climate, with specific soil conditions. The ability of species to adapt to climates is controlled by the physiological tolerance of the species (for example, seed production or flowering and growth of certain plants may be limited by high-temperature conditions). Hence, changes in climatic conditions may have possible negative effects on biodiversity. Consequently, an estimated 23% of the Fynbos biome could be vulnerable to species extinction (SANBI, 2018). In addition, climate change can also lead to a shifting of geographical ranges or adaptation strategies.

Modelling of species' geographic ranges shows that for endemic species of the CFR, the ranges tend to shrink (Midgley et al. 2002, Midgley et al. 2003) This is because the CFR is located at the southern tip of the African continent. With increased temperatures geographic ranges of species up mountain slopes are forced southwards in the ocean. Over time species affected by shrinking geographical ranges may be extinct (SANBI, 2007).

Lötter (2015) investigated whether there is evidence of climate change over the rooibos distribution area. The study examined various climatic parameters, including rainfall frequency, intensity, temperature extremes, and wind speed, which affect rooibos production. The results indicate that the crop will experience shorter periods of winter rainfall and prolonged exposure to high temperatures and water stress in the future (Lötter, 2015). Under these conditions, climate modelling suggests that by 2070, wild and cultivated rooibos types are at risk of losing between 49.8% and 88.7% of the natural growing area, particularly along the western and northern border of the rooibos production area (Lotter, 2015).

According to Rafferty (2018), climate change projections suggest that the much-needed precipitation will arrive later than expected, which poses a significant threat to rooibos production. The production of rooibos varies according to the amount of rainfall received since it is a rain-fed crop (Lotter et al., 2013). Research shows that water stress during summer is a significant factor affecting rooibos' growth and productivity (Boyer, 1982). This is because of water stress in *A.Linearis* is associated with a significant decrease in stomatal conductance and transpiration (Lotter et al., 2014).

Regarding concerns about climate change, there has been a noticeable difference between cultivated and wild rooibos crops. The cultivated Nortier type is less resistant to droughts and pests compared to the wild types (SANBI, 2007; Lotter, 2015). Garcia et al. (2004) mention that although some crops are adapted to survive harsh environmental conditions, yields are affected because crops must sacrifice production to develop drought and frost resistance mechanisms.

Archer et al. (2008) conducted research to obtain the knowledge of local farmers on climate change and its effect on rooibos by employing a participatory action research (PAR) approach. The results revealed that the late arrival of winter rainfall, increased occurrences of drought episodes and heat stress might decrease yield and overall quality of rooibos. In support of these findings, Sishi (2018) also mentions that recurring droughts have contributed largely to the decrease in production yield and export of *A. Linearis*. Henceforth this will affect the sustainable growth of the endemic rooibos crop, which has significant medicinal and commercial value.

2.5. Environmental factors influencing water use of crops.

Understanding the process of evapotranspiration is crucial in determining water use by a plant since the quantity of water required for plant growth greatly depends on the quantity of water lost through transpiration (Schuch & Burger, 1997). Hence the total amount of transpiration for a particular plant over an entire growing region is the same as the seasonal water requirements of the plant. Recently much research has focused on addressing the impacts of climate change on evapotranspiration in relation to the increase in vapour pressure deficit, temperature, precipitation and wind speed (Harmsen et al., 2009). Sarkar and Sarkar (2018) highlighted that ET rates depend on energy, water availability at the evaporation site and the vapour pressure deficit. As much as ET is influenced by several climatic and biological factors, precipitation influences 60% of the total ET (Hu et al., 2018).

There are four changing factors in climate that will affect the water use of plants. These factors are increasing carbon dioxide (CO_2) concentrations, increasing temperatures, more variable precipitation, and variations in humidity (Haltfield and Dold, 2019). The mentioned changes will result in the increase of atmospheric water demand by crops and decrease soil water availability especially for soils with low water holding capacity. Xiao et al. (2013) observed that the spatial patterns in carbon and water fluxes were dependent on annual temperatures, precipitation and length of growing season when they compared these fluxes across a range of latitudes using eddy covariance flux systems.

When moisture is not a limiting factor, ET depends primarily on solar energy available to vaporise the water. Due to the importance of solar energy, ET also varies with latitude, the season of the year, the time of the day and cloud cover. According to Hanson (1991), the distribution of the average daily solar radiation for the United States shows a regional variation similar to that of mean annual lake evaporation as well as mean annual temperature. The temperature increase due to climate change might increases the rate of ET due to increased vapour pressure deficit. In addition, higher temperatures might cause the plant cells, which control the openings (stoma), where water is released into the atmosphere, to open, whereas colder temperatures cause the openings to close. Minimum ET rates usually occur during the year's coldest months, whereas maximum ET rates occur during summer (warmest months). Climate change projections for the Western Cape suggest a warming of 1.5°C to 3°C around 2050 (WIDER, U.N.U, 2016). As a result, parts of the province will experience more hot days, fewer cold days and increased evaporation.

According to Lawrence (2005), the amount of water vapour that the air can hold, the saturation vapour pressure, is a curvilinear function of air temperature. Thus, as global land surface temperature increases, the saturation vapour pressure of the atmosphere increases. However, actual vapour pressure has not been increasing at the same rate such that the difference between the saturation and actual vapour pressure, known as vapour pressure deficit (VPD), is rising (Hatfield & Prueger, 2015). High VPD causes plants to close their stomata to minimize water loss and avoid critical water tension within the xylem (Running, 1976), reducing the rate of photosynthesis. High VPD increases the land surface's evaporative demand, thereby increasing ET rates (Massmann et al., 2019). As atmospheric demand for water increases, ecosystems may begin to reach their water conservation limits and might be unable to entirely limit ET flux to the atmosphere. This increases water loss rates from moist soils, causing drying and heating of the terrestrial surfaces and contributing to more frequent, severe drought events and plant water stress (Dai, 2013). As such, VPD is a significant determinant of global water resources and plant water relations and could become increasingly crucial for vegetation dynamics over the coming decades due to global temperature rise.

Sarkar and Sarkar (2018) reviewed several research studies on the impact of climate change on evapotranspiration. One of the studies reviewed was conducted in India (semi-arid areas of Rujathan) to investigate the sensitivity of ET to global warming. The study suggested an increase of 14.8% in total ET demand with an increase in temperature by 20 % (maximum 8°C). Further, a study conducted by Harmsen et al. (2009) in the Lajas location of Puerto Rico on the effect of climate change on evapotranspiration showed an increase in ET rates due to increasing temperature and precipitation. Sarkar and Sarkar (2018) concluded that the rate of ET increases with the increase in temperature, precipitation and wind speed and decreases with the increase in humidity in the atmosphere.

Jovanovic et al. (2015) studied evapotranspiration dynamics in South Africa using MOD16 ET satellite-derived data. The results showed that rainfall and atmospheric evaporative demand are the main climatic variables driving ET, particularly its transpiration component. Additionally, evapotranspiration (ET) is strongly dependent on transpiration (T) in all climatic regions, and occasionally on soil evaporation (E) in dry areas with sparse vegetation. The highest ET, canopy E, soil E and T were under tropical conditions and the lowest in an arid and semi-arid climate. The Institute of Food and Agricultural Sciences (1999) in Florida found that citrus tree ET estimated using soil water balance followed a seasonal pattern, with the lowest values during December and the highest values in July (Florida receives rainfall during winter). These findings suggest that water availability influences a significant part of the process of ET.

2.6 Water Use Efficiency (WUE)

WUE is expressed as a ratio between the total yield of the plant and the energy or resource invested in the process (Bhattacharya, 2019), which is the water used to produce the crop, which is equivalent to evapotranspiration (Equation 2.1). Blum (2009) suggests that WUE can be used to imply that rain-fed plant production can be increased per unit of water used, resulting in “more crop per drop”. An overview of water use efficiency is provided below (Figure 2.2).

WUE is given by:

$$WUE = \frac{Yield}{ET} (\text{kg/m}^3) \tag{2.1}$$

where yield is expressed in kilograms per hectare (kg/ha) and ET is expressed in cubic meters/hector (m^3 /ha).

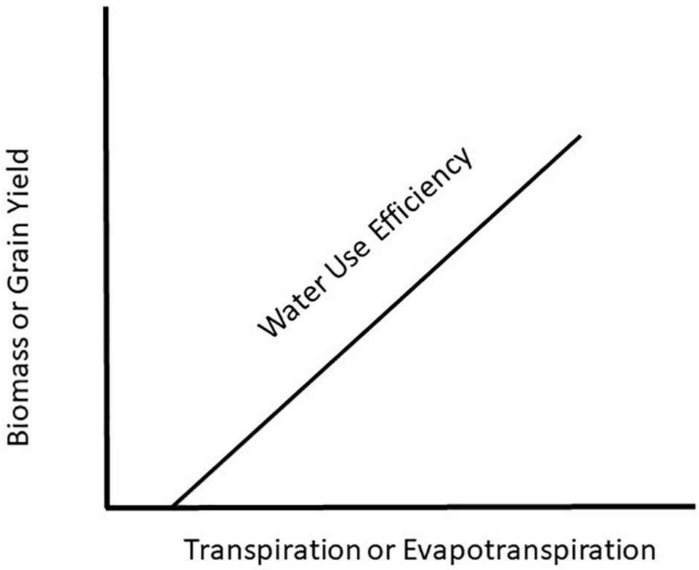

Figure 2.2: Generalized relationship of water use efficiency as a function of the water use by a crop relative to biomass or grain production (Basso and Ritchie, 2018).

WUE can be estimated at different scales. At an agronomic level, it is defined as the ratio of water used in crop production versus biomass or yield (Medrano et al., 2015). At a plant physiology level, WUE is the amount of carbon dioxide fixed in photosynthesis relative to the amount of water vapor lost to the atmosphere (Condon et al., 2004). Different plant species have different WUE for example, the

WUE of C4 plants is two times more than that of C3 plants. This is due to C4 plants' advantage over C3 plants in photosynthesis rates. Another factor that increases WUE is partial stomatal closure, which generally reduces water loss out of a leaf more than it reduces CO_2 uptake into the leaf, thus increasing dry matter accumulation per unit of water transpired (Zhang et al., 2017). Improving crop water use efficiency can increase crop production levels and the efficient use of water resources under climate change conditions.

Niu et al. (2011) tried to understand climate change's influence on WUE at different scales. WUE was investigated at leaf, canopy and ecosystem levels under increased rainfall and temperature conditions in a temperate grassland in Northern China from 2005 to 2008. They measured gross ecosystem productivity, net ecosystem CO_2 exchange, evapotranspiration, evaporation, canopy transpiration, and leaf photosynthesis and transpiration of a dominant species. The results showed that increased precipitation stimulated WUE at a canopy and ecosystem level by 17.1% and 10.2%, respectively, but decreased leaf WUE by 27.4%. Over 4 years, WUE at the plot, canopy and ecosystem level linearly increased, but leaf level WUE of the dominant species linearly decreased with increasing precipitation. The differential responses of canopy or ecosystem WUE and leaf WUE to climate change suggest that caution should be taken when upscaling WUE from leaf to larger scales.

Zhang et al. (2015) investigated the impact of climate change (temperature, precipitation) and agronomic measures (e.g., fertilization, cropping patterns) on crop WUE in the late twentieth century (1983–1999) and a drier, warmer environment in the early twenty-first century (2000–2010). Crop WUE was sensitive to climate change and agronomic measures. Changes in temperature and precipitation during the past 3 decades enhanced crop WUE by 8.1%-30.6%. Furthermore, crops tend to reach the maximum WUE in a warm-dry environment while reaching a stable minimum WUE in a warm-wet environment. These results show that crops have the ability to adjust WUE, which allows plants to respond to subsequent periods of favorable water balance as well as tolerate drought stress and reasonable agronomic practices could enhance this resilience. However, this capacity would break down due to climate changes and improper agronomic practices (e.g., excessive N/P/K fertilizer or traditional continuous cropping).

Guojo et al. (2013) investigated the effects of climate change on crop WUE in a semi-arid region by statistically analyzing crop yields, soil moisture, rainfall and temperature data over 50 years. The results showed that a temperature rise of 1.6 °C and an annual rainfall reduction of 105.6 mm occurred between 1990 and 2009 and the WUE of wheat, potatoes and corn increased by 10.7, 4.5 and 12.2 kg hm^{-2} mm^{-1}, respectively. This, therefore, proves that climate change can improve WUE.

Lötter (2014) conducted a study on photosynthesis and water relations of rooibos. The results showed that during late winter, under favourable soil moisture conditions the cultivated rooibos crop had increased gas exchange rates compared to the wild rooibos type. On the contrary, during the dry summer months, the wild tea exhibited an increased ability to adapt to the limited soil moisture conditions by sustaining higher photosynthetic rates. In addition, *A.lineris* showed an ability to maintain high WUE's enabled by effectively controlling water loss through transpiration. This enhanced ability to adapt to dry conditions may be related to their higher sclerophylly index, an essential protective mechanism to resist extreme climatic conditions (Turner, 1994). Nevertheless, under present conditions, the wild rooibos type is better adapted to summer drought and has greater WUE.

van Schalkwyk, (2018) determined the average biomass water use efficiency (WUE_B) of rooibos on the 27th of February 2017. The results showed that WUE_B of rooibos under unfertilized shallow soils was higher compared to fertilized deep soils. Although the soil water content on shallow soils was lower compared to the deep soils. Nonetheless, the WUE_B results were found to be inconclusive due to the stoppage of the SWB in April 2017 whilst the plants were still immature. Given how the soil water content was during the growing seasons, the WUE_B on deeper soils may be the highest due to the likelihood of higher water storage and biomass production at the deep site. This is evident in the study's conclusion, which is young rooibos plants growing in deeper soils with higher soil water storage will result in higher yield.

2.9 Quantifying water uptake of plants

Knowledge of the water use by vegetation is essential for water resources management, especially in arid regions that experience water stress. In these regions, evapotranspiration (ET) is the dominant component of the water balance and potential evaporation is much higher than rainfall. It is imperative that ET be accurately quantified (Jovanovic et al., 2012). As this is a crucial variable in water resources management, agriculture, and ecology (Khan et al., 2010). Several methods are used to quantify ET. These methods are divided into the following categories: hydrological approaches (Lysimeter, water balance), micro-meteorological methods (Bowen ratio, eddy covariance, scintillometer, Penman

Monteith method), plant physiological approaches (sap flow technique, stable isotope technique) and use of remote sensing data (Liu and Xu, 2019). The choice of ET quantification method should be based on a thorough understanding of the strengths and limitations of each method, as well as its suitability for the specific research objectives and conditions.

2.9.1 Penman-Monteith equation

The well-known Penman-Monteith (PM) evapotranspiration equation was adopted by the United Nations Food and agriculture organisations (FAO) as a global standard for calculating reference evapotranspiration from climatic data (Allen et al., 1998). According to Ellen et al. (1998), reference evapotranspiration is defined as the ET rate from a uniform surface of dense, actively growing vegetation having specified height (0.2 m) and surface resistance (70 s/m), albedo (of 0.23) not short of soil water and representing an expanse of at least 100 m of the same or similar vegetation (Allen et al., 2005). This method uses meteorological data which can be acquired from a weather station.

The Penman-Monteith equation is expressed as:

$$ETo = \frac{0.48\Delta(Rn-G)+\gamma\left(\frac{900}{T+273}\right)u_2\,(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)} \quad \text{mm/day} \qquad (2.2)$$

where ET_o = reference evapotranspiration, mm day^{-1}; R_n = net radiation at the crop surface, MJ m^{-2} d^{1}; G = soil heat flux density [MJ m^{-2} d^{-1}]; T = mean daily air temperature at 2 m height [°C]; u_2 = wind speed at 2 m height [m s^{-1}]; e_s = saturation vapour pressure [kPa]; e_a = actual vapour pressure [kPa]; e_s-e_a = saturation vapour pressure deficit[kPa]; Δ = slope of the vapour pressure curve [kPa ºC^{-1}]; γ= psychrometric constant [kPa °C^{-1}.].

This equation is commonly considered the most reliable in a wide range of climates and locations because it is based on physical principles and considers the main climatic factors (namely air temperature, radiation, wind speed and humidity) which affect evapotranspiration. Furthermore, reference evapotranspiration gives a standard by which evapotranspiration of different periods of the year or different regions can be compared, and the evapotranspiration for different crops can be related.

The disadvantage of using the Penm"n-Monteith equation is that it requires a very large number of inputs, many of which are difficult to accurately estimate or observe in regions with few observations (Ahooghalandari et al., 2016). Often in developing countries available meteorological datasets are inaccurate, and sparse, especially concerning global radiation or sunshine hours, water vapour, pressure or relative humidity, and wind speed (Almorox et al. 2015).

2.9.2 Surface renewal method

Surface renewal (SR) is one agro-meteorological method used to estimate crop ET (McElrone et al., 2013). This method is appropriate in flat and large fields to ensure a uniform fetch around the flux tower. SR method is based on analysing the energy budget of air parcels that reside ephemerally within the crop canopy during the turbulent exchange process. This theory suggests that an air parcel quickly moves to the surface and remains connected with the surface for a period of time, after which it is cooled due to the sensible heat exchange between the air and plant canopy elements. The air parcel then moves upwards and is renewed by another parcel that moves towards the surface (Castellv et al., 2008; Yongguang et al., 2018). The SR method has been modified over the years to make it reliable without needing calibration. With the SR method, ET for a given crop surface is determined by calculating latent heat flux density (LE) as the residual of the following energy balance equation:

$$LE = Rn - G - H \quad (W/m^{-2}) \tag{2.3}$$

where LE is the latent heat flux (energy used to evaporate water), Rn is the net radiation absorbed by the surface, G is the soil heat flux into or out of the ground and H is the sensible heat flux (energy used to warm up the air). Rn is measured using a net radiometer, G is measured using soil heat flux plates installed in the ground, and H is measured using a fine wire thermocouple which measures air temperature at a high frequency, typically 10Hz. All the mentioned parameters are measured using the same unit W/m -2. Rn is a positive number when the net flux is downward (energy added to the surface), LE and H are positive numbers when the flux is upwards (energy added to the air), and G is a positive number when the flux is downward (energy added to the soil). LE (MJ/m2sec) is then divided by the latent heat of evaporation (L=2.45 MJ/kg) to obtain the mass flux density of water vapour from the surface (i.e., ET).

The advantage of this method is that measurements can be replicated at a lower cost and is easy to use. Furthermore, the SR method is useful for non-homogenous surfaces and can produce acceptable results on hilly fields. The SR method performs well for surfaces with dense canopies. Several studies have successfully utilized this method, including Moran et al., (2015), Suvočarev et al., (2019), and Gray et al., (2021). However, a disadvantage of this method is that it must be calibrated against a sonic anemometer to account for unequal heating of air parcels below the temperature sensor height and other potential deviations from the assumptions used in formulating surface renewal theory (Mengistu, 2008). In addition, the SR method cannot produce acceptable results in places with high humidity. The Accuracy of this method is highly dependent on the correct estimation of Rn and G.

2.9.3 Eddy covariance (EC) method

The eddy covariance system was initially used for meteorological and research purposes; however, due to the cost of equipment becoming affordable, it is now used in agriculture and water resources research (Moorhead et al., 2019). EC is a micro-meteorological method popular for directly observing the exchange of gas and energy momentum between the land surface and the atmosphere (Allen et al., 2011). The EC method obtains turbulent flux data by calculating the covariance of fluctuations in the vertical wind velocity and the quantity of interest (plant canopy). This method is also able to directly measure the carbon, water, and heat flows between plant communities and the atmosphere. With currently available technology, air mass and energy flux fluctuations on several time scales (hour, day, season and year) and on spatial scales of 100-2000 m can be measured (Liang et al., 2012). Studies have confirmed the EC technique to be the most efficient method for measuring the interactions between a terrestrial biosphere and the atmosphere on an ecological scale (Baldocchi, 2008).

The eddy covariance system is based on fluxes of momentum, heat and mass over crop canopies due to eddies that result in air turbulence. These fluxes can be determined by measuring the air temperature (Ta). Moreover, vertical wind speed (ω) at high frequencies, usually 10-20 Hz, and by calculating the covariance between them. Measurements are based on the correlation between the turbulent motions of air and the turbulence of constituents being transported by turbulent motions, e.g., heat or water vapour (Stevens, 2007). Sensible heat flux is therefore estimated as:

$$H = P_a C_p \sum(\omega - \bar{\omega})(Ta - T\bar{\bar{\bar{a}}}\ ) \qquad (2.4)$$

Where Ta is the air temperate, Ta ω is the instantaneous deviation of the vertical wind speed, H is the sensible heat flux, Pa is the air density, whilst Cp is the specific heat at constant pressure. The latent heat flux λE is calculated as the residual of Equation (2.4). Using Equation (2.4) assumes surface energy balance closure (Burba and Anderson, 2010) which is not always attained in practice. Hence an alternative way to obtain direct measurements of ET can be achieved using the EC through the covariance of the vertical wind speed and the atmospheric water vapour concentration, which is measured by and infrared gas analyser.

$$\lambda E = \lambda \frac{Mw/Ma}{P_a}\ P_a\ \overline{\omega' e'} \qquad (2.5)$$

Where *Mw* and *Ma* are the molar masses of water vapour and air (g mol-144), P_a (kPa) is the atmospheric pressure, ω' is the instantaneous deviation of the vertical wind speed and e' is the air vapour pressure.

Figure 2.6.: Eddy covariance micrometeorological station in Porterville farm.

The disadvantage of the EC method is the cost of the equipment. It is prone to distortions produced in the sonic signal by rainfall, fog, insects and dirt. Additionally, a complete understanding of the optimal system set-up and the handling of EC raw data is still under development (Castellvi et al., 2008).

2.9.4 Soil water balance

Evapotranspiration can be determined by measuring the various components of the soil water balance. Rain or irrigation water reaching a unit area of soil surface may infiltrate into the soil or leave the area as surface runoff. The infiltrated water may (a) evaporate directly from the soil surface, (b) be taken up by plants for growth or transpiration, (c) drain downward beyond the root zone as deep percolation, or (d) accumulate within the root zone, (Figure 2.7) Evaporation from the soil coupled with crop transpiration reduces water from the root zone.

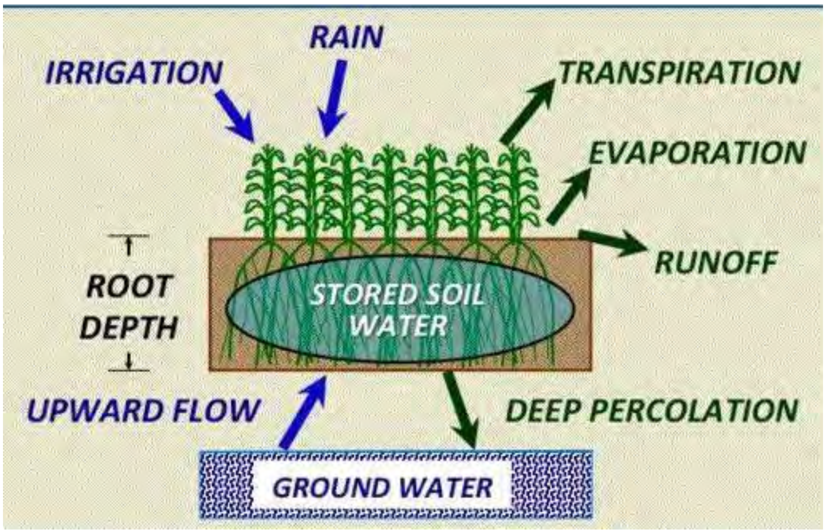

Figure 2.7: Showing the distribution of soil water for crop production (Steve Melvin, 2019)

The water balance method is based on the conservation of mass which states that change in soil water content (ΔS) of a root zone of a crop is equal to the difference between the amount of water added to the root zone (Qi) and the amount of water withdrawn from it (Qo) in a given time interval (Hillel, 1998) expressed in an equation as:

$$\Delta S = Q_i - Q_o \quad (2.6)$$

Equation 2.6 can be used to determine evapotranspiration of a given crop as follows:

$$ET = P + I + U - R - D - \Delta S \quad (2.7)$$

ΔS = change in root zone soil moisture storage, P = Precipitation, I = Irrigation, U = upward capillary rise into the root zone, R = Runoff, D = Deep percolation beyond the root zone, ET = evapotranspiration. All quantities are expressed as volume of water per unit land area (depth units)

In order to use equation (2.7) to determine evapotranspiration (ET), other parameters must be measured or estimated. Measuring the amount of water added to the field by rain and irrigation is relatively easy. The amount of runoff is generally small in agricultural fields, so it is often considered negligible. When the groundwater table is deep, capillary rise U is negligible. The most difficult parameter to measure is deep percolation D. If soil water potential and moisture content are monitored, D can be estimated using Darcy's equation. The water balance approach is simple and sound in theory and warrants an accurate estimate of ET as long as the other water components can be accurately measured (Tilahun and John 2012).

2.9.5 Lysimeters

A lysimeter consists of a mass of soil in an enclosed container which can be accurately weighed to determine the amount of water lost or gained per unit of time (Moorhead, 2018). There are two main types of lysimeters: the drainage and weighing types. The drainage lysimeter obtains evaporation as the difference between the added and drained water quantity. In weight-based lysimeters, changes in the total weight of the soil sample are measured (Johnson and Odin, 1978); where ET is estimated:

$$ET = \frac{Vl + Vr + \Delta V_S}{A} \tag{2.8}$$

Where P is the precipitation, Vl is the volume drainage loss m3, Vr is volume of surface runoff m^3, ΔVs is the change in the volume of soil water in the lysimeters and A is the area of the lysimeters m^2 (Seyfriend et al*.,* 2001).

The disadvantage of using the lysimeter is that they can be very complex and expensive to install and operate. Additionally, lysimeters estimate ET for a single point and may not be applicable to large areas (Mkunyana, 2018).

2.9.6 Sap flow technique

At a plant scale, a sap flow-based technique is mainly applied to measure transpiration in herbaceous plants. Transpiration flow through a plant is measured by sap sensors that monitor the ascent of sap within the xylem tissue. These measurements can be made in the trunks, stems, branches or tillers. Since transpiration is sensitive to the water status of a plant, with the effect being mediated by openings of the stomata, sap flow can be used as an indicator of plant water status. Two different methods can be used to measure sap flow: the stem (or trunk) heat-balance method and the heat–pulse method.

The stem (or trunk) sector heat balance method explores a section of the stem. The circumference of the stem is electrically heated and then the axial and radial heat loss is measured. The sap flow rate is calculated as a function of the heat dissipated by the ascending sap. Whilst the heat-pulse method requires a heater and temperature sensor probes to be placed inside the stem in a radial direction. The velocity of sap is determined by the time required for the flowing sap to transport heat from the source to the sensor up and down the stem (Kirkham, 2014). The heat-pulse method has been in use since the time of Huber (1932) and is relatively older than the heat-balance method, which can be traced to Vieweg and Zeigler (1960).

The sap flow technique has the ability to not induce modification of the environment and allows for continuous monitoring over a prescribed period of time. It measures transpiration only (Chabot et al., 2005). However, when using the sap flow technique, it is crucial that the user is aware of potential sources of error and takes suitable precautions. Otherwise, errors in sap flow rates can become much more significant (Groot and King, 1992), especially if assumptions in underlying theory are contravened.

2.9.7 Fruitlook

Water is essential for agricultural productivity. Hence, the Western Cape Department of Agriculture (WCDoA) has provided farmers with a tool called Fruitlook to increase their water use efficiency (WCDoA, 2016). The Fruitlook tool enables the user (farmers) to improve their WUE by using spatial data derived from remote sensing as well as meteorological data measured locally. Fruitlook uses eLEAF's Pixel Intelligence technology (PiMapping), which consists of a toolkit of proprietary algorithms that combines satellite data with meteorological and other bio-physical information, i.e. data that can be recorded as mm, kg, °C on crop, water, and climate processes.

The PiMapping data components are based on the Surface Energy Balance Algorithm for Land (SEBAL), which has become one of the leading algorithms internationally for estimating actual evapotranspiration (Roux et al., 2019). The data products describing crop water and growth status are calculated through the SEBAL algorithm. The SEBAL model estimates energy and evapotranspiration fluxes from earth observation data at different spatial scales ranging from the field to entire catchments. Inputs on land characteristics and atmospheric properties (such as the vegetation index, surface albedo, and surface temperature) are derived from satellite data. In addition, SEBAL requires spatially extrapolated meteorological data (wind speed, humidity, and air temperature) from local weather stations. SEBAL determines actual and potential evapotranspiration on a pixel-by-pixel basis. Besides crop evapotranspiration, SEBAL estimates biomass production, evapotranspiration deficit, leaf area index, and biomass water use efficiency on a weekly basis. The results produced with the data processing tools are available through the Fruitlook web portal (Fruitlook Manual, 2019).

2.10 Chapter summary

This chapter highlights the herbal teas that are of commercial importance in South Africa. It also notes that climate change poses a significant threat to the sustainability of the rooibos industry. Rooibos is a crop that holds value for South Africa's economy, culture, health, and history; therefore, it is important to conserve it. However, the cultivated rooibos crop is less resistant to drought than the wild type, which means that climate change projections are likely to have a more significant impact on the plant yield and performance of the cultivated rooibos crop. Climate change is already evident in the Western Cape Province, and several researchers have explored the expected changes. In 2015, the Western Cape Province recorded its lowest annual rainfall since 1904, and Cape Town recorded its highest temperature in the last 100 years at 42°C (Western Cape Government, 2018). Projections of climate change in the rooibos growing region are alarming as they indicate increased variation in precipitation amount and intensity, longer dry spells, changes in seasonal cycles and increased temperatures and frequent heatwaves. However, there is limited understanding of the water requirements for rooibos crop production and the environmental factors influencing the growth and productivity of rooibos.

Quantifying the water uptake of crops is important for an improved understanding of hydrological, climatic and ecosystem processes. Several methods to quantify ET have been developed in the past decades. These include hydrological approaches, micro-meteorological methods, plant physiological approaches and the use of remote sensing data. After exploring the advantages and disadvantages of the different methods used to quantify water uptake (evapotranspiration), the lysimeter could not be applied to the current study as it is most suitable to be used in controlled environments. Additionally, lysimeters estimate ET for a single point and may not be applicable to large areas.

3: MATERIALS AND METHODS

3.1 Selection of the study area

The study was carried out in a key rooibos tea-producing area in the Western Cape Province. The following criteria were considered for selecting the study site:

1. A well-managed farm in which conservation farming practices are applied to produce optimal yield. This is done to limit the number of factors that influence crop development and evapotranspiration in order to improve the accuracy of results.
2. Large field (20 hectors or more) to allow the use of micrometeorological instrumentation that requires a large uniform fetch.
3. Security of equipment from vandalism.
4. Co-operation from the farmer for the smooth running of the project. Furthermore, considering the farmer's knowledge about the crop, he/she can help identify a secure and suitable area to install the equipment and share information about the history of the selected location, farming practices and management of the crop.

The selected rooibos farm was identified with assistance from the South African rooibos tea industry experts. The farm identified is 5 km outside Porteville along the Jakkalskloof road to Piketberg (Figure 3.1).

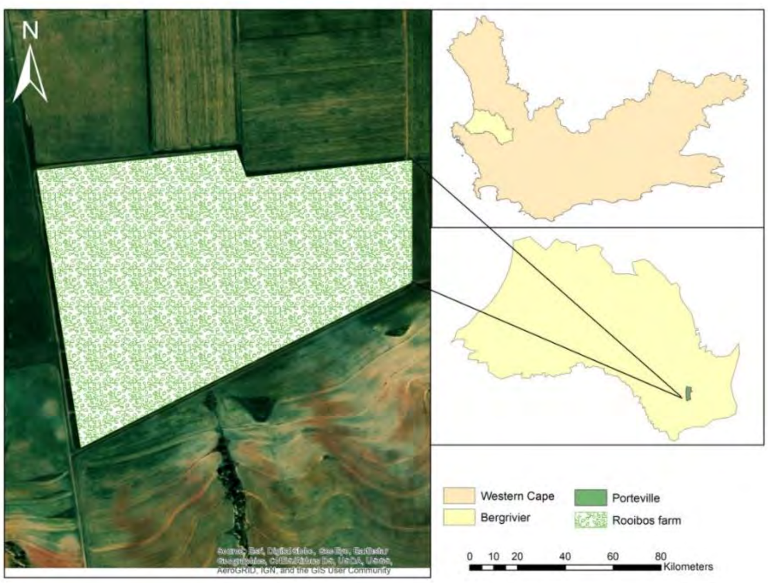

Figure 3.1: The rooibos farm located 5 km from Porterville and selected for the study.

3.1.1 Selected site

The study site is approximately 25 hectares in size with relatively flat and homogenous (in terms of soil properties) across its extent. Production of the rooibos crop was established in 2015 and the first harvest took place in 2016. Ever since the rooibos crop is harvested on a yearly basis on this farm.

Figure 3.2**:** Preparation of the study site and changes that have occurred over the years.

Porterville is situated 140 km away from Cape Town in the Western Cape Province of South Africa. Porterville forms part of the Berg River Local Municipality located within the West Coast District. Towns located within the Berg River Municipality include Aurora, Eendekuil, Piketberg, Redelinghuys, Velddrif and Porterville. The selected study area is further south of the rooibos production areas indicated in Figure 3.3. Projected climate change suggests that rooibos crop production will extend further south and upslope (Lotter and Le Maitre, 2014).

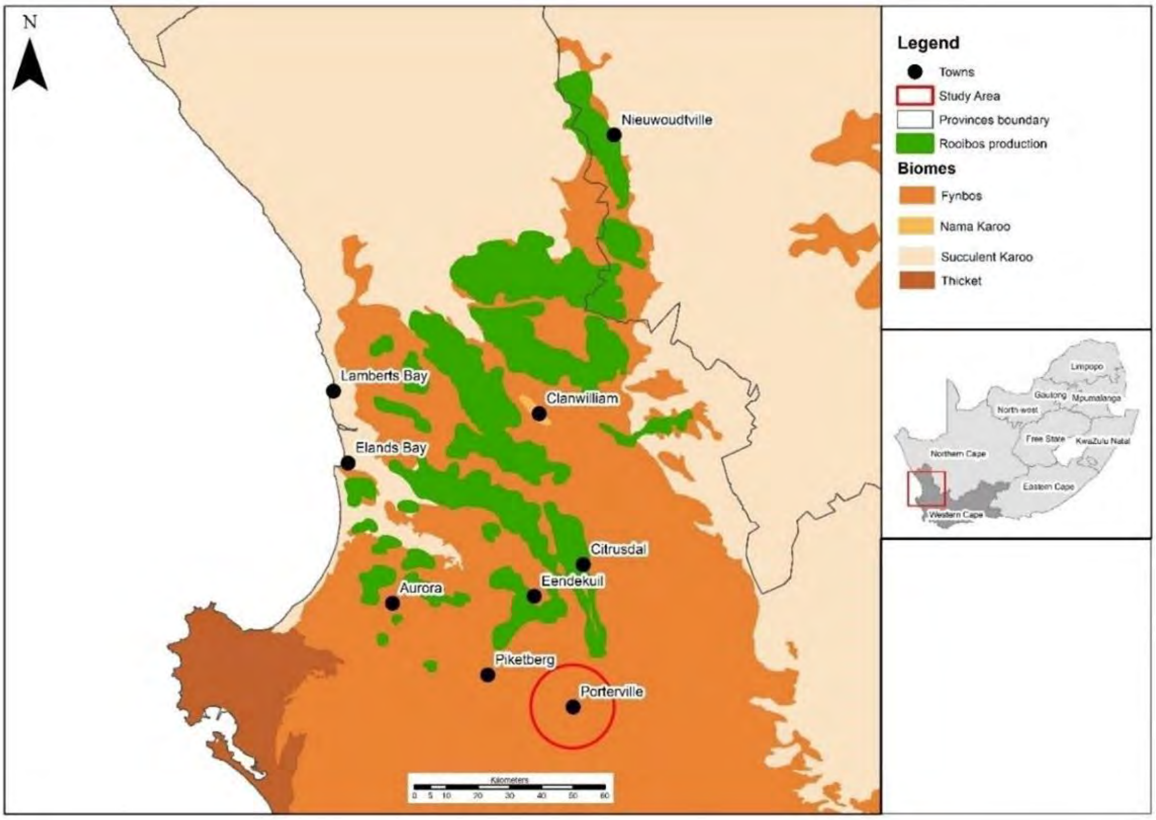

Figure 3.3: Rooibos production areas in the Northern and Western Cape of South Africa.

3.1.3 Geology and Soils

The study area is underlain by the Late Precambrian meta-sediments of the Malmesbury Group and the Klipheuwel group (Almond, 2012). The Malmesbury group is overlain by sandstone from the Table Mountain Group (TMG) (also known as the Table Mountain Sandstone) (Western Cape IWRM Action Plan, 2017). The soil at the study site is mainly composed of sand with a low water-holding capacity. Sandy soils are suitable for cultivating rooibos since the rooibos crop is well adapted to obtaining nutrients from nutrient-poor, low water holding capacity, sandy, acidic soils. The terrain is relatively flat with a slope of less than 3 degrees, whilst the altitude of the study area varies from 300 to 600 m above sea level.

3.1.4 Climate

Porterville experiences a Mediterranean climate characterized by warm, cool summers and wet, cold winters, with very little rainfall in summer. Porterville normally receives about 445 mm/year of rainfall. The average minimum rainfall received in this area is approximately 2.7 mm/month in January, while the average maximum rainfall of approximately 25.6 mm/month is received in June. Snowfall occurs on mountain peaks during the winter season, coupled with storm rolling’s from the

Atlantic coast in the west. The average maximum temperatures experienced in this area are 31.6 °C, the minimum temperature is approximately 7 °C and the average annual temperature is 17.7°C 9 (WWO, 2021).

3.1.5 Land-cover/ Land use

Agriculture (farming, forestry and fishing) covers 33% of the land in the Berg-river Municipality and plays a vital part in the area's economic, social and political development (Figure 3.4). Porterville is famously known for growing flowers and grapes and producing wines primarily exported to Europe. Other dominant economic activities include manufacturing contributing 20.9% and wholesale and retail trade, catering and accommodation, contributing 13.3 % (Municipalities of South Africa, 2020).

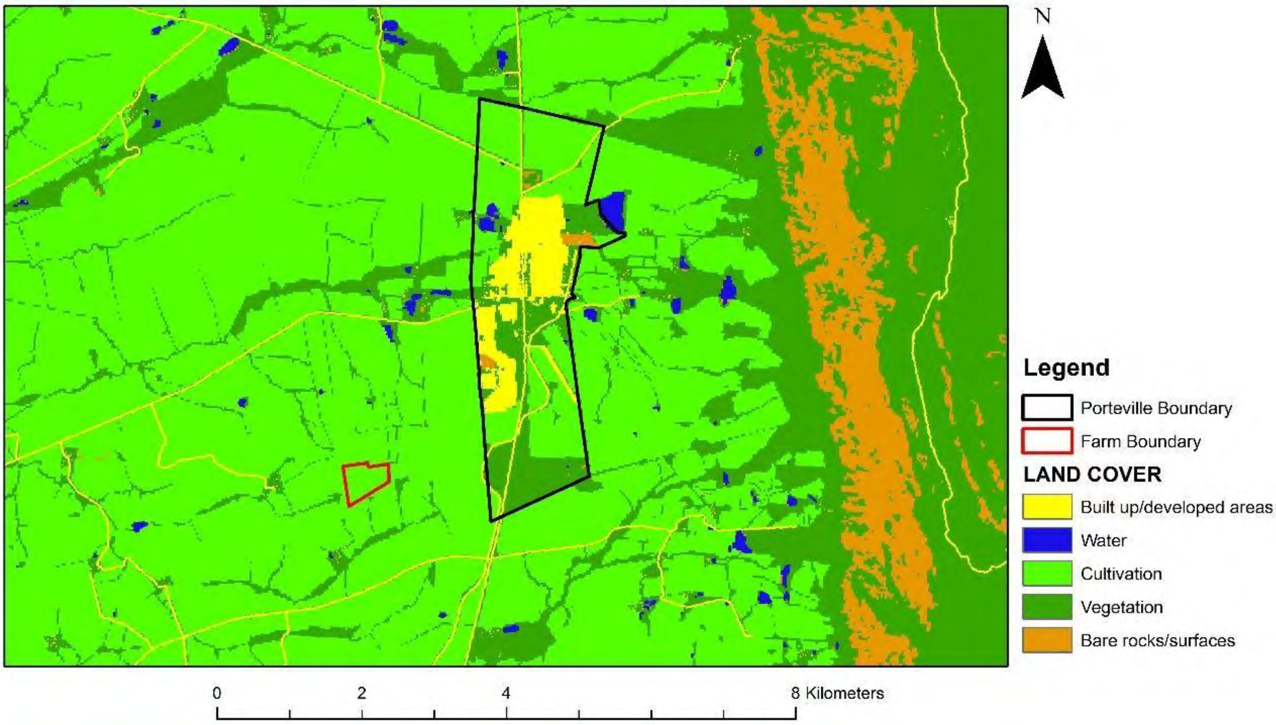

Figure 3.4: Land cover at Porterville (DFFE, 2020)

3.2 Data collection

In order to achieve the aim of this study which is to: investigate the water use patterns of rooibos crops and determine the environmental factors that affect rooibos growth, water use dynamics and environmental factors influencing rooibos crop production in the selected study area were determined. Thus data on different weather parameters, soil and plant characteristics were collected.

3.2.1 Weather data

Weather data at an hourly interval was obtained from an automatic weather station (AWS) operated by the Agricultural Research Council and located at 33°00'44.9"S and 18°59'58.1"E, 5 km from the study site. The variables measured by the AWS are solar irradiance, maximum and minimum air temperatures, maximum and minimum relative humidity, wind speed and direction, and rainfall. Data collected from the AWS spans from May 2019- June 2020. Additionally, a tipping bucket rain gauge was installed at the farm to improve the accuracy of estimated rainfall for the study site. The Penman-Monteith method was used to estimate the study site's daily reference evapotranspiration (ETo) based on the measured weather variables.

3.2.2 Soil properties and water content

As part of the soil water balance assessment, information on the field capacity of the soil is necessary. A soil pit of 2-meter depth was dug using a shovel and soil samples were taken at 20 cm intervals (typically done to ensure accuracy of the spatial variability of SMC (Li et al., 2019)) up to 100 cm depth and kept at 15°C until they were analysed (Figure 3.5). These soil samples were sent to a commercial laboratory, Bemlab, for a full soil type and texture analysis. Soil type and texture are important as they influence soil physical properties such as drainage, water holding capacity, fertility, aeration and penetration of roots to the soil.

Figure 3.5 Soil profile for characterizing the soil physical properties at the study site.

3.2.3 Plant growth measurements

The monitoring of crop growth and performance during developmental stages is an important aspect of agricultural management. It enables the farmer to implement timely interventions that ensure optimal yields at the end of the season. Monitoring of rooibos growth commenced at the beginning of May

2019 – January 2020 on a monthly interval due to the slow growth of the shrub. Growth of the rooibos crop was observed by monitoring plant height and leaf area index (LAI).

Leaf Area Index (LAI)

The Leaf area index (LAI)is the total one-side area of a photosynthetic tissue per unit ground surface area. The field LAI was measured using LAI-2000 leaf area meter (LICOR Inc., NEBRASKA, and USA) at monthly intervals throughout the growing season (May 2019- June 2020). LAI data were collected either at sunset, early in the morning before sunrise or during overcast conditions when the assumption that plant leaves behave like black bodies was most realistic. According to Beer-Lambert law, this non-destructive method assumes that the total amount of irradiance intercepted by the canopy depends on the incident radiation, the structure of the canopy (i.e., LAI) and the leaf area meter's optical properties (Stroppiano et al., 2006).

Plant sampling and measurement of plant height/ dimension

The LAI measurements were calibrated with destructive sampling from known grounds within the rooibos crop field. This was done by randomly selecting ten rooibos shrubs from the field. Each of the ten shrubs was numbered and measured for height, width and breadth once a month from the commencement of the study until harvest time (May 2019-January 2020).

3.2.4 Water use dynamic

After exploring the advantages and disadvantages of the different methods used to quantify water uptake (evapotranspiration) the following methods were selected to achieve the study's objectives: eddy covariance, sap flow technique, Penman-Monteith equation, Surface renewal method, soil water balance and FruitLook. The soil water balance, Eddy covariance, Penman-Monteith, Surface Renewal and FuitLook provide estimates of evapotranspiration which include evaporation from the soil and the plant whilst the sap flow method was used to measure transpiration only. Using these different methods allows for accurate partitioning of soil evaporation and transpiration of the crop. Each of these methods has uncertainties and errors associated with them however, using different methods allows an error range hence minimizes uncertainties in data.

Sap flow measurements

Transpiration of the rooibos crop was monitored using Dynagage sap flow sensor, one SGA9-ws and two SGA13-ws. The sap flow sensors were manufactured by Dynamax in the USA (as indicated in Table 3.2). Transpiration data was measured at hourly intervals from August 2019-November 2019.

The sap flow sensors were installed according to the manufacturers' recommendation (van Bavel and van Bavel, 1987).

Table 3.2: Specifications of the stem heat balance sap flow probes used to monitor the transpiration of the rooibos crop.

Model No.	**Gage Height (mm)**	**Shield Height (mm)**	**Stem Diameter (mm)**			**Thermo couple Gap (mm)**	**No. Pairs**	**Input Voltage (Volts)**	**Input Power (Watts)**
			Min.	**Typ.**	**Max.***				
Stem Flow Gage									
SGA9ws	70	180	8	9	10	4	2	4	0.1
SGA13ws	70	180	12	13	16	4	2	4	0.15

The following steps were taken when installing the Dynagage sap flow sensor.

- Three rooibos plants were chosen randomly in order to install the stem flow gauges.
- A branch with a stem diameter which corresponds with the appropriate stem diameter specifications of the gauge was chosen. For example, if it is the SGA9, then the stem diameter must be between 8 and 10 mm.
- The diameter of the selected branch was measured with a calliper and recorded together with the model number of the stem flow gauge used on the specific plant.
- The stem diameter of the first plant was measured at the midpoint of the gauge installation and recorded for loading as a stem parameter into the software later.
- Any loose bark, small branches or leaves were removed from the part of the stem that would be used to install the Sap flow sensors.
- The branch was prepared by sanding with fine grain sandpaper the stem very slightly to ensure a smooth surface. This is done to ensure good contact between the stem surface and the heater.

- A lubricant (canola release spray) was applied to the branch to ensure smoothness further improving contact between stem and heater, preventing ingress of water, condensation and sensor corrosion from the expansion of the stem.
- The stem flow gauge was put into place securely and tightly wrapped around the stem.
- The heater impedance found on the sensor serial number was labelled as well as the cable number corresponding to the sensor/plant was also recorded to be processed in the Eddy Pro software.
- O rings were installed at the upper and lower bottom of the stem flow gauge and both parts were sealed with reusable putty adhesive to prevent water from entering the system.
- Lastly, the whole gauge and part of the branch were covered with aluminium bubble foil and sealed with tape. This acts as a radiation shield to reduce the effects of exogenous heating and maintain steady-state conditions around the gauges.
- The Dyangage sensors remained on the three plants for one month after which they were removed (on the 15 th of October 2019) and reinstalled on three other branches.
- After the relocation of the SAP flow sensors, the branch leaf area (AL) was measured destructively using the Li-3000 leaf area meter (LICOR Inc., NEBRASKA, USA) in the laboratory.

Figure 3.6: sap flow gauge monitoring transpiration rates of the rooibos crop.

Analysis of sap flow data in order to get average daily sap flow (SF) of the rooibos crop was estimated using Equation (4.1) which is found in the Dynagage Sap Flow Sensor Manual (2005, p38).

$$SF = \frac{Pin - Qr - Qv}{Cp \times dT} \quad (4.1)$$

where SF is the instantaneous sap flow rate (SFR; g h−1); Pin is heat input (W); Qr is radial heat dissipation (W); Qv is vertical thermal conductivity (W); Cp is specific heat of water (4.186 J/g × C); and dT is average voltage of the two vertical thermocouples (◦C).

The sap flow sensors only measure sap flowing through the selected stems however this study intends to determine field level transpiration rates in order to establish crop water use. Hence transpiration (T, in mm/h) of the whole field was determined using the approach of Mobe et al., (2020). According to this approach, if SF_i is the branch sap flow (in g/h) at a given time, (i), then the field transpiration can be expressed as the following function:

$$T_i = \frac{\sum_{i=1}^{N} \frac{SF_i}{A_i}}{N} xLAI \quad (4.2)$$

Whereby SF is the average branch sap flow rate (cm^3/ day) measured by all the sensors, A_i is the average leaf area of the instrumented branches (in cm^2) and LAI is the leaf area index (m^2 of leaf area per m^2 of ground area) of the field. N is equal to the number of sap flow gauges used in the entire study field.

Eddy covariance (EC)

The EC tower was used to monitor actual evapotranspiration of the rooibos crop. The EC flux system consisted of an open path infrared gas analyser (IRGA) (Model: LI-7500A, LI-COR Inc., Nebraska, USA) for measuring water vapour and carbon dioxide and 3 dimensional (3D) ultrasonic anemometers (Model: CSAT3, Campbell Sci. Inc., Utah, USA) which measures wind speed in 3D.

Installation of the Eddy Covariance was as follows:

- Firstly, a tower type was chosen to achieve the precision and accuracy needed to meet the scientific objections, which include minimising flow distortions and bias by preferential flow and maintaining the site's ecological integrity. Hence the eddy covariance tower was set with sensors 3 meters above ground and 2 meters above the top of vegetation because over short vegetation, a small tower is sufficient.

- Vegetation height measurements were taken at monthly intervals to ensure that the sensors are above the surface roughness sublayer and that there is enough fetch around the sensor.
- Sensors were placed low enough to ensure the footprint does not extend beyond the fetch of interest during atmospheric conditions.

- Sensors were placed away from the main tower to reduce the tower structure's direct effect on the mean airflow and direct reflection effects on the measured radiation.
- The separation between the sonic anemometer and gas analyser was set between 20 and 30 cm to ensure measurements of the same air parcels.
- All the sensors were connected to a CR5000 data logger (manufactured by Campbell Scientific), which records data at hourly intervals. The high-frequency data collected at 10 Hz, is being stored on 2 GB memory cards
- A 100 Ah 12V battery was used to supply the system with energy.
- A computer was used for data collection, online flux processing and additional data storage.
- The high-frequency eddy covariance data was corrected for lack of sensor levelness (coordinate rotation) and fluctuations in air density using the EddyPro v 6.2.0 software (LI-COR Inc., Nebraska, USA)

Figure 3.7: Installation of the open path eddy covariance and surface renewal systems over a rooibos crop.

The EC system determines ET from the LE values determined by the water flux. using the equation (4.3).

$$LE = \lambda \frac{Mw/Ma}{pa} \ pa \ \overline{\omega' e'} \tag{4.3}$$

Where Mw and Ma = molar masses of water vapour and air (g mol-144), Pa = atmospheric pressure (kPa), ω' = instantaneous deviation of the vertical wind speed e' = air vapour pressure and LE= latent heat flux. The latent heat flux (LE) can be converted to ET by dividing by the latent heat of vaporization.

Surface renewal method

The surface renewal method was used as a backup of the eddy covariance technique in the case of data losses and to ensure further accuracy of the results. SR method is an agro-meteorological technique used to estimate ET. The surface renewal method measures the sensible heat flux of the component of the surface heat energy balance. With the SR method, ET for a given crop surface is determined by calculating latent heat flux density (LE) as the residual of the following energy balance equation.

$$LE = Rn - G - H \qquad (4.4)$$

Measurements of Rn and G are relatively straightforward and inexpensive. Direct measurements of H are more complex and require high-frequency data acquisition. Nonetheless, the sensible heat flux (H) was estimated using measurements of air temperature at a single level using fine wire thermocouples. Moreover, there additional sensors such as net radiometers and soil heat flux plates were installed to measure soil heat flux (G) and net radiometer (Rn). This data provided detailed information on the partitioning of water use between the beneficial and non-beneficial components.

Measuring soil heat flux (G)

- Two soil heat flux plates (Hukseflux, The Netherlands) were inserted at 5 cm depth (at a distance to the EC tower to avoid interference). These plates are buried below the soil surface in order to avoid interception solar radiation.
- Then soil thermocouples were inserted at approximately the same depth (thermocouples measure the temperature change from the beginning to the end of the sampling period (30 min) \uf0b7 Extension wires of the sensors were then connected to a CR1000 data logger.

Figure 3.8: Installation of Soil heat flux plate to monitor soil moisture content at Porterville farm.

Measuring net radiation (Rn)

- A net radiometer was used to measure Rn (Model: CNR 1, Kipp & Zonen, The Netherlands). The net radiometer is on the cross-arm boom above the canopy.
- Net radiometer was connected to the CR1000 data logger.

Measuring sensible heat flux (H)

- A fine wire thermocouple was installed on the tower above the canopy enabling air temperature to be sampled at 10 Hz.
- The thermocouple was then connected to a data logger.
- At the same height as the thermocouple, a sonic anemometer was installed.
- Power was applied to the data logger.
- Data logger was connected to a laptop to access data.

Lastly, the latent heat flux (□E, in W/m^2) data was corrected for lack of energy balance closure using the Bowen ratio method as described by Cammalleri et al (2010) wherein:

$$\square E = \frac{Rn-G}{1+\beta} \tag{4.5}$$

where □ is the Bowen ratio defined as H/□E where H is the sensible heat flux measured by the eddy covariance system, Rn is net irradiation and G is the soil heat flux.

Installation of soil moisture sensors

- Two holes of about 2-meter depth were dug to access the root zone of the rooibos crop. One hole was dug close to the rooibos crop and the second hole was dug in the open spaces between the plant rows.
- The CS616 sensor rods were numbered from 1 - 8
- In each hole, 4 soil moisture sensors were inserted vertically (in ascending order) at different depths (20, 40, 60, 80 and 100 cm). This is done to measure the soil moisture content at different depths on an hourly basis over the study period.
- The rods were connected to a data logger according to their numbering to monitor the output (the soil water content of the rooibos filed). The rods were buried to measure the volumetric water content of the soil. The universal soil water balance equation was used to provide estimates of daily ET from the soil water content measurements and the rainfall according to Allen et al (1998).

 

Figure 3.9: Installation of soil moisture sensors to monitor the volumetric soil water content in the root zone of the rooibos crop.

Soil water balance

The soil water balance uses soil moisture sensors (model CS616, Campbell Sci. Ltd, USA). The CS616 consists of 30 cm long stainless-steel rods which are connected to measuring electronics. The CS616 sensors measure the amount of water content of porous media (for example sand) using time-domain measurement method. The elapsed travel time and pulse reflection are then measured and used to calculate soil volumetric water content. Runoff is assumed to be negligible as sandy soil has high infiltration rates although it is mainly affected by intensity of rainfall.

Surface water balance is expressed using the following equation.

$$\mathrm{R} = Ro + DP + ET + \Delta S \qquad (4.5)$$

Where R= rainfall, Ro=runoff, DP=Deep percolation, ET =evapotranspiration and ΔS=change in storage. For the selected study site deep percolation and runoff are assumed to be zero. Therefore, ET can be expressed as:

$$ET = R \pm \Delta S \qquad (4.6)$$

Which is similar to:

$$ET = R \pm Dri - \mathrm{Dri} - 1 \qquad (4.7)$$

Where Dri-1 is water content in the root zone at the beginning of the day (mm), R is rainfall on day i (mm), ET is the crop evapotranspiration mm and depletion at the end of day i is Dri.

The initial depletion can be derived from measured soil water content by using the formula below:

$$Dri = 100(\theta FC - \theta i - 1)Zr \quad (4.8)$$

Where θFC (m3 /m3) is soil field capacity, θi-1is the average initial soil water content for the root zone and Zr (m) is depth of buffer vegetation root zone (Muñoz-Carpena, 2012).

In order to determine which actual evapotranspiration rates are a true representation of the study area equation 4.9 was used.

$$Diff = ETa_{ES} - T_{OB} \quad (4.9)$$

Where *Diff* is the difference between the estimated actual evapotranspiration (SWB and Fruitlook data, Eddy Covariance) and the observed water use by the rooibos crop which is represented by transpiration data (T). ETa_{ES} is the estimated actual evapotranspiration and T_{OB} is the observed actual evapotranspiration from the Eddy covariance system.

3.2.6 Power used to run the equipment.

Initially, the different systems (the eddy covariance, sap flow and surface renewal systems) were powered using 2 x 65Ah batteries connected in parallel. However, over time the batteries could not provide enough power to run the equipment; this led to systems shutting down when power was low. As a result, the loggers could not capture a continuous dataset. To solve this problem, a 270W solar panel with a voltage regulator and a 100AH deep cycle battery was used. The systems were monitored regularly to ensure that the equipment was operating properly and that there was enough power supply to download the stored data.

FruitLook

FruitLook is a web platform provided to farmers by the Western Cape Department of Agriculture

(WCDoA) to increase their water use efficiency (WCDoA, 2016). This tool estimates evapotranspiration, biomass, water use efficiency, evaporation deficit and LAI of different crops in the Western Cape region of South Africa. To test the accuracy and functionality of Fruitlook remote sensing data in estimating the water use of the rooibos crop, actual evapotranspiration data from the FruitLook software was used. ETa data from FruitLook spanned between April 2019 – November 2019.

3.2.5 Estimating WUE

To determine the amount of yield produced per unit of water used by the rooibos crop water use efficiency was estimated using equation 4.10. Where the water productivity is calculated as the ratio of the yield to the annual ET. The total wet yield produced over the entire field (which is 25 ha) was reported by the farmer to be approximately 20 tons. Yield per hector was calculated by dividing the reported annual yield (tons) by the total hectors of the entire field and multiplying the results by 1000 to convert to (kg's). Total ET (mm/annum) over the entire field was converted to (m^3 /ha) by diving by 10.

$$WUE = \frac{Yield}{ET} \tag{4.10}$$

where yield is expressed in kilograms per hectare (kg/ha) and ET is expressed in cubic meters/hector (m^3 /ha).

3.2.6 Future climate scenarios

In 2021, the Intergovernmental Panel on Climate Change (IPCC) Sixth report proposed a set of scenarios known as Shared Socioeconomic Pathways (SSPs) to represent different possible trajectories of greenhouse gas (GHG) emissions, atmospheric concentrations, air pollutant emissions, and land use changes throughout the 21st century (Masson-Delmotte et al., 2021). These scenarios include SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. SSP1-1.9 and SSP1- 2.6 represents a strict mitigation scenario with very low to low Green House Gas (GHG) emissions, while SSP2- 4.5 represents an intermediate scenario and SSP-3-7.0 and SSP5-8.5 represent high and very high GHG emissions, suggesting the absence of significant mitigation policies.

This study utilized two SSPs, namely SSP1- 2.6 and SSP5- 8.5, obtained from the ICHEC-EC-EARTH Global Climate Model and ARC4 Regional Climate Model combination. These models were selected based on how they have been used in other climate studies in southern Africa (Mhlanga et al., 2018; Mpakairi et al., 2020). These models extracted projections of various climatic variables, including maximum and minimum temperatures, radiation, average relative humidity, and wind speed. The future climate data were obtained from the Coordinated Regional Climate Experiment (CORDEX) database, available at a spatial resolution of 50 km by 50 km. The usage of CORDEX data followed the terms of use specified at (http://wcrpcordex.ipsl.jussieu.fr/). Subsequently, the climate variables were extracted for the Potterville area within a Geographic Information System (GIS) environment. These variables were then utilized to estimate reference evapotranspiration using the Penman-Monteith method. The estimation was performed for the period spanning from 2019 to 2040.

4: RESULTS AND DISCUSSION

4.1 Introduction

Rooibos's crop yield depends more on an adequate water supply than any other environmental factor. Increased frequencies of dry spells, late onset of winter rains and heat stress have been reported by farmers to cause severely diminished yields and quality of rooibos (Archer et al., 2008). This chapter presents results aimed at understanding the water use dynamics of rooibos as well as environmental conditions affecting rooibos yield. This chapter first examines the micro-climate and soil physical properties of the selected study area, followed by the plant attributes of rooibos and, lastly, the water use dynamics of cultivated *A. linearis*.

4.2 Weather conditions

Solar radiation and temperature.

Weather conditions play a significant role in controlling the water use dynamics of crops. Hence, to determine rooibos crop water requirements, the influence of meteorological factors on evapotranspiration was investigated. Meteorological data of the study site were observed from May 2019 June 2020.

Seasonal changes in weather conditions are shown in Figures 4.1- 4.6. The highest solar irradiance (32.83 MJ/m^2/day) was recorded in December 2019 and the lowest (2.09 MJ/m^2/day) in May 2019 (Figure 4.1). Average daily radiation increased from 11.08 MJ/m^2/day in winter to 23.67 MJ/m^2/day in summer. Based on the results, more radiation is reaching the surface during the dry season compared to the wet season. This is because the southern hemisphere is closer to the sun during the summer season and there is less cloud cover since the study area receives winter rainfall. Solar radiation influences air temperature. As a result, in winter, the highest daily maximum temperature recorded was 31.74 °C (May 2020), whereas in summer it was 41.17 °C (February 2020) (Figure 4.1). The lowest temperature recorded in winter was 2.27 °C (August 2019) and 10.01°C in summer (December 2019). The overall daily annual temperature of the study area was 18.05 °C.

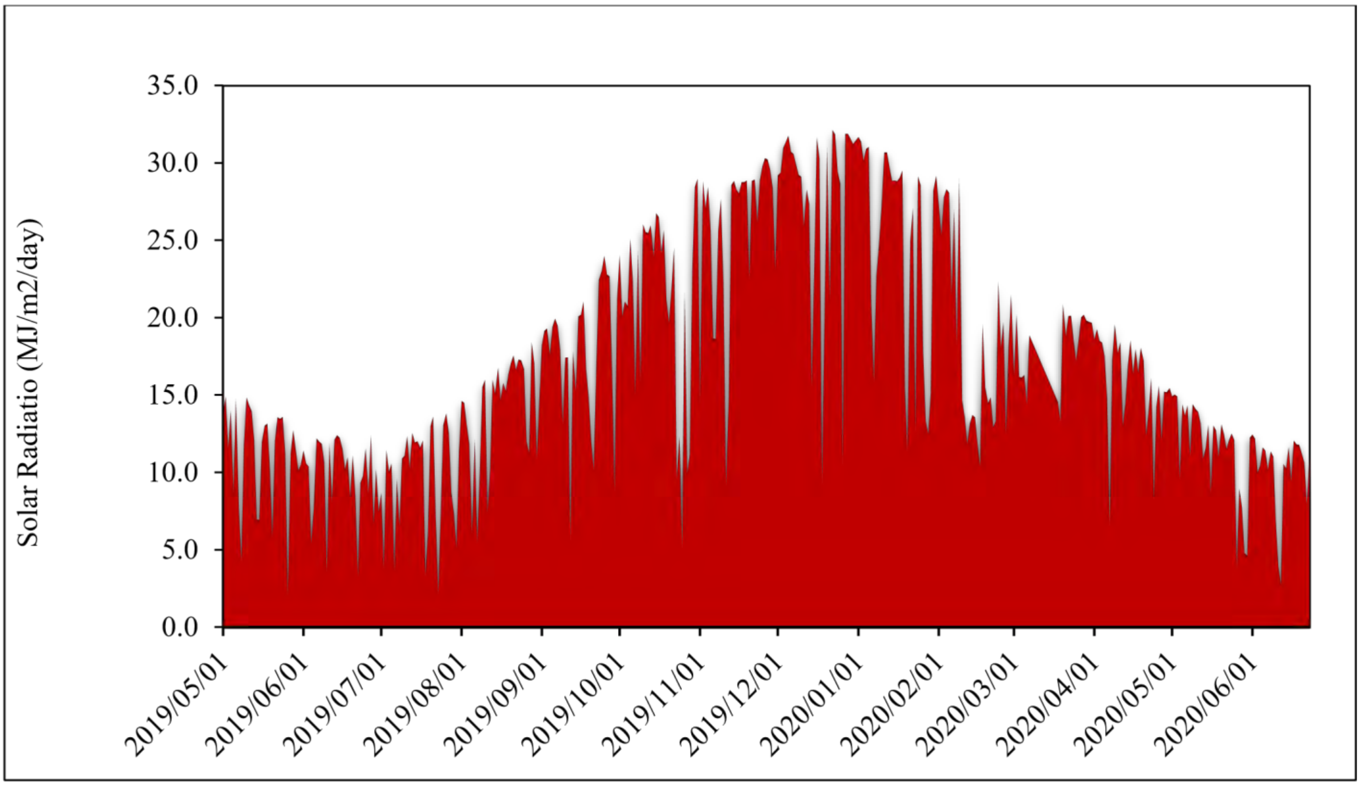

Figure 4. 1: Daily solar radiance at Porterville farm.

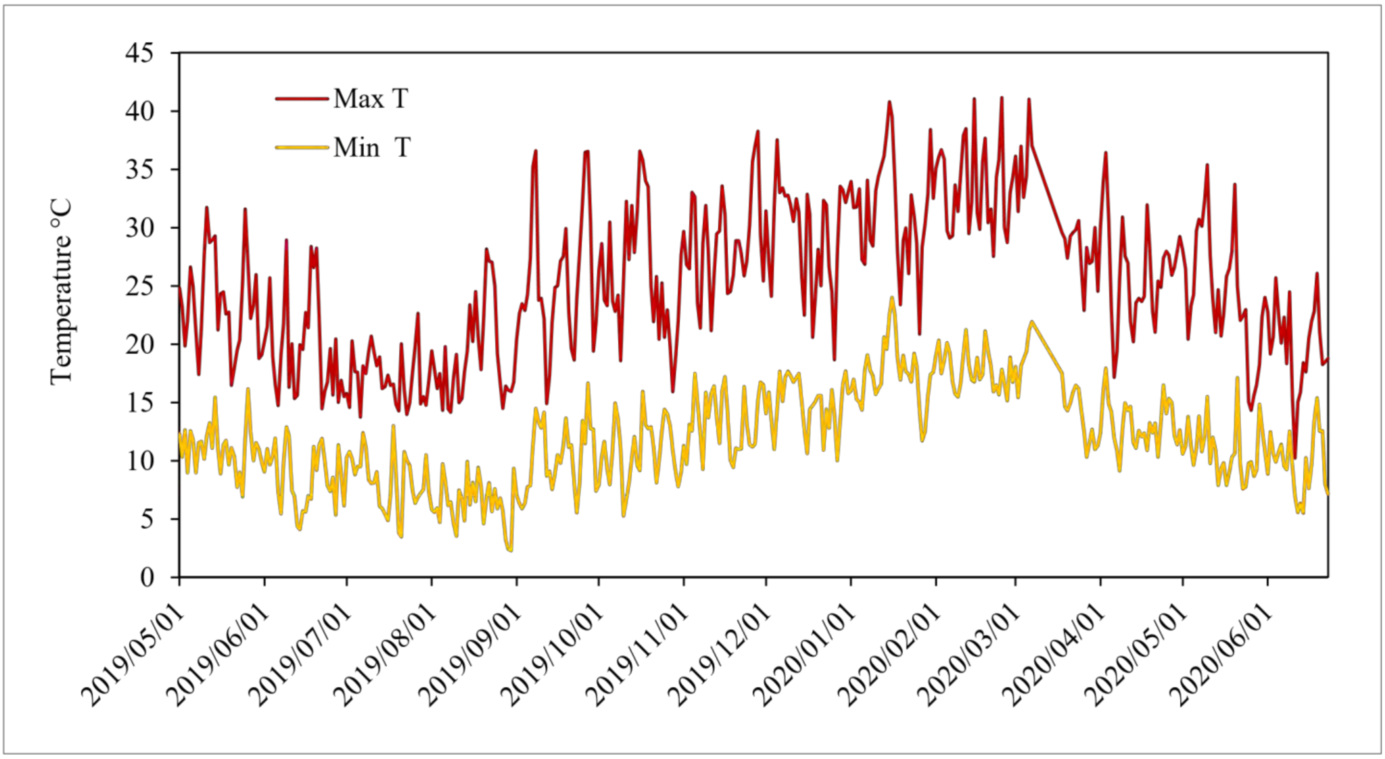

Figure 4. 2: Daily maximum and minimum temperature in Porterville farm.

Relative Humidity (RH) and Vapour Pressure Deficit (VPD)

The highest RH (98.73%) was recorded in June 2019 and the lowest (5.23%) in December 2019. As expected, RH is inversely proportional to temperature and solar radiation. This is because colder air (in winter) does not require as much moisture to become saturated as warmer air (in summer) (Gregory, 2021). VPD reached the highest peak at 3.5 kPa (February 2020) and the lowest recorded VPD was 0.1 kPa during the wet season (July 2019). Overall, the average daily VPD of the selected study area is 1.0 kPa. These results are expected because the increase in VPD is strongly related to increases in temperature and low relative humidity (Will et al., 2013).

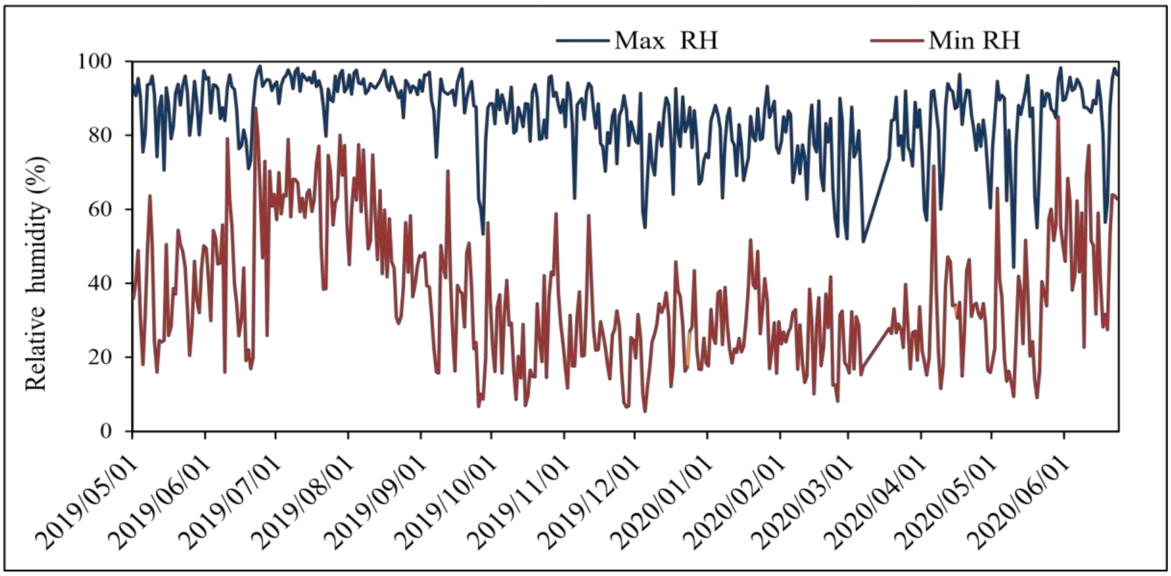

Figure 4.3: Maximum and minimum daily RH at the Porterville farm.

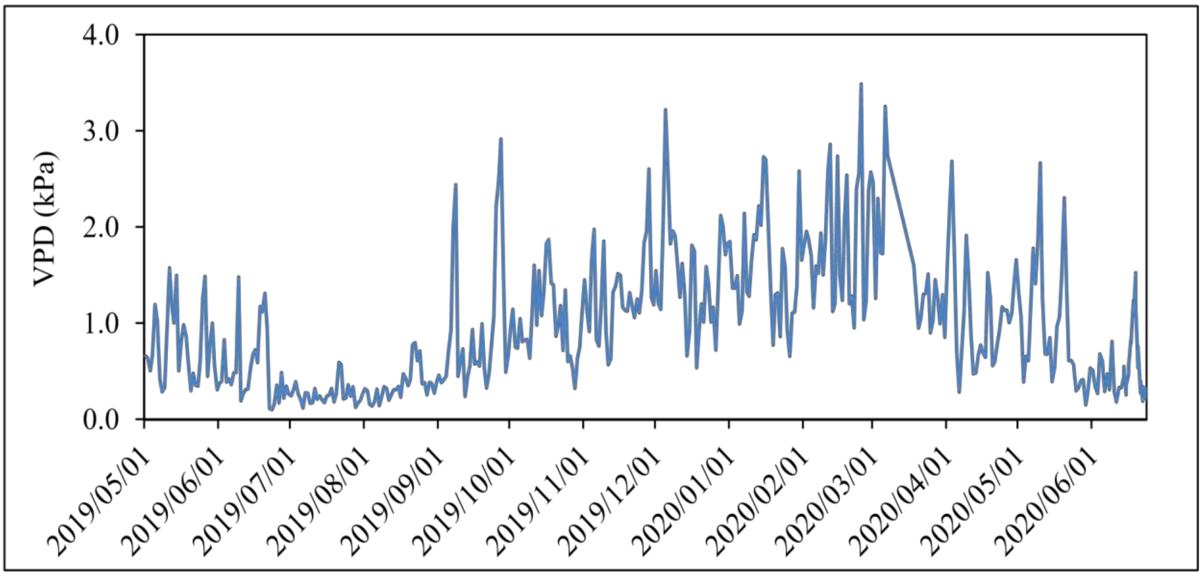

Figure 4.4: Daily Vapour Pressure Deficit at the Porterville farm.

Wind speed

The highest daily wind speed recorded was 5.69 m/s (February 2020) and the lowest wind speed recorded was 0.2 m/s (May 2020) (Figure 4.5). Although there are more days with high wind speed in winter, most of these values are below 1 m/s whilst the wind speed is mostly above 1 m/s in summer. The observed seasonal trend in wind speed was also encountered by Ramulifho (2012) in a study conducted in the Cape Columbine region of the Western Cape Province, South Africa.

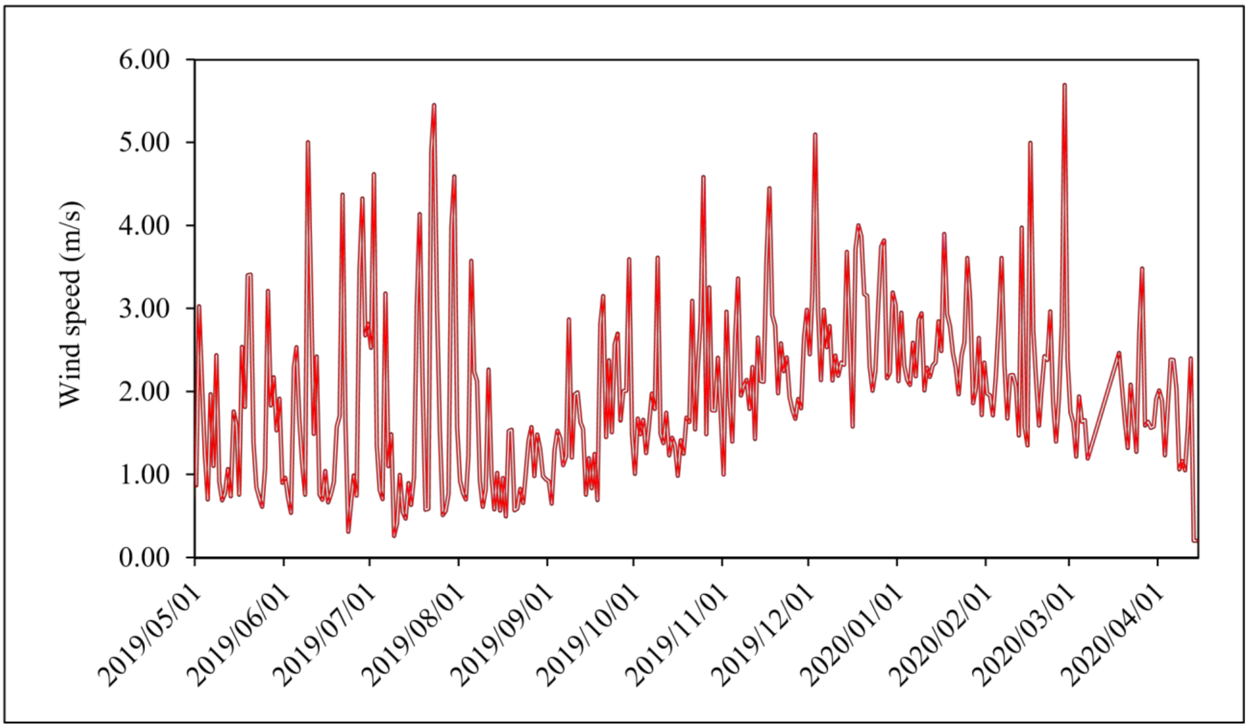

Figure 4.5. Average wind speed at Porterville farm.

Rainfall and reference evapotranspiration.

The total amount of rainfall received during the observation period (May 2019-June 2020) (Figure 4.6) was 408.1 mm, of which 267 mm of rainfall was received in 2019 and 141.01 mm was received during the year 2020. During 2019, approximately 79.82 % of the rainfall was received during the wet season (May to August) whilst 20.18% was received during the dry season (September to December). The same trend is observed in 2020, as 94.10 % of rainfall is received during the wet season (April to June) and only 8.83% falls during the dry season (January to March). Rainfall peaked at 87.81 mm (July-2019), whilst the lowest amount of rainfall was 0.25 mm in February 2020 (Figure 4.6). these results are expected as the study area experiences a Mediterranean climate. Discussion with local farmers suggests that the rainfall received during the observation period was relatively lower than the average rainfall in this area which is 445 mm/yr. Porterville has recently been afflicted by drought events and the below-average rainfall suggests that there is a continuation of drought events.

The atmospheric evaporative demand (depicted by reference evapotranspiration, ETo) is higher in summer as compared to winter. ETo peaked in December 2019 at 193.61 mm/month and dropped significantly in June 2020 (33,79 mm/month) (Figure 4.5). Reference evapotranspiration (ETo) at Porterville exceeds the total rainfall received during the observation period (May 2019-June 2019) as the total ETo is 1472.02 mm. July was the wettest month (87.81 mm/month) but ETo was relatively low at 59.83 mm/month. Therefore, an increase in precipitation will not necessarily result in increased ETo due to other climatic variables such as reduced solar radiation, air temperature, VPD, and wind speed (Allen et al., 1998).

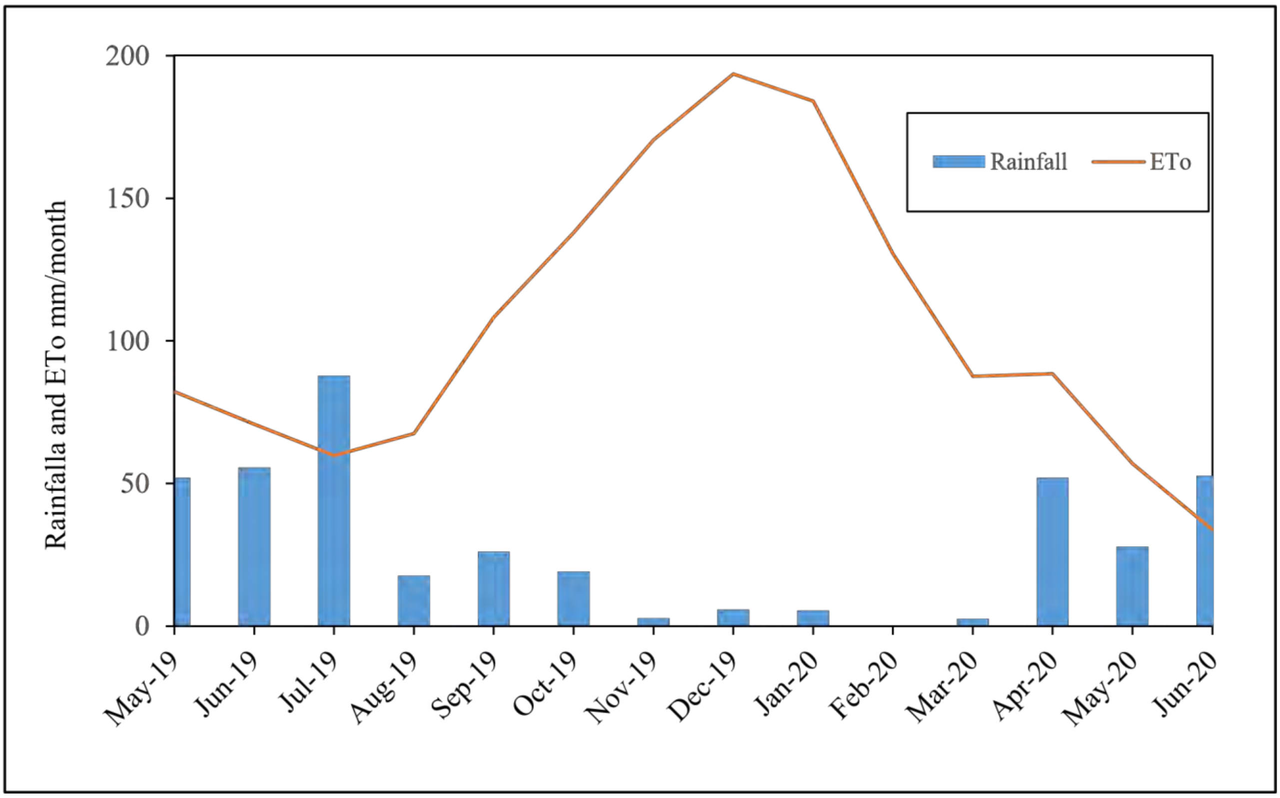

Figure 4. 3: Monthly rainfall and ETo at Porterville farm.

4.3 Soil water dynamics

4.3.1 Soil type at the selected study site.

The soil at the rooibos field is composed of sand, clay and silt in varying amounts and textures depending on the depth of the soil profile (Table 4.2). Generally, sand is the dominant soil type. Clay and silt increase with depth within the soil profile. Based on the soil texture triangle, the soil profile can be classified as sandy soil at 20 cm, loamy sand at 40 cm, sandy loam at 60 and 80 cm, and sandy clay at 100 cm depth. Medium to coarse-grained sand particles are more dominant in the top horizons. However, their proportion decreases with depth. For instance, at 20 cm, the soil is composed of 31.2% course-grained sand: however, at a depth of 100 the percentage of coarse sand decreases to 12.0%. Stone particles were found to be least at the bottom of the pit (3.3%) and the top horizon (6.6%), more stones were found at 60 cm (42.7%).

Table 4.2: Soil physical properties at the selected rooibos field.

Depth (cm)	Clay %	Silt %	Sand %	Fine Sand %	Medium Sand %	Course Sand %	Stone % (v/v)	Classification	Water holding Capacity 10 kPa %	100 kPa %	mm/m
20	7	2	91	28,8	31.0	31.2	6.2	Sa	16.44	9.06	73.81
40	9	4	87	38,0	29.0	20.0	12.6	LmSa	17.47	9.24	82.27
60	13	6	81	25,5	30.0	25.5	42.7	SaLm	11.60	7,.2	44.84
80	19	22	59	6,3	28.0	24.7	38.5	SaLm	16.15	11.98	41.67
100	45	6	49	19,6	17.4	12.0	3.3	SaCl	28.90	21.18	77.21

Sa= Sand, LmSa= Loamy Sand, SaLm=Sandy Loam, SaCl=Sandy Clay.

Soil Water Holding Capacity

The soil water-holding capacity is directly related to the amount of silt, clay and organic matter in the soil (Thomas and Morgan, 2008). The selected study site is predominantly composed of sandy soil, which is known to have a low water-holding capacity (WHC). Generally, the rooibos crop requires deep sand soil with low water holding capacity for adequate growth (DoA, 2012). The WHC at the site varies with depth as different depths are composed of different soil types and soil size particles. Soils with higher WHC were found at 100 cm, 80 cm and 40 cm, while the soils with lower WHC were found at 60 and 20 cm depth (Table 4.1). Soils with higher WHC (at 100 cm and 80 cm depth) have a higher content of silt and clay. This is expected as increasing clay content in the soil profile is associated with greater water-holding capacity.

The high WHC at 100 cm depth is also due to few stones and more fine sand particles. Fine soil particles have a much larger surface area allowing the soil to hold more water than coarse soils (Ball, 2001). Hence, the high WHC at 40 cm depth can be attributed to the presence of fine-grained soil particles (38.0%) even though there is less content of silt and clay compared to other horizons. As expected, the depth with the lowest WHC (60 cm) has the highest composition of stone (42.7%) and more coarse sand particles (25.5%).

4.3.2 Soil moisture content (SMC)

Daily SMC in the root zone of the rooibos crop showed clear seasonal trends influenced mainly by rainfall events and plant water uptake (Figure 4.7a, b). Soils are wetter in winter, with the highest moisture content recorded in July (0.134 cm^3/cm^3) (bare inter-row) and 0.126 (next to the rooibos crop) both at the same depth of 60 cm. In spring (September - November) SMC is still relatively high as the highest SMC recorded in October 2019 was 0.103 cm^3/cm^3 (bare inter-row at 60 cm) and 0.092 cm3/cm^3 (next to rooibos crop at 100 cm). In summer (December –February) the highest moisture content was 0.094 cm^3/cm^3 (December 2019) (bare inter-row at 60 cm3/cm3) and 0.072 cm^3/cm^3 (December 2019) (next to the rooibos crop at 100 cm). The observed seasonal water dynamics in the soil profiles are expected because the study area receives winter rainfall. The wetness of the soil increases with depth, which is supported by the results of van Schalkwyk (2019) who noted that shallow soils have lower SWC compared to deep soil. According to the results of this study, the wettest depth in the soil profile is found at 60 cm, although this soil has the highest composition of stone particles and a higher composition of medium-grained sand particles (higher infiltration rate). It is found above two soil layers that have more clay and silt, making it difficult for water to infiltrate these soil layers due to the low porosity of the soil. The driest depth in the soil profile is found at 20 cm because of the high sand content with the least silt and clay. In addition, this layer (20 cm) is affected by soil water evaporation as it is directly exposed to environmental factors such as solar irradiance and wind.

The soil profile next to the rooibos crop is slightly drier compared to the soil away from crops on the bare inter rows (Figure 4.7a, b). For instance, when observing SMC on the wettest days, that is, July 2019 (30.98 mm/day), October 2019 (34.544mm/day), April 2020 (44.956 mm/day), SMC following these wet events is higher at all depths in the bare inter rows compared to the soil close to the rooibos crop. The reduced SMC in the soil next to the rooibos crop suggests active root water uptake by the rooibos crop. Additionally, a reduction in SMC from August (2019) to March (2020) occurred at all depths in the range of 0 to 100 cm suggesting that rooibos root water uptake occurs up to at least 100 cm depth. These results are expected as the rooibos crop has a tap root system that is approximately 2 meters. When observing Figure 4.7b, the rooibos crop uses water in the upper soil layers (20- 40 cm) during the wet season and as it gets dry, it uses water stored in the deeper soil layers (60-100 cm). This ability to partition water use within the soil layers sustains the rooibos crop through the summer drought periods. Wu et al. (2013) also found that declining water availability in the shallow and middle soil layers during dry summer caused both *N. tangutorum* and *T. ramosissima* to compete for the deep-water sources.

4.3.3 Field Capacity

The average volumetric soil water content at field capacity (FC) for the 0 to 100 cm depth was around 0.064 cm^3/cm^3. SMC in the soil profile next to the rooibos crop from May-August was above FC at 60 cm, 100 cm, and 40 cm and mostly below FC at 20 cm (Figure 4.7b). From the end of October 2019 to May 2020, SMC gradually dropped below FC at 20 cm, 40 cm, 80 cm and 100 cm, with the driest soil observed from December 2019 to the beginning of April 2020. Therefore, this suggests that the rooibos crop is under water stress during the dry season. Ahmed et al., (2019) conducted a study under Mediterranean climatic conditions and they found out that soil water deficit is experienced during the dry season. McAlister et al, (2020) found that rooibos crops grown at low moisture conditions were more sensitive to drought as evidenced by their reduced gas exchange parameters and almost 50% lower biomass production compared to plants grown under adequate moisture conditions. Hence, the depletion of soil water content in the root zone coupled with little or no rainfall, increased solar radiation and VPD during the dry season, contributed to water stress as a result some rooibos crops and weeds in the field were dead during the dry season (Figure 4.15).

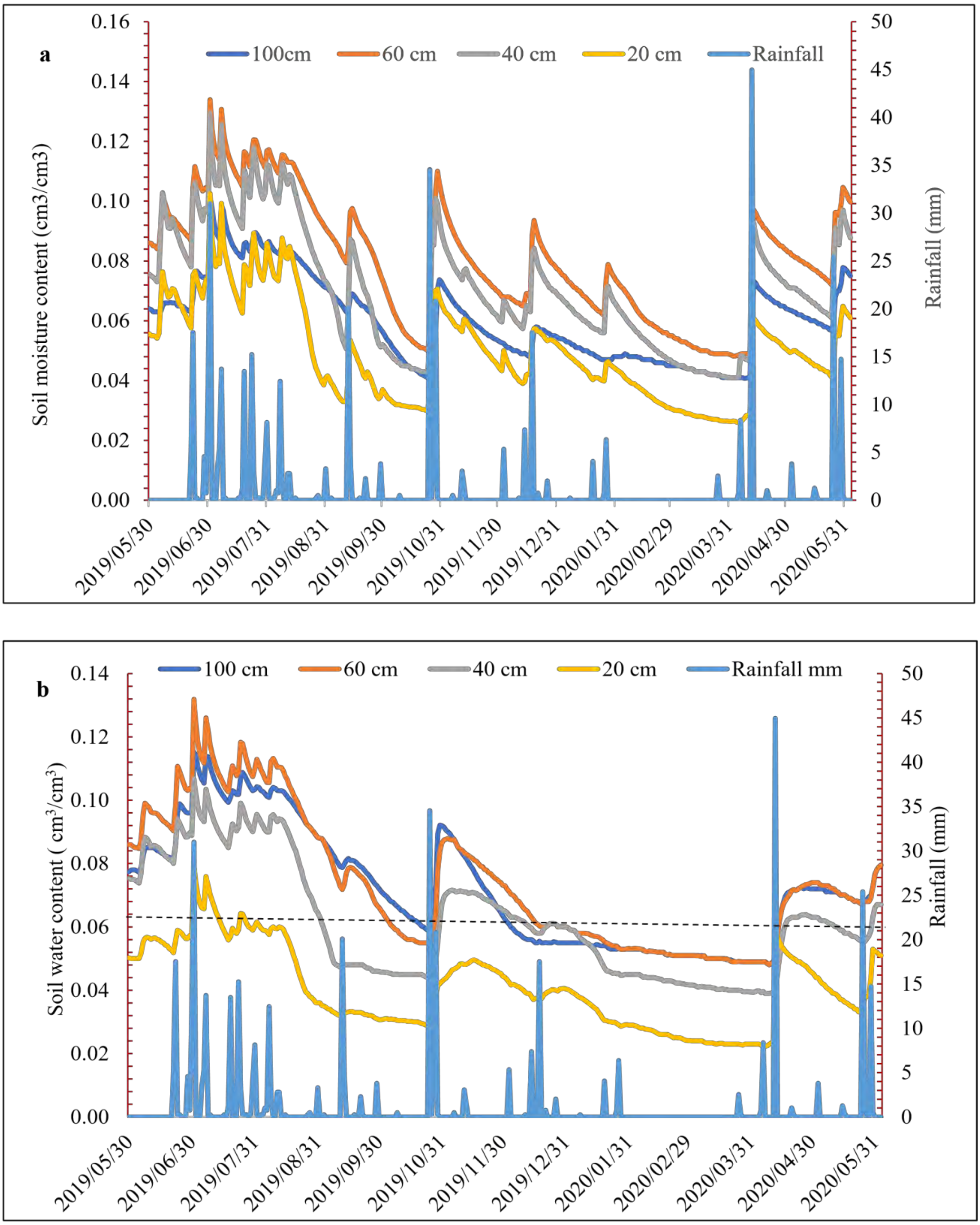

Figure 4. 4: Changes in the volumetric soil water content (a) on a bare inter-row area, and (b) next to a rooibos crop. The dotted line shows the position of the volumetric water content at field capacity in the soil profile.

4.4 Plant growth and development.

4.4.1 Height measurements and leaf area index

The average height of the rooibos shrub at the beginning of the study was approximately 111 cm and increased to 160 cm by the time of harvesting. Over the observation period, the average growth of rooibos increased from 1 cm (June to July) to 12 cm (October-November) per month. Based on height measurements, the rooibos shrub experiences slow growth in winter; for instance, from June to July height only increased by 1 cm and from July to August it increased by 7 cm. However, the rooibos shrub showed active growth from October to January as height increased by 12 cm from October to November and by 11 cm from December to January. Slow growth during the dry season is due to the plant prioritizing root development over the above-ground parts of the plant Louw (2006). Root development allows the shrub to preserve moisture and nutrients in the enlarged root system for the subsequent growth and flowering season (Malgas and Oetle, 2007; Brunner et al. 2015). The rooibos shrub grows predominantly in spring (September- November) since the plant has maximum nutrients and water available at this time. van Schalkwyk (2019) also found that rooibos biomass in unfertilized treatment on deep soils was the highest on the 25th of September 2017.

Nonetheless, Rooibos has a deep root system that penetrates the soil up to 2 meters; hence growth is extended to the summer season even though the amount of rain at this time is negligible and temperatures are high. The deep root system allows the crop to access water that is stored deep in the soil layers. Nonetheless, the average height of the rooibos crop decreased by 1 cm in summer, this is a period when SWC is below FC and there is minimal rainfall. These results support those of Lotter (2015) who found out that the more the drought stress increased, the slower the height of the rooibos crop would increase.

LAI is one of the most important parameters that can be used to assess the growth and vigour of vegetation on the planet (Matthews, 2014). This is because leaves are the major eco-physiological part of the plant that interacts with the atmosphere (Trimble, 2019). Figure 4.8 shows that LAI increased from 0.28 in June 2019 to 1.56 in January 2020. LAI increased by 0.08 from June-August 2019, 0.15 from September-November and 0.34 from December to January 2020. These results are similar to those of Louise et al., (2006), who found that LAI always peaks during early to mid-dry season and reaches minimal values in wet-season months. In addition, in winter the rooibos crop experiences a rest phase which slows growth in the leaves and branches and promotes root development. This phase is broken in spring when the temperatures have risen, and the plant begins to grow more actively (Malgas and Oettle, 2007). LAI is directly proportional to the height of the rooibos crop. This trend is expected because nearly 90% of the biomass of a plant is produced by leaves as shown in Figure (4.5) (Kinhal, 2019). Wiechers et al., (2011) mention that LAI significantly affects plant development and yield through its effect on light interception. The rooibos crop has tiny feathery leaves on fairly thick branches hence, much of the LAI recorded by the leaf area meter is the non-transpiring branches. Therefore, the effective LAI could be about 50% of the recorded values.

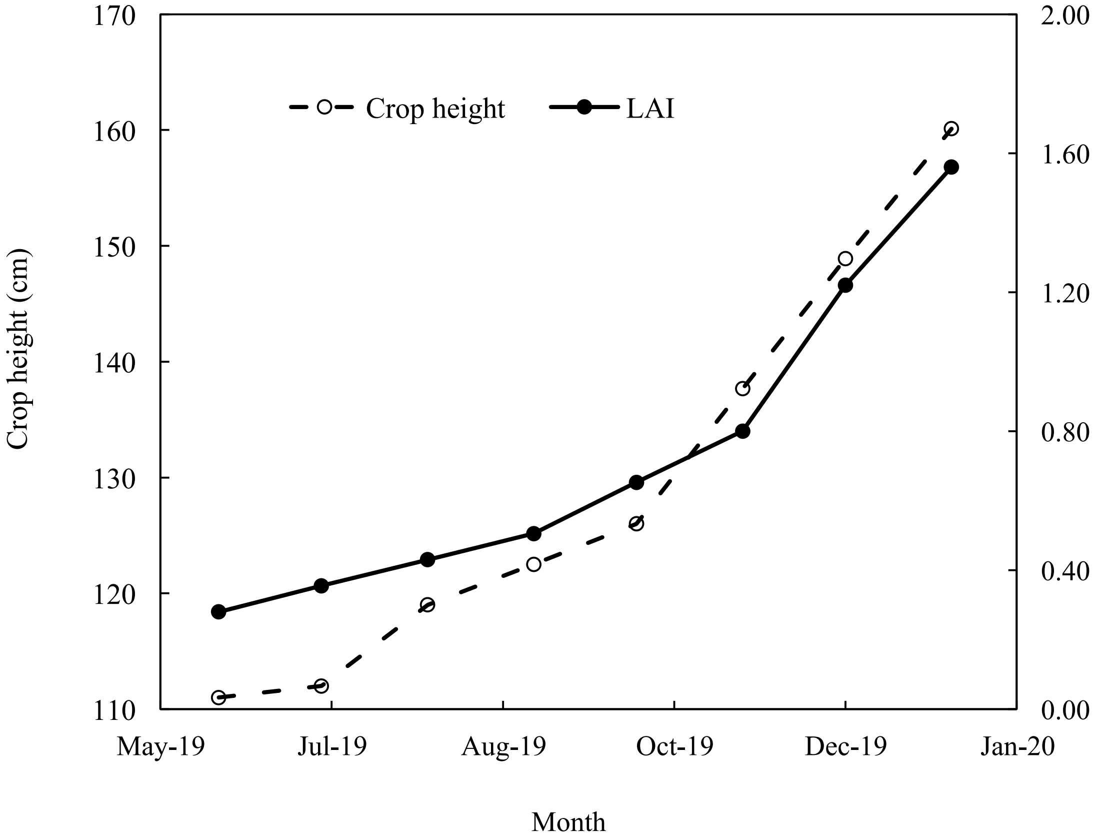

Figure 4.5: Plant height and leaf area index of rooibos during May 2019- January 2020 at Porterville farm.

4.5 Water use dynamics

To assess biomass production and the allocation of scarce water resources, it is important to partition evapotranspiration (ET) into evapotranspiration from the soil (E) and transpiration through the stomata of plants (T) (Kool et al., 2014). Various methods were employed to achieve this, including Sap Flow, Penman-Monteith, eddy covariance, Soil water balance method, and FruitLook software.

4.5.2 Reference Evapotranspiration

The atmospheric evaporative demand (depicted by reference evapotranspiration (ETo), was estimated using the Penman-Monteith equation from May 2019 to June 2020 (Figure 4.9). ETo was relatively low in winter (May-August 2019), ranging between 4.68 mm/day (May 2019) and 0.92 mm/day (July 2019). ETo increased in September, peaking at 6.04 mm/day. The lowest recorded ETo in Spring was 1.87 mm/day (October 2019). During the dry period, ETo increased, reaching the highest peak at 8.86 mm/day and 8.19 mm/day in January (2020). The total amount of ETo during the observation period is 1450,30 mm/year of which, 36.19% occurred in summer (December – January), 29.35% in Spring (September- November), 20.26% in Autumn and 14.24% in winter. ETo rates at the study site are three times more than the rainfall received. The seasonal variation in ETo is expected since ETo is a climatic variable estimated using meteorological data. Hence, the high evaporative demand (ETo) at the rooibos farm can be attributed to the increased solar radiation, Vapor pressure deficit (VPD). High VPD increases the land surface's evaporative demand thereby increasing ET rates (Massmann et al., 2019).

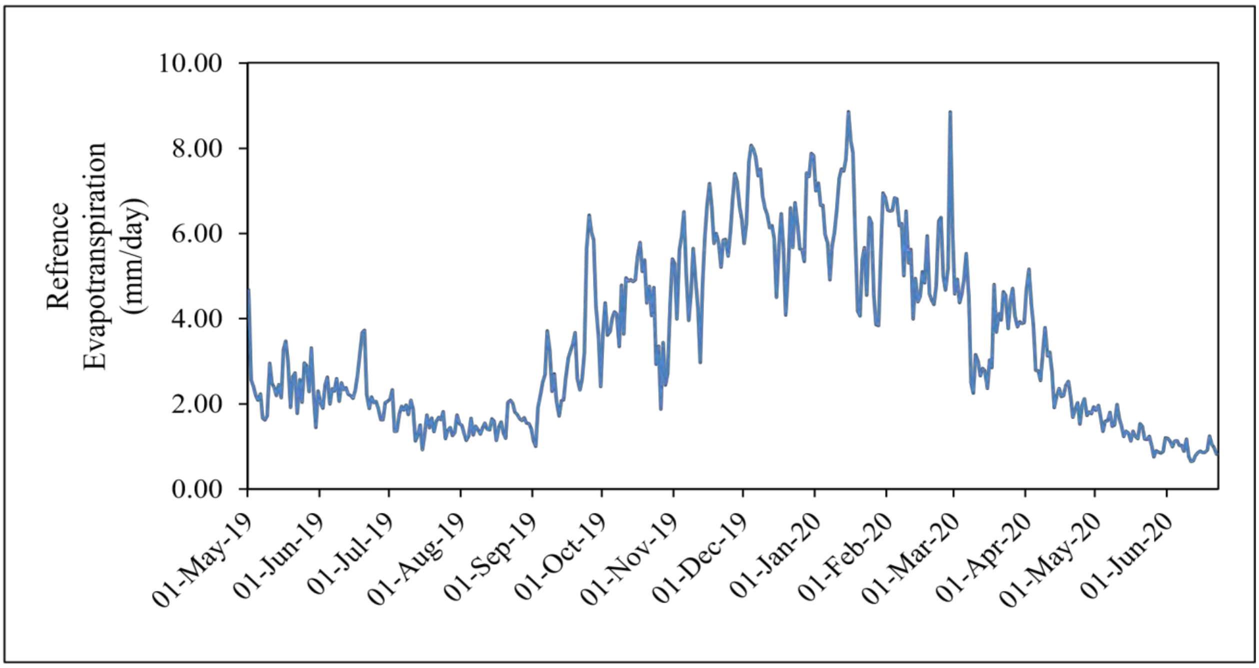

Figure 4.9: Reference evapotranspiration at the study site.

4.5.1 Transpiration

Transpiration rates of rooibos were measured at hourly intervals from August 2019-November 2019 (Figure 4.10). Transpiration rates are low in winter ranging from 0.05 to 0.72 mm/day. The highest transpiration rate was 2.07 mm/day in September. In October and November, transpiration rates ranged from 0.47 mm/day to 1.64 mm/day. Overall transpiration rates are low in winter and increase in spring. According to Kirschbaum (2000), the most crucial changes in transpiration rates will be determined by the interplay between the increase in VPD, air temperature and canopy properties that control heat and vapour exchange. Hence increase in transpiration rate in the rooibos field can be associated with an increase in climatic variables such as VPD, air temperature, solar radiation and wind speed. These results support the findings of MacAlister et al. (2020) mentioned that *A. linearis* plants show evidence of transpiration leaf cooling during summer to mitigate the heat effect due to increased temperatures. High transpiration rates of rooibos can also be associated with the active growth (Figure 4.8) as well as the flowering of the rooibos crop which occurs in predominantly between September and November. According to Sun and Schulz (2017), the seasonal maximum LAI may represent the time of maximum photosynthesis in the canopy. Hence low transpiration rates in winter can be attributed to the low LAI. When crops are small, the portion of ET due to transpiration is minimal as the surface area of the leaves is small. During the observation period (August 2019 to November 2019), the total amount of transpired water was 65.3 mm which is 8.07% more than the amount of rain (52.9 mm) observed during the same time frame.

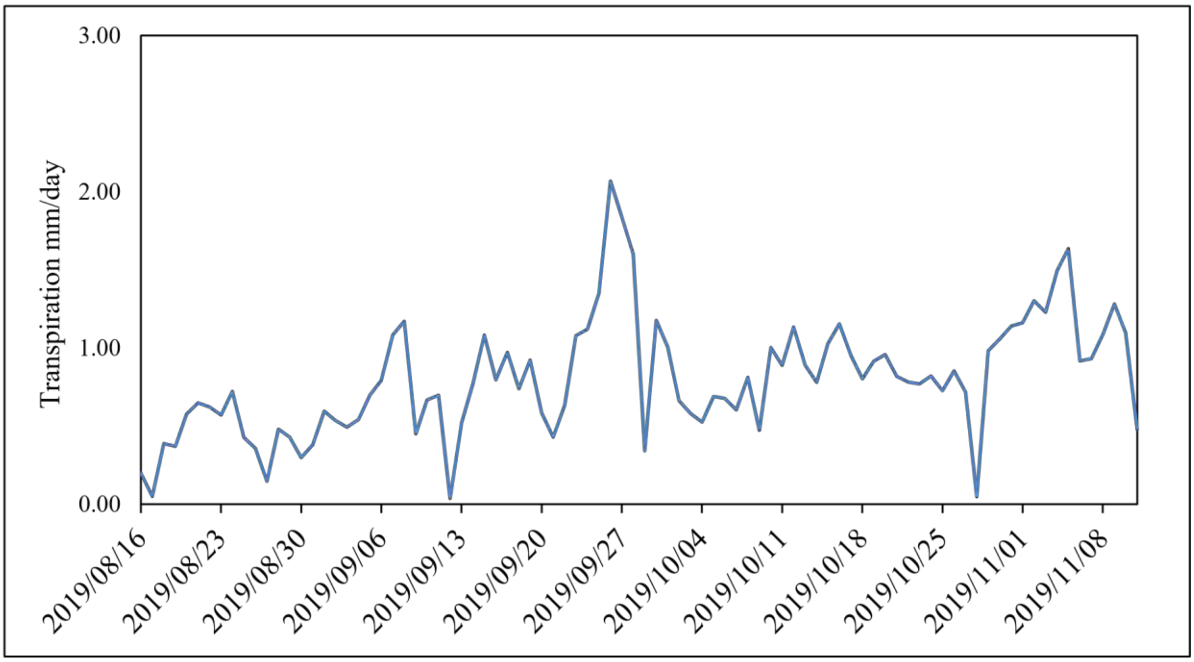

Figure 4. 10: Transpiration rates at the rooibos field

4.5.3 Actual Evapotranspiration (ETa)

Soil water balance (SWB) ETa

The soil water balance approach was used to determine actual evapotranspiration from the rooibos field. During the wet season, ETa gradually increased from 0.04 mm/day to 2.81 mm/day). At the beginning of spring ETa remained high reaching the highest peak on 14 September (2019) at 2.93 mm/day (Figure 4.11). However, ETa dropped towards mid-September to 0.28 mm/day. From mid-spring (October 2019) to summer (February 2020), ETa values fluctuate. However, they remain below 2 mm/day. During the harvest period (end of January 2020- February 2020), ETa drops, and it is almost negligible. The increase in ET rates in winter can be attributed to high precipitation resulting in increased SWC, thereby increasing water availability to the crop. The continued increase in ETa values in spring is expected due to the availability of water in the soil layers and plant phenology (the crop is flowering, and active growth begins at this period). Reduced ETa rates from mid-spring to summer correlate with the reduction in rainfall during this period. Additionally, SMC was below field capacity during the dry season, suggesting that the rooibos crop did not have enough water supply. Montazar et al. (2020) mention that ETa from soil water balance is limited by water deficit. According to the results, the total amount of water used by the rooibos crop during the observation period is approximately 349.54 mm/year, of which 42.31% occurred in winter, 31.14% in spring, 15.99 % in summer and 10.55% in autumn. Based on the results, the total amount of water used by the rooibos crop is 12.14% more than the rainfall received at the same time frame, this could suggest that the rooibos crop uses soil moisture from deeper layers (exceeding the measure depth of 100 meters).

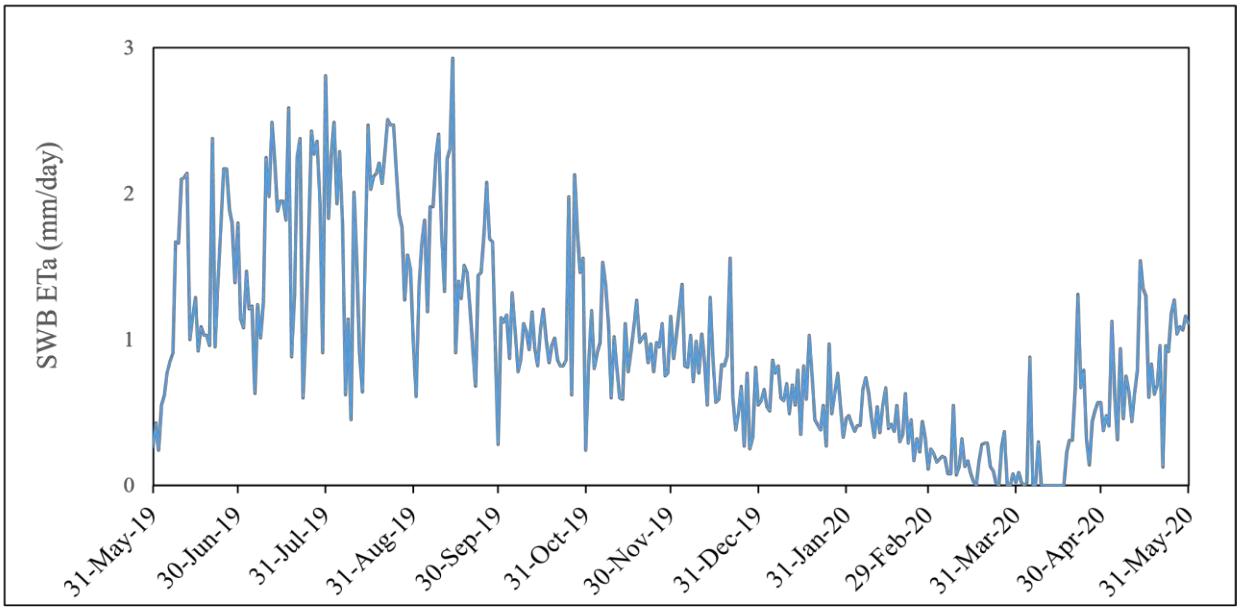

Figure 4.11: Surface Water Balance ET

Eddy Covariance ET

Actual evapotranspiration (ETa) from the rooibos fields was quantified using an open-path eddy covariance system (Figure 4.12). Results show that ETa was generally low in winter (below 2 mm/day) with the highest ETa rate being 2.76 mm/day (August 2019) and there are days where it was negligible. At the beginning of spring (September 2019) ET increased to 3.22 mm/day. The lowest ET rate recorded in spring was 0.43 mm/day (October 2020), whilst the highest ET was 4.52 mm/day (October 2020). Towards the end of spring (November 2019) ETa began to drop when SMC was below FC and rainfall received was almost negligible. According to the results, ETa peaked in October 2019, when the rooibos crop was actively growing. The cumulative amount of ETa recorded from May- November 2019 is equal to 146.49 mm this highlights the crop's water demand and the extent of moisture uptake by the plant. However, there are days with missing data; the period with consistent data set was from 12 September 2019 to 11 November 2019; during this period total ETa is 109.45 which is 42.2% more than the recorded rainfall during the same period.

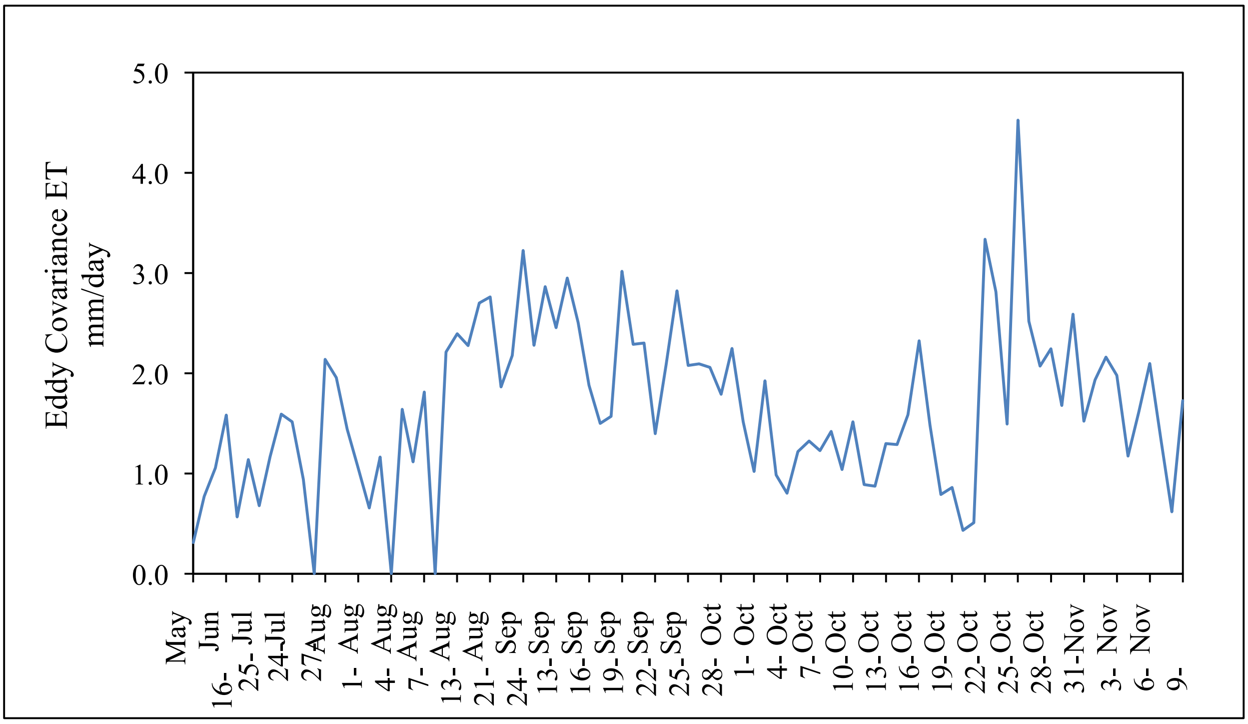

Figure 4. 12: Eddy Covariance ET

Actual evapotranspiration (ETa): FruitLook

Actual evapotranspiration from FruitLook data was low during the wet season compared to the dry season (Figure 4.13). The highest ETa in winter was 10.6 mm/week recorded in May 2019 and the lowest was 2.21 mm/week (August). In spring, ETa peaked at 21.27 mm/week during the first week of October and the lowest ETa was 3.27 mm/week in September. Although ETa values remain high through the summer period, the values are lower than ETa in spring. A significant drop in ETa occurred in December, recorded as 3.89 mm/week (lowest ETa in summer). The low ETa values in winter can be attributed to low temperature, solar radiation and VPD, as water is not a limiting factor during the wet period and vice versa. According to the Fruitlook results, the total amount of water used at the rooibos field from May 2019 to January 2020 is approximately 320.91 mm which is 13.86 % more than the total rainfall recorded at the same time frame.

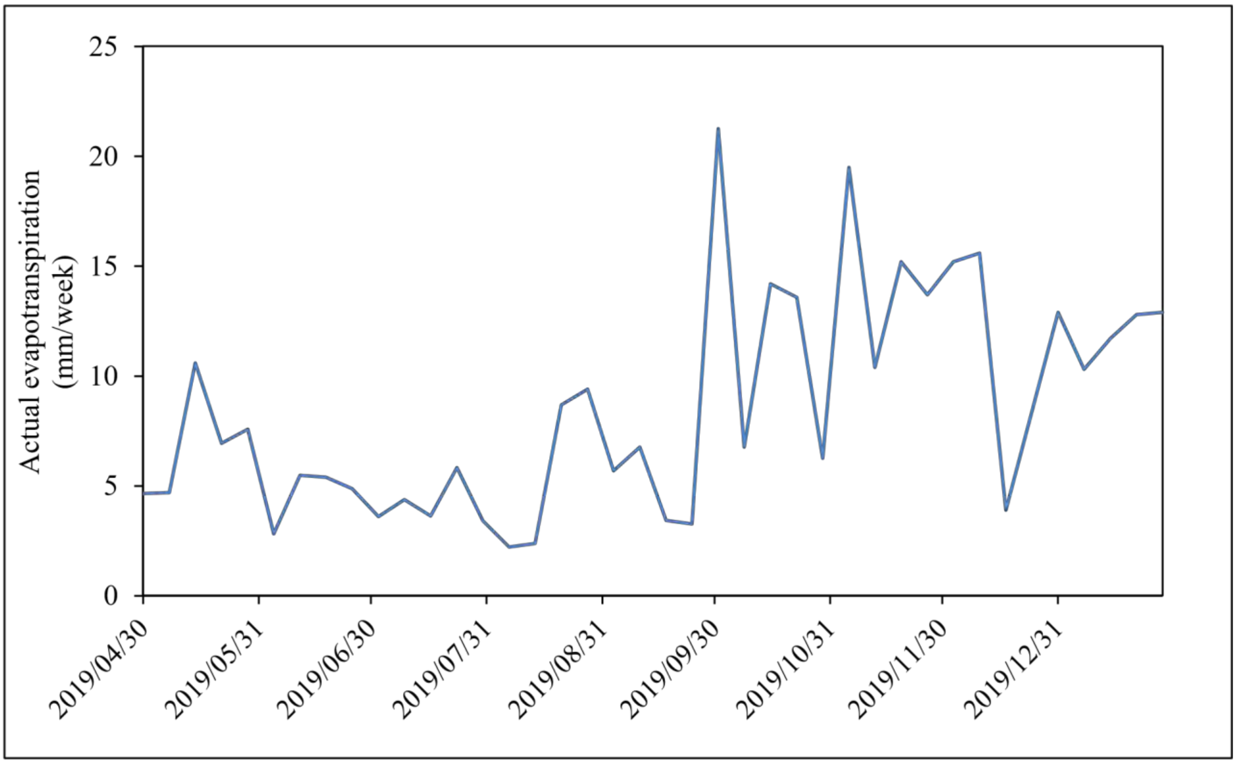

Figure 4. 13: FruitLook ETa at Porteville farm.

4.5.4 Comparing Actual ET from the EC, SWB and Fruitlook

To determine which method of actual evapotranspiration is representative of rooibos water use at the field, the estimated actual evapotranspiration from the EC, SWB and Fruitlook method was compared through regression analysis to the observed water use from the sap flow method (T) (Figure 4.14) using Equation (4.9). To achieve this, ET data from October was used as it is the only month with full data set from all the methods. The results show that the SWB ETa overestimate rooibos monthly water use by 11.60 mm/ month. In comparison the EC ETa method overestimated by 21.96 mm/month and the Fruitlook method by 22.90 mm/month. Additionally, the coefficient of determination (R^2) of SWB ETa and T ($R^2 = 0.81$) was stronger than that of EC (R^2=0.55) and Fruitlook ETa (R^2=0.58). Based on these findings, it can be concluded that the SWB method provides ETa results that are better representative of the rooibos water use at the study field.

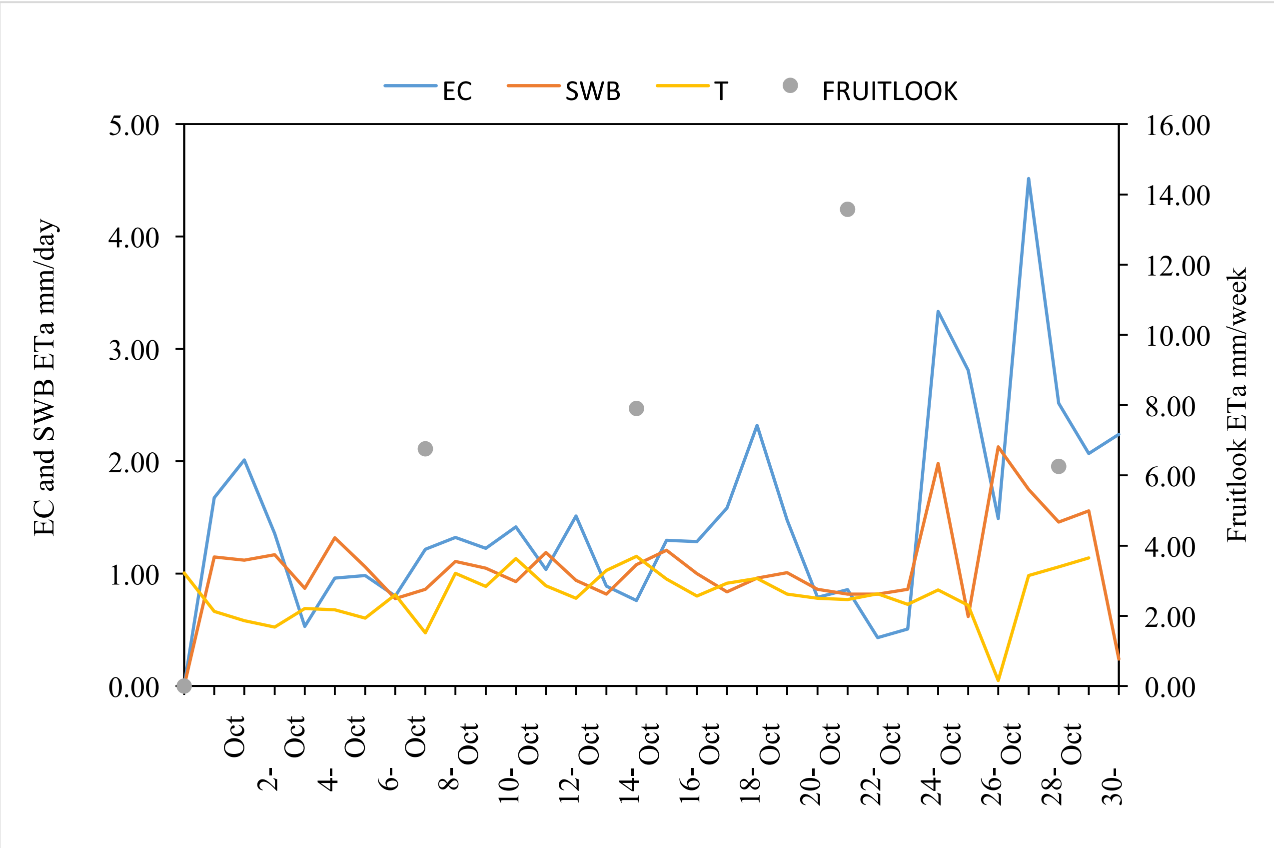

Figure 4.14: Comparison of EC, SWB FruitLook ETa and T data at Porteville farm.

4.5.6 Comparison of Transpiration (T), Reference Transpiration (ETo) and Actual Evapotranspiration Eta

For most plants, actual evapotranspiration follows a similar trend with reference evapotranspiration. For instance, in a study conducted by González et al. (2017) actual evapotranspiration measured with the eddy covariance method presented the same pattern of variation as the reference evapotranspiration obtained from the FAO Penman-Monteith method. However, this is not the case for the rooibos crop as the peak of ETa is reached in September instead of December (ETo peak) (Figure 4.15). The lag between ETa and ETo reflects that soil water content was the limiting factor for rooibos water use. An increase in evaporative demand at the study area increases plant stress as soil water deficit increases. This is depicted by the increasing ETo whilst ETa decreases to almost being negligible. In August 2019 LAI is low and growth of the rooibos crop is slow but ETa is high. When observing Figure:4.16 (a) the rooibos crop is in its early stages of growth and its branches are dry with little or no leaves however, the weeds are green, these weeds grow more actively around July (Figure:4.16b) and die out around October (Figure:4.16c). Henceforth the high ETa rates can be attributed to the presence of weeds in the rooibos field. Evidently, after the weeds are dead, ETa rates drop significantly, ranging above 1.6 mm/day for most days from July- September to being below 1.6 mm/day for most days from October till harvesting.

In addition, when observing T, ETa and ETo from August to mid-September, transpiration values are the lowest. This suggests that most water use at the rooibos field is attributed to weed vegetation. Moreover, when observing transpiration and actual evapotranspiration between August and November 2019, there are similarities in the patterns of the graph. This is around the time when the leaves have completely dried out (October2019-November 2019) (Figure: 4.16c). Therefore, ETa rate after the weeds are dead is the true reflection of ET of the rooibos crop.

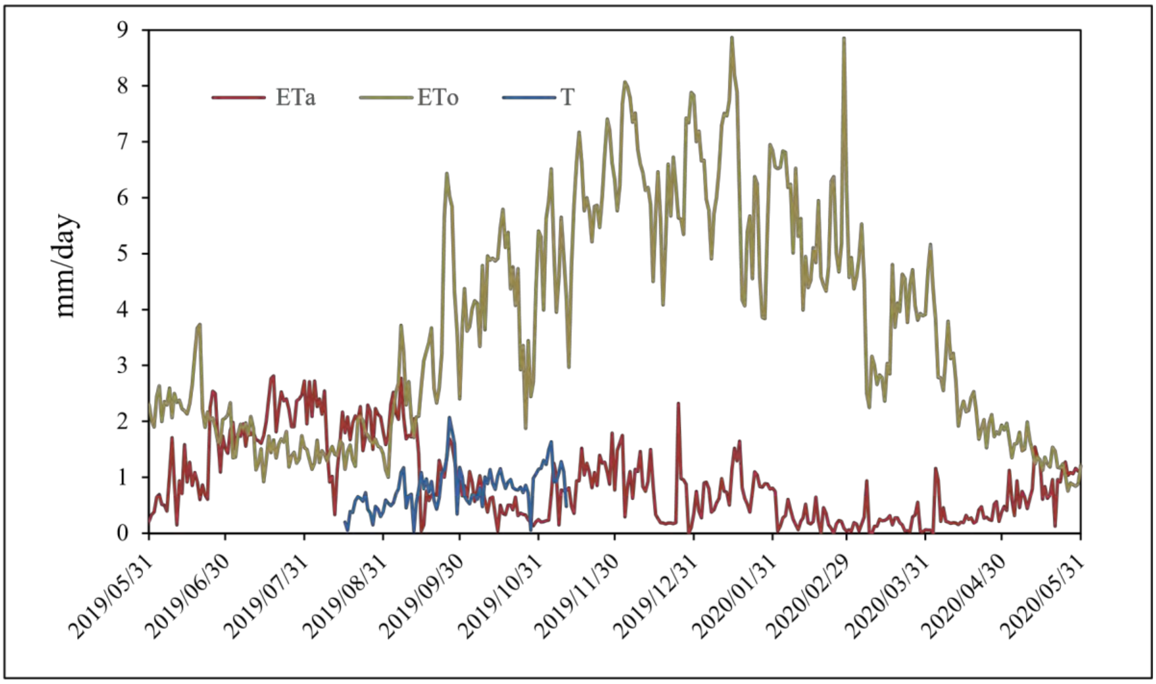

Figure 4. 15: Comparison of reference transpiration, actual evapotranspiration and transpiration at the rooibos field.

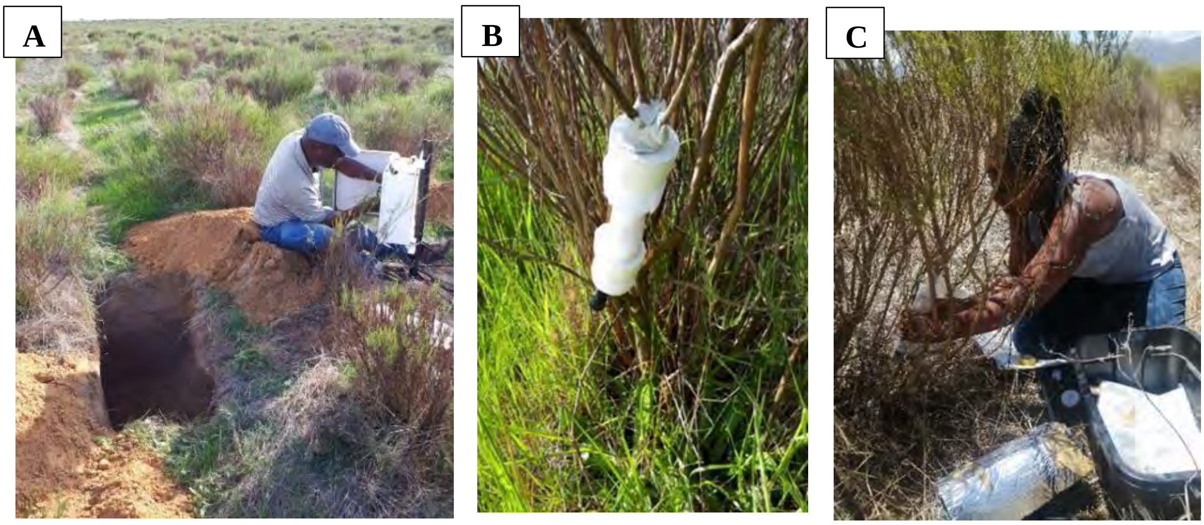

Figure 4.16: Water use dynamics at the rooibos farm as well as changes in the quantity of weeds image (a) taken May 2019 image (b) July 2019 and (c) October 2019.

4.6 Drivers of water use

Drivers of water use in the rooibos field were determined by regression analysis transpiration, reference evapotranspiration, actual evapotranspiration with weather data (which includes VPD, wind and solar radiation) and soil water deficit (results are shown in Table 4.3). Based on the results, transpiration of the rooibos crop is mainly driven by radiation and VPD (R^2 = 0.39). As expected, ETo is mainly controlled by weather conditions with the strongest relation being as follows: radiation (R^2 = 0.61), VPD (R^2 = 0.47) and wind speed (R^2 = 0.24). ETa from FruitLook is mainly driven by VPD (R^2 = 0.67) and radiation (R^2= 0.55). Additionally, ETa from SWB approach is mainly driven by soil water deficit as (R^2 = 0.45). Lastly, ETa from the open path Eddy Covariance system shows a weak relation with all-weather variables and the strongest relation observed was with soil water deficit (R^2=0.09).

The strong influence of solar radiation and VPD on rooibos water use is expected because as more solar radiation reaches the surface of the earth, temperatures increase and warm air holds more water, creating a larger driving force for water movement out of the plant, increasing rates of transpiration (Sterling, 2004). According to the Beaufort Wind Scale, the wind at the rooibos farm ranges between calm and light breeze; hence it did not have a strong influence on rooibos evapotranspiration. Additionally, the weak association between SWD and transpiration as well as ETa from EC and Fruitlook method coupled with the moderate influence of SWD on SWB ETa as well as the moderate association between Plant attributes (Figure 4.13) suggest that the rooibos crop uses soil water from other water sources besides the one available within the 100 cm depth, given that it has a root system that is 2 meters long.

Table 4.3: The Coefficient of determination (R^2) for weather variables and water use derived from different methods. The bold values represent high values.

		Water use				
		Reference Evapotranspiration	Transpiration	Eddy Covariance derived ET	Soil-Water balance ET	Fruitlook derived ET
Weather variables	Radiation	**0.61**	0.39	0.02	0.20	**0.55**
	VPD	0.48	0.39	0.04	0.09	**0.67**
	Wind speed	0.34	0.03	0.00	0.01	0.08
	Soil moisture deficit	0.24	0.05	0.09	0.46	0.10

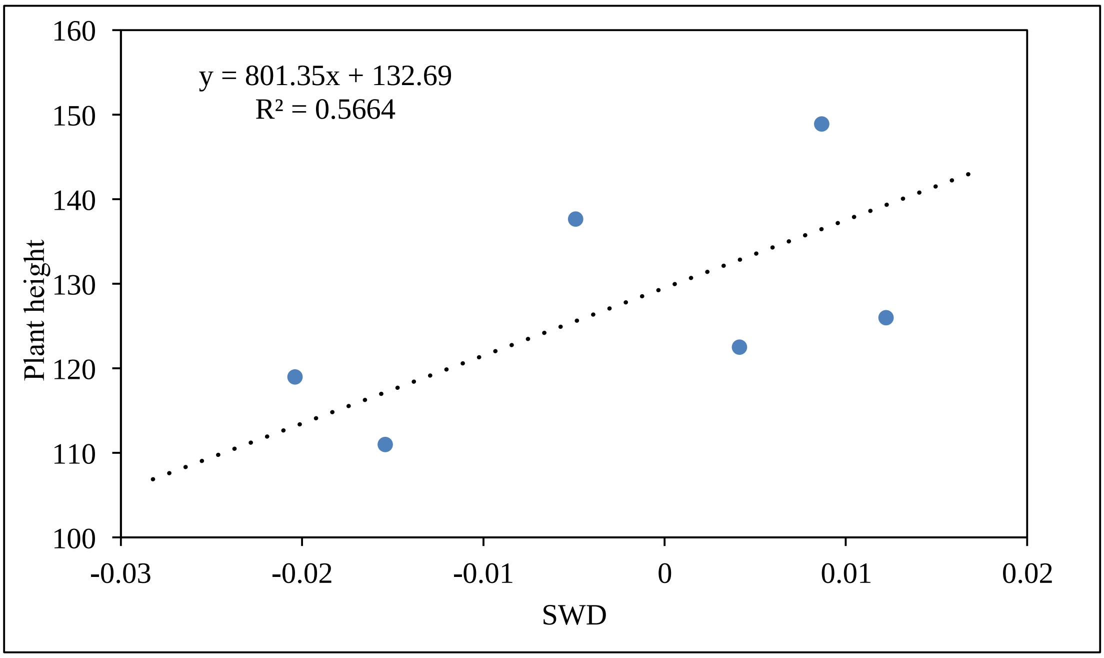

Figure 4.17: Influence of SWD on plant growth.

Comparison of rainfall and rooibos water use.

Rooibos water use was compared with rainfall received at Porterville rooibos farm (Table 4.4). Results show that during the early stages of growth (May-July 2019) the amount of water used by the rooibos crop is 47.57% less than the rainfall received. However, from August till harvesting, water used by the rooibos crop exceeds the amount of rainfall received by approximately 48.14%. This trend is also observed in the transpiration data (October-November). Although there is a significant difference between water used by the rooibos crop and rainfall at the study site, there is not much difference in the change in SMC. Hence it can be reasoned that the rooibos crop uses water stored beyond the 1-meter depth (groundwater).

Table 4.4: Summary of the rainfall, SMC as well water use of the rooibos at the study site.

	Rain (mm)	ETo (mm)	ET (SWB) (mm/d)	T (mm/d)	SWC (cm3/cm3)
May-19	52,1	82,2	11,2	-	0,071
Jun-19	55,6	70,8	39,8	-	0,080
Jul-19	87,8	59,8	51,7	-	0,096
Aug-19	21,6	75,0	54,2	-	0,086
Sep-19	29,2	110,5	47,9	26,2	0,062
Oct-19	19,2	138,0	33,6	25,3	0,052
Nov-19	3,3	176,4	29,2	13,8	0,069
Dec-19	5,8	195,6	24,1	-	0,058
Jan-20	5,5	184,1	19,6	-	0,053
Feb-20	0,3	144,1	13,2	-	0,047
Mar-20	2,5	118,7	5,4	-	0,041
Apr-20	52,1	92,3	8,0	-	0,057
Total	**334,8**	**1447,5**	**337.8**	**65.3**	

4.7 Water use efficiency

The total wet yield produced over the entire field (which is 25 ha) was reported by the farmer to be approximately 20 tons which is equal to 0.84 tons per hectare. The estimated water productivity was about 0.24 kg of rooibos per m^3 of water consumed. Generally, WUE of the rooibos crop is low compared to other rain-fed crops such as potatoes, sugarcane, wheat, rice and maize (Panigrahi et al., 2020). Katerji et al. (2009) presents a table with WUE of crops cultivated in the Mediterranean region and Wang et al. (2018) presents various studies conducted to calculate and improve crop WUE's. In both mentioned studies WUE of rooibos is low compared to other crops except for cotton which ranges between 0.2 kg/m^3 and 0.8 kg/m^3. van Schalkwyk (2018) conducted a study on rooibos WUE however, the biomass WUE results were found to be inconclusive due to the stoppage of the SWB when the plants were still immature.

Lotter et al. (2014) found a significant seasonal variation in the water use efficiency of the rooibos crop. Both wild and cultivated rooibos showed lower WUE in winter compared to summer. Hence significant growth of the rooibos crop occurred during the dry season (in spring and summer). The ability of the rooibos crop to adapt to dry summer conditions may be related to the higher sclerophylly index which Turner (1994) argues to be an important protective mechanism to resist extreme climatic events (Lotter et al., 2014). Grubb (1998) mentions that a reduction in the rate of photosynthesis is an adaptive strategy for sclerophylls in arid regions to cope during the dry period. Additionally, several studies have reported a general increase of WUE with decreasing water availability (e.g. Erdem et al., 2001; Rusere et al., 2012; Mabhaudhi et al., 2013; Chibarabada et al., 2015). Hence rooibos water use (ETa and T) decreased as the evaporative demand increased at the rooibos field (Table 4.4).

4.8 Future climate change

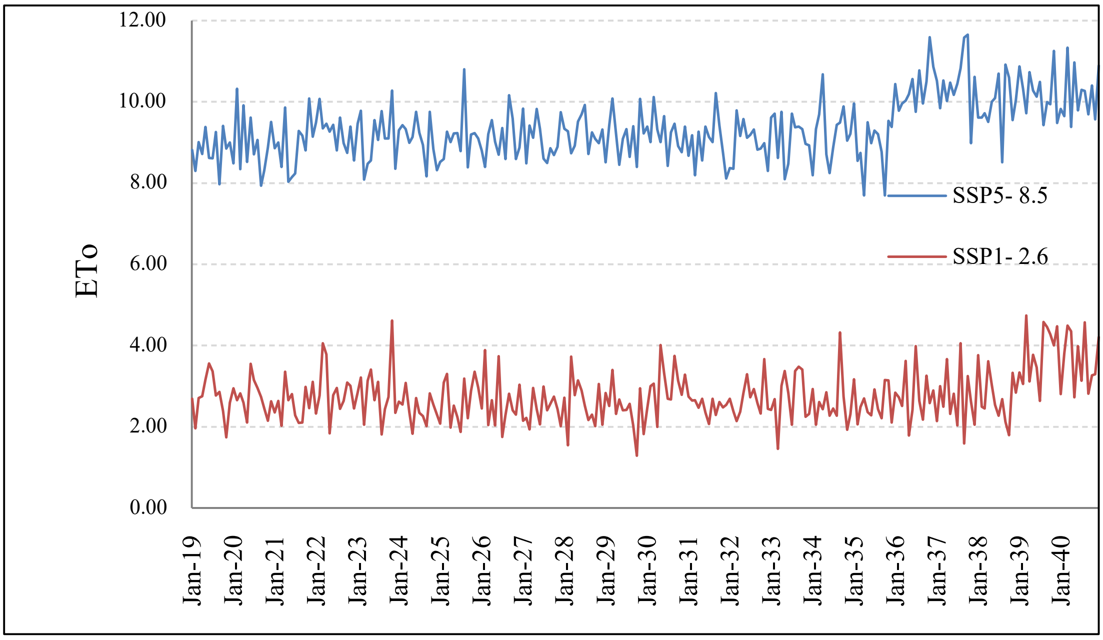

Figure 4.18. Future ETo from 2019-2040 under SSP1- 2.6 and SSP5- 8.5

The atmospheric evaporative demand (ET_o) from SSP1-2.6 and SSP5-8.5 data was estimated using the Penman Montheith equation with data spanning from Jan 2019 to December 2040 (Figure 4.18). Evaporative demand observed under SSP1-2.6 shows that ET_o is relatively low as it ranges between 1.28 mm/month (October 2029) and 4.61 mm/month (November 2023). According to Olaka et al. (2019), SSP1-2.6 represent optimistic projections characterised by very low concentration and emission levels of GHGs. Hence, the evaporative demand induced by climate change is expected to be low under SSP1-2.6.

On the other hand, under SSP5-8.5, ET_o values range between 8-10 mm/month from 2019 – 2035 and between 10 - 12 mm/month from 2036-2040 (Figure 4.18). The evaporative demand represented by the SSP5-8.5 model is higher than that of SSP1-2.6 because SSP5-8.5 scenario represents a pessimistic projection with high GHG concentration and emissions (Olaka et al., 2019). The increase in evaporative demand could be attributed to increased temperatures, solar radiation and vapour pressure deficit induced by climate change (Massmann et al., 2019). The changes in evaporative demand as a result of climate change could immensely affect rooibos water use and growth patterns. The observations made are coherent to the findings of Lötter (2015) in the study which investigated whether there is evidence of climate change over the rooibos distribution area. Lötter (2015) predicted that, the rooibos crop would likely experience extended exposure to high temperatures and water stress conditions, reducing the natural growing area of the plant wild and cultivated rooibos crop.

Chapter summary

Micro-climate conditions at the selected study site (Porterville) were typically that of the Mediterranean climatic zone, with 80-90% of rainfall received in winter whilst 5-20% is received in summer. Soil content at the Porterville farm is mainly composed of sand silt and clay in varying amounts and textures across different depths of the soil profile. SMC is high in winter, and the rooibos crop experiences a water deficit during the dry season. The rooibos crop relies on SMC for growth and development. The average growth of the rooibos crop was 1.0 cm/month in winter and increased to 11 cm in summer and 12cm in spring. LAI of the rooibos crop increased steadily over the months and reached its highest peak in summer. The rooibos crop has tiny feathery leaves on fairly thick branches; hence, much of the LAI recorded by the leaf area meter is the non-transpiring branches. As a result, LAI and rooibos height growth are directly proportional.

Plant canopy develops during the growing season, and the increase in leaf area is proportional to plant growth and transpiration (Ritchie, 1972). Hence transpiration rates for the rooibos plant increased significantly in spring when the rooibos crop was flowering and when the growth rate peaked. Actual evapotranspiration in the study area was determined using the Eddy Covariance, Soil Water Balance approach and FruitLook. To determine which method of ETa was representative of rooibos water use, observed data (from the sap flow method) was compared with estimated data ETa (SWB, eddy covariance system and FruitLook). ETa estimated from the SWB method was more accurate than ETa observed using the eddy covariance and FruitLook. The SWB, eddy covariance and FruitLook methods overestimated ETa by 11.60 mm/ month, 21.96 mm/month, and 22.90 mm/month, respectively.

Overall, the data from sap flow, open path eddy covariance system, and FruitLook support the finding that the rooibos crop utilizes the highest amount of water during the spring season. Comparison of transpiration, reference evapotranspiration and actual evapotranspiration (SWB) shows that the peak of actual evapotranspiration (ET) and the reference evapotranspiration (ETo) was out of phase with ET reaching a maximum in (August and early September) while the ETo peaked much later in mid-summer (December to January). This trend can be attributed to the high-water consumption by the dense weed cover from May to September. During the dry season, there is an increase in evaporative demand and soil water deficit, but simultaneously, the growth and leaf area index (LAI) of the rooibos crop reach their highest peak. Additionally, all the different methods used to determine water use suggest that the rooibos crop uses more water compared to the rainfall received. This indicates that the rooibos crop could be using water stored beyond 100-meter depth.

Climatic factors such as VPD of the air and solar radiation were the strongest drivers of transpiration, ETo and ETa by rooibos, while the soil water deficit had a weak to moderate influence which was rather unexpected. The water productivity was determined by calculating the yield ratio in relation to the annual evapotranspiration (ET), resulting in a value of approximately 0.24 kg of rooibos per m3 of water consumed. Climate change projections derived from SSP5-8.5 indicate that in the absence of greenhouse gas (GHG) policies, there will be an escalation in evaporative demand within the rooibos cultivation region of Porterville. This implies that the growing conditions for rooibos, in terms of water availability and usage, may be adversely affected by the anticipated changes in climate associated with SSP5-8.5.

5 CONCLUSION

Understanding water use patterns of the rooibos crop is crucial for sustainable farming practices in South Africa. This study investigated the water use patterns of the rooibos crop under different climate and environmental conditions. The results showed that, Rooibos water consumption exhibited a distinct seasonal pattern, with higher usage during spring and summer months. This trend aligned with various measurements, including evapotranspiration (ETa) and transpiration rates. The results also showed that, weather parameters like vapor pressure deficit (VPD) and radiation were identified as primary drivers of rooibos water use, while wind speed had minimal impact.

Despite having a lower water use efficiency compared to other rain-fed crops, rooibos demonstrated remarkable adaptability to dry summer conditions. This ability can be attributed to its deep taproot system, allowing it to access water from deeper soil layers even when surface moisture is limited. This adaptation was further evident by the continued growth (height and leaf area) even during periods of low soil moisture content. However, based on future climate projections, the study anticipates an increase in evaporative demand in the rooibos growing region, posing potential challenges for sustainable water management.

Overall, the study provides valuable insights into rooibos's water use strategies and highlights the need for proactive measures to address the potential impacts of climate change on the rooibos. These findings have the potential to inform future water management practices and promote the long-term sustainability of rooibos cultivation in South Africa.

Limitations and recommendations

In order to improve the accuracy of current research, the current study was supposed to be conducted on another study site with different climatic and soil conditions for rooibos growth. The intention was to provide additional insights and aid in the interpretation of data. However, although the new site had already been identified, the study could not be carried out due to the Covid-19 pandemic. In addition, the lack of previous research limited access to a literature review, which would have enabled a more informed conclusion. There is limited transpiration data (spanning from August to November 2019) and ETa data from the Eddy Covariance system because of measurement errors.

Based on the analysis of the data and considering the limitations of the study, the following recommendations are proposed:

- Redoing the same study at a different site to compare results and improve the accuracy of this study. In addition, explore alternative methods of quantifying transpiration rates to validate sap flow measurements.
- Determine the water table at the study site to determine if groundwater is an alternative water source of rooibos.
- Management strategies such as removing weeds in the rooibos crop field will improve the rooibos crop's yield and water use efficiency.

Information from this study can be valuable in developing yield models and predicting how crop yield may be influenced by changing climate conditions, such as declining rainfall and increasing evapotranspiration. These predictive models can aid farmers and policymakers in making informed decisions and implementing adaptive strategies to mitigate the potential impact of climate change on rooibos cultivation.

References

Allen R.G. Pereira L.S., Howell T.A., Jensen M.E., 2011., Evapotranspiration information reporting: I. Factors governing measurement accuracy. Agric. Water Manag. 98, 899–920

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: 1998. Crop evapo-transpiration Guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations,

Advanced Remote Sensing 2012., Editor(s): Shunlin Liang, Xiaowen Li, Jindi Wang, Chapter 18 - Terrestrial Evapotranspiration, Academic Press, 2012, Pages 557-588, ISBN 9780123859549.

Ahooghalandari, M.; Khiadani, M.; Jahromi, M.E. 2016. Developing equations for estimating reference evapotranspiration in Australia. Water Resour. Manag. 2016, 30, 3815–3828

Ahmed, C.B., Rouina, B.B., Sensoy, S., Boukhriss, M., 2009. Saline water irrigation effectson fruit development, quality, and phenolic composition of virgin olive oils, cv.Chemlali. J. Agric. Food Chem. 57, 2803–2811.https://doi.org/10.1021/jf8034379.

Almorox, J; Quej, V. H.; Martí, P., 2015 Global performance ranking of temperature-based approaches for evapotranspiration estimation considering Köppen climate classes. Journal of Hydrology, v. 528, p. 514–522. https://doi.org/10.1016/j.jhydrol.2015.06.057

Amitav Bhattacharya. 2019.Changing Climate and Resource Use Efficiency in Plants, Academic Press, , Pages 307-314, ISBN 9780128162095.

Angrish, R., & Rani, C. 2007. PLANTS WATER STATUS. *Research Methods in Plant Sciences: Allelopathy Vol. 5 (Plant Physiology)*, 109.

Archer, E. et al. 2009. 'Climate change, groundwater and intensive commercial farming in the semiarid northern Sandveld, South Africa', Journal of Integrative Environmental Sciences, 6(2), pp. 139– 155. doi: 10.1080/19438150902916589.

Archer E.R.M., Oettle N.M., Louw R. and Tadross M.A. 2008. Farming on the edge in arid western South Africa: climate change and agriculture in marginal environments Geography, 93 (), pp. 98107

Arendse, A. 2001. Trade, environment & sustainable development. Briefing document: 4. Rooibos trade and small-scale production. Environmental Monitoring Group, Cape Town.

Almond J.E.., 2012. Recommended exemption from further palaeontological studies & mitigation: proposed Wolseley wind energy facility near wolseley, Western Cape.

Baker, J.M. and C.H.M. van Bavel. 1987. Measurement of mass flow of water in stems of herbaceous plants. Plant, Cell, and Environment 10: 777-782.

Baldocchi, D. 2008., Turner Review No. 15. 'Breathing' of the terrestrial biosphere: Lessons learned from a global network of carbon dioxide flux measurement systems, Aust. J. Bot., 56, 1–26

Ball J. 2001. Soil and Water Relationships. Noble Research Institute. https://www.noble.org/news/publications/ag-news-and-views/2001/september/soil-and-waterrelationships/

Basso, B., and Ritchie, J. T. 2018. Evapotranspiration in high-yielding maize and under increased vapor pressure deficit in the US Midwest. *Agric. Environ. Lett.* 3:170039. doi: 10.2134/ael2017.11.0039

Blum, A., 2009. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field Crops Research 112, 119–123. https://doi.org/10.1016/j.fcr.2009.03.009

Botai, C. M., Botai, J. O., de Wit, J. P., Ncongwane, K. P., & Adeola, A. M. 2017. Drought characteristics over the Western Cape Province, South Africa. *Water (Switzerland)*, *9*(11). https://doi.org/10.3390/w9110876

Boyer J.S. 1982. **Plant productivity and environment**. Science, 218 (1982), pp. 443-448

Burba, G. and Anderson, D., 2010. A brief practical guide to eddy covariance flux measurements.LICOR Biosci., 1212

Cheney, R.H., Scholtz, E., 1963. Rooibos tea, a South African contribution to world beverages. Economic Botany 17, 186–194

Chabot, R., Bouarfa, S., Zimmer, D., Chaumont, C., Moreau, S., 2005. Evaluation of the sap flow determined with a heat balance method to measure the transpiration of a sugarcane canopy. Agricultural Water Management 75, 10–24. https://doi.org/10.1016/j.agwat.2004.12.010

Castellví F., Snyder R.L, and Baldocchi D.D. 2008. "Surface energy-balance closure over rangeland grass using the eddy covariance method and surface renewal analysis," *Agricultural and Forest Meteorology*, vol. 148, no. 6-7, pp. 1147–1160, 2008.

Chazarenc, F., Naylor, S., Comeau, Y., Merlin, G. & Brisson, J. 2010. Modeling the effect of plants and peat on evapotranspiration in constructed wetlands. International Journal of Chemical Engineering. 2010:1–6 Stellenbosch University https://scholar.sun.ac.za

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., et al. 2013. "Long-term climate change: projections, commitments and irreversibility," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen (Cambridge: Cambridge University Press).

Condon A. G., Richards R. A., Rebetzke G. J., Farquhar G. D. 2004. Breeding for high water-use efficiency.*J. Exp. Bot.* 2447–2460. 10.1093/jxb/erh277, PMID:

Dai AG. 2013. Increasing drought under global warming in observations and models. *Nature Climate Change* **3**: 52– 58.

Dahlgren R. 1988. Revision of the genus Aspalathus Flora of Southern Africa, 16 , pp. 1-430

Department of Agriculture Forestry & Fisheries. 2014. *A Profile of the South African Broiler Market Value Chain*. 48. http://www.nda.agric.za/doaDev/sideMenu/Marketing/Annual Publications/Commodity Profiles/Livestock/Broiler market value chain profile 2014.pdf

Department of Environmental Affairs (DEA). 2013. Long-term adaptation scenarios flagship research programme (LTAS) for South Africa: Climate change implications for the biodiversity sector in South Africa. Pretoria, South Africa: DEA

Department of Forestry, Fisheries and the Environment (DFFE). 2020. 2020 South African National Landcover Data and the CALC system.

Dynamax Inc, 2005. Dynagage Sap Flow Sensor: User manual 107 (pg 35-42)

Emmons, L.H., Chatelet, P., Cournac, L., Pitman, N.C. a, Aguila, L.F. Del, Dubois, M. a, 2006. Seasonal change in leaf area index at three sites along a south American Latitudinal gradient. Tropical Ecology 12, 87–102.

Feng, Y., Cui, N., Zhao, L., Gong, D., Zhang, K., 2017. Spatiotemporal variation of reference evapotranspiration during 1954–2013 in Southwest China. Quaternary International 441, 129–139. https://doi.org/10.1016/j.quaint.2017.01.023

FruitLook Manual 2019, FruitLook.co.za

Flexas, J., Gulías, J., Jonasson, S., Medrano H., Mus, M., 2001.Seasonal patterns and control of gas exchange in local populations of th Mediterranean greenshrub PistacialentiscusL. ActaOecol.22,33–43,

Gray, B.A., Toucher, M.L., Savage, M.J. and Clulow, A.D., 2021. The potential of surface renewal for determining sensible heat flux for indigenous vegetation for a first-order montane catchment. Hydrological Sciences Journal, 66(6), pp.1015-1027.

Gadow, A. von, Joubert, E., And and Hansmann, C. F. 1997. 'Comparison of the Antioxidant Activity of Aspalathin with That of Other Plant Phenols of Rooibos Tea (*Aspalathus linearis*), α-Tocopherol, BHT, and BHA'. American Chemical Society. doi: 10.1021/JF960281N

Gómez-Alonso, S.E., García-Romero, E.. 2010. Effect of irrigation and variety onoxygen (d18O) and carbon (d13C) stable isotope composition of grapes cultivated in a warm climate. Aust. J. Grape Wine Res. 16, 283–28

Groot A, King KM. 1992. Measurement of sap flow by the heatbalance method: numerical analysis and application toconiferous seedlings. Agricultural and Forest Meteorology59, 289-308

Hawkins H-J, Malgas R, Biénabe E. 2011. Ecotypes of wild rooibos (*Aspalathus linearis* (Burm. F) Dahlg., Fabaceae) are ecologically distinct. South African Journal of Botany 77: 360−370.

Hawkins, Heidi & Malgas, Rhoda & Biénabe, Estelle. 2011. Ecotypes of Wild Rooibos (Aspalathus linearis (Burm. F) Dahlg., Fabaceae) Are Ecologically Distinct. South African Journal of Botany. 77. 360-370. 10.1016/j.sajb.2010.09.014.

Hewitson, B. C., & Crane, R. G. 2006. *Consensus between GCM climate change projections with empirical downscaling: precipitation downscaling over South Africa. International Journal of Climatology, 26(10), 1315–1337.* doi:10.1002/joc.1314

Hewitson, B.C., Tadross, M. & Jack, C. 2005. Historical precipitation trends over Southern Africa: A climatology perspective. In Schulze, R. Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation (pp. 319-324). Water Research Commission, Pretoria, SA.

Harmsen, E.W., Miller, N.L., Schlegel, N.J., Gonzalez, J.E., 2009. Seasonal climate change impacts on evapotranspiration, precipitation deficit and crop yield in Puerto Rico. Agric. Water Manage. 96, 1085–1095

Hanson, R.L., 1991, Evapotranspiration and Droughts, in Paulson, R.W., Chase, E.B., Roberts, R.S., and Moody, D.W., Compilers, National Water Summary 1988-89--Hydrologic Events and Floods and Droughts: U.S. Geological Survey Water-Supply Paper 2375, p. 99-104

Hatfield JL, Prueger JH. 2015. Temperature extremes: effect on plant growth and development. *Weather and Climate Extremes* **10**: 4– 10

Hatfield, J.L., Dold, C., 2019. Water-use efficiency: Advances and challenges in a changing climate. Frontiers in Plant Science 10, 1–14. https://doi.org/10.3389/fpls.2019.00103

Hu, Z., Wang, G., Sun, X., Zhu, M., Song, C., Huang, K., & Chen, X. 2018. Spatial-Temporal Patterns of Evapotranspiration Along an Elevation Gradient on Mount Gongga, Southwest China. *Water Resources Research*, *54*(6), 4180–4192. https://doi.org/10.1029/2018WR022645

Hatfield, J.L., Dold, C., 2019. Water-use efficiency: Advances and challenges in a changing climate. Frontiers in Plant Science 10, 1–14. https://doi.org/10.3389/fpls.2019.00103

Hillel, D., & Guron, Y. 1973. *Relation between evapotranspiration rate and maize yield. Water Resources Research, 9(3), 743–748.* doi:10.1029/wr009i003p00743

Hopkins, W. G. 2008. *Introduction to plant physiology*. John Wiley & Sons.

IPCC, 2007. Climate Change Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, in: Pachauri, R.K, Reisinger, A., (Eds.), IPCC, Geneva, Switzerland, pp.104

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp

Joubert, E., de Beer, D., & Malherbe, C. J. 2017. Herbal teas—Exploring untapped potential and strengthening commercialisation. *South African Journal of Botany*, *110*, 1–3. https://doi.org/10.1016/j.sajb.2017.01.204

Joubert, E., Jolley, B., Koch, I. S., Muller, M., Van der Rijst, M., & de Beer, D. 2016. Major production areas of rooibos (Aspalathus linearis) deliver herbal tea of similar phenolic and phenylpropenoic acid glucoside content. South African Journal of Botany, 103, 162–169. https://doi.org/10.1016/j.sajb.2015.08.015

Joubert, E., and de Beer, D. 2011. Rooibos (*Aspalathus linearis*) beyond the farm gate: From herbal tea to potential phytopharmaceutical. South African Journal of Botany, 77(4), 869–886. https://doi.org/10.1016/j.sajb.2011.07.004

Jensen, M. E., Burman, R. D., and Allen, R. G. 1990. (Eds): Evapotran-spiration and irrigation water requirements, ASCE Manuals andReports on Engineering Practice, 70,

Jovanovic, N., Mu, Q., Bugan, R., & Zhao, M. (2015). Dynamics of MODIS evapotranspiration in South Africa. Water SA, 41(1), 79. doi:10.4314/wsa.

Jovanovic, N., Bugan, R., & Israel, S. 2013. *Quantifying the Evapotranspiration Component of the Water Balance of Atlantis Sand Plain Fynbos (South Africa). Evapotranspiration - An Overview.* doi:10.5772/53405

Jovanovic, NZ, Jarmain, C, de Clercq, WP, Vermeulen, T, & Fey, MV. 2011. Total evaporation estimates from a Renosterveld and dryland wheat/fallow surface at the Voëlvlei Nature Reserve (South Africa). *Water SA*, *37*(4), 471-482.

Joubert, E. and Schulz, H., 2006. Production and quality aspects of rooibos tea and quality products A review. Journal of Applied Botany and Food Quality 80, 138–144.

Kruger, A. C., & Sekele, S. S. 2012. Trends in extreme temperature indices in South Africa: 19622009. International Journal of Climatology, 33(3), 661–676. doi:10.1002/joc.3455

Jovanovic, NZ et al. 2011. Total evaporation estimates from a Renosterveld and dryland wheat/fallow surface at the Voëlvlei Nature Reserve (South Africa). *Water SA* [online]., vol.37.

Klasmeyer, K. & Shaw, R. 2009. Climate change, habitat loss, protected areas and the climate adaptation potential of species in mediterranean ecosystems worldwide. PLoS ONE, 4, e6392

Khan, S., Y. Hong, B. Vieux, and W. Liu 2010, Development evaluation of an actual evapotranspiration estimation algorithm using satellite remote sensing meteorological observational network in Oklahoma, Int. J. Remote Sens., 31(14), 3799–3819.

Kinhal V. 2019. The Importance of Leaf Area Index (LAI) in Environmental and Crop Research. Published March 11, 2019.

Katerji, N., Mastrorilli, M., & Rana, G. 2008. *Water use efficiency of crops cultivated in the Mediterranean region: Review and analysis. European Journal of Agronomy, 28(4), 493– 507.* doi: 10.1016/j.eja.2007.12.00

Kramer P.J., Boyer J.S., 1995 **Water Relations of Plants and Soils** Academic Press, London (1995).

Kirkham M.B.2014. Chapter 21 - Sap Flow, Editor(s): M.B. Kirkham, Principles of Soil and Plant Water Relations (Second Edition), Academic Press, , Pages 375-390, ISBN 9780124200227.

Liu S., Xu Z. 2019 Micrometeorological Methods to Determine Evapotranspiration. In: Li X., Vereecken H. (eds) Observation and Measurement of Ecohydrological Processes. Ecohydrology, vol 2. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-48297-1_7

Li, Z., Liu, H., Zhao, W., Yang, Q., Yang, R. and Liu, J., 2019. Quantification of soil water balance components based on continuous soil moisture measurement and the Richards equation in an irrigated agricultural field of a desert oasis. *Hydrology and Earth System Sciences*, *23*(11), pp.4685-4706.

Lambers, H., Shane, M. W., Cramer, M. D., Pearse, S. J., & Veneklaas, E. J. 2006. Root structure and functioning for efficient acquisition of phosphorus: Matching morphological and physiological traits. Annals of Botany, 98(4), 693–713. https://doi.org/10.1093/aob/mcl114

Lötter, D. (2015). *Potential implications of climate change for Rooibos (A. linearis) production and distribution in the greater Cederberg region, South Africa. January*

Louw, R.R., 2006. Sustainable harvesting of wild rooibos (Aspalathus linearis) in the Suid Bokkeveld, Northern Cape. Unpublished MSc. (Bot.) Thesis. Leslie Hill Institute for Plant Conservation, Botany Department, UCT

Lerotholi, L., Chaudhary, S. K., Combrinck, S., & Viljoen, A. 2017. Bush tea (Athrixia phylicoides): A review of the traditional uses, bioactivity and phytochemistry. *South African Journal of Botany*, *110*, 4–17. https://doi.org/10.1016/j.sajb.2016.06.005

Latimer AM, Silander JA, Gelfand AE et al. 2004 A method for quantifying the magnitude of threat to plant biodiversity from alien plant invasions and other anthropogenic factors – a case study in the Cape Floristic Region, South Africa. South African Journal of Science, 100, 81–86.

Lötter,, Daleen & Le Maitre, David. 2014. Modelling the distribution of Aspalathus linearis (Rooibos tea): Implications of climate change for livelihoods dependent on both cultivation and harvesting from the wild. Ecology and evolution. 4. 1209-21. 10.1002/ece3.985.

Lötter, r, D., Valentine, A. J., Archer Van Garderen, E., & Tadross, M. 2014. Physiological responses of a fynbos legume, Aspalathus linearis to drought stress. *South African Journal of Botany*, *94*, 218–223. https://doi.org/10.1016/j.sajb.2014.07.005.

Lakhiar . 2018., "Surface Renewal Application for Estimating Evapotranspiration: A Review", *Advances in Meteorology*, vol. 2018, Article ID 1690714, 11 pages, 2018. https://doi.org/10.1155/2018/1690714

Louw, R.R. 2006. Sustainable Harvesting of Wild Rooibos (Aspalathus linearis) in the Suid Bokkeveld, Northern Cape.Unpublished MSc. thesis, Leslie Hill Institute for PlantConservation, Botany Department, University of Cape Town

Li, Z., Chen, Y., Yang, J., Wang, Y., 2014. Potential evapotranspiration and its attribution over the past 50years in the arid region of Northwest China. Hydrological Processes 28, 1025–1031. https://doi.org/10.1002/hyp.9643

Lötter, D., Archer van Garderen, E., Tadross, M., & Valentine, A. J. 2014. *Seasonal variation in the nitrogen nutrition and carbon assimilation in wild and cultivated Aspalathus linearis (rooibos tea). Australian Journal of Botany, 62(1), 65.* doi:10.1071/bt13237

MacAlister, D., Muasya, A. M., Crespo, O., Ogola, J. B. O., Maseko, S., Valentine, A. J., … Chimphango, S. B. M. 2020. Stress tolerant traits and root proliferation of Aspalathus linearis (Burm.f.) R. Dahlgren grown under differing moisture regimes and exposed to drought. South African Journal of Botany, 131, 342–350. https://doi.org/10.1016/j.sajb.2020.03.003

Masson-Delmotte, V.P., Zhai, P., Pirani, S.L., Connors, C., Péan, S., Berger, N., Caud, Y., Chen, L., Goldfarb, M.I. & Scheel Monteiro, P.M., 2021. IPCC, 2021: *Summary for policymakers. in: Climate change 2021: The physical science basis. contribution of working group i to the sixth assessment report of the intergovernmental panel on climate change*.

Marcini Govender*, 2007.* National Herbarium 2007 ***South African National Biodiversity Institute June 2007 http://pza.sanbi.org/aspalathus-linearis.***

Morton, Julia F. "Rooibos Tea, Aspalathus Linearis, a Caffeineless, Low-Tannin Beverage." *Economic Botany*, vol. 37, no. 2, 1983, pp. 164–173. *JSTOR*, www.jstor.org/stable/4254477. Accessed 16 Mar. 2021.

Malgas, R.R., Potts, A.J., Oettlé, N.M., Koelle, B., Todd, S.W., Verboom, G.A., Hoffman, M.T., 2010. Distribution, quantitative morphological variation and preliminary molecular analysis of different growth forms of wild rooibos (Aspalathus linearis) in the northern Cederberg and on the BokkeveldPlateau. South African Journal of Botany 76, 72–81

Malherbe, J., Engelbrecht, F.A., Landman, W.A., 2013. Projected changes in tropical cyclone climatology and landfall in the Southwest Indian Ocean under enhanced anthropogenic forcing. Climate Dynamics 40, 2867–2886.

Marnewick J.L. 2011 Rooibos and honeybush: Recent advances in chemistry, biological activity and pharmacognosy. In: Juliani H., Simon J.E., Ho C.T., editors. *African Natural Plants Products: New Discoveries and Challenges in Chemistry and Quality.* American Chemical Society; Washington, DC, USA: 2010. pp. 277–294. (ACS Symposium Series). ISBN13: 978084126987

McKenney MS, Rosenberg NJ. 1993. Sensitivity of some potential evapotranspiration estimation methods to climate change. Agric For Meteorol.; 64:81–110

McKay, Diane and Blumberg, Jeffrey. 2007. A review of the bioactivity of South African herbal teas: Rooibos (Aspalathus linearis) and Honeybush (Cyclopia intermedia). Phytotherapy research: PTR. 21. 1-16. 10.1002/ptr.1992.

Mhlanga, I., Ndaimani, H., Mpakairi, K., & Mujere, N. 2018. Climate change: An uncertain future for dairy farming in Zimbabwe. *Transactions of the Royal Society of South Africa*, 73(3), 237-242.

Midgley GF, Hannah L, Millar D et al. 2002 Assessing the vulnerability of species richness to anthropogenic climate change in a biodiversity hotspot. Global Ecology and Biogeography, 11, 445–451.

Midgley GF, Hannah L, Millar D et al. 2003 Developing regional and species-level assessments of climate change impacts on biodiversity in the Cape Floristic Region. Biological Conservation, 112, 87–97.

Midgley, G.F., Chapman, R.A., Hewiston, B., Johnston, P., de Wil, M., Ziervogel, G., Mukheibir, P., van Niekerk, L., Tadross, M., van Wilgen, B.W., Kgope, B., Morant, P.D., Theron, A., Scholes, R.J. & Forsyth, G.G. 2005. A status quo, vulnerability and adaptation assessment of the physical and socio-economic effects of climate change in the Western Cape. Report to the Western Cape Government, South Africa, CSIR Report No., Cape Town.

Muofhe, M.L., and Dakora, F.D. 2000. Modification of rhizosphere pH by thesymbiotic legume *Aspalathus linearis* growing in a sandy acidic soil. Aust. J. Pl.Physiol. 27: 1169–1173

Moorhead, J.E., Marek, G.W., Gowda, P.H., Lin, X., Colaizzi, P.D., Evett, S.R., Kutikoff, S., 2019. Evaluation of evapotranspiration from eddy covariance using large weighing lysimeters. Agronomy 9, 1–17. https://doi.org/10.3390/agronomy9020099

Morán A, Ferreyra R, Sellés G, Salgado E, Cáceres-Mella A, Poblete-Echeverría C. 2020 Calibration of the Surface Renewal Method (SR) under Different Meteorological Conditions in an Avocado Orchard. *Agronomy*; 10(5):730. https://doi.org/10.3390/agronomy10050730

McElrone, A. J., Shapland, T. M., Calderon, A., Fitzmaurice, L., Paw U, K. T., & Snyder, R. L. 2013. *Surface Renewal: An Advanced Micrometeorological Method for Measuring and Processing Field-Scale Energy Flux Density Data. Journal of Visualized Experiments, (82).* doi:10.3791/50666

Medrano, H., Tomás, M., Martorell, S., Flexas, J., Hernández, E., Rosselló, J., et al. 2015. From leaf to whole-plant water use efficiency (WUE) in complex canopies: limitations of leaf WUE as a selection target. *Crop J.* 3, 220–228. doi: 10.1016/j.cj.2015.04.002

Mobe N.T., Dzikiti S, Zirebwa S.F., Midgley S.J.E., Von Loeper S, Mazvimavi D.,Ntshidi Z., Jovanovic N.Z. 2020. *Estimating crop coe ffi cients for apple orchards with varying canopy cover using measured data from twelve orchards in the Western Cape Province, South Africa* Agric. Water Manag., 33, Article 106103, 10.1016/j.agwat.2020.106103

Mpakairi, K. S., Ndaimani, H., Tagwireyi, P., Zvidzai, M., & Madiri, T. H. 2020. Futuristic climate change scenario predicts a shrinking habitat for the African elephant (*Loxodonta africana*): Evidence from Hwange National Park, Zimbabwe. *European Journal of Wildlife Research*, *66*, 1-10.

Muñoz-Carpena R., 2012. Technical Report continuous-simulation components for pesticide environmental assessments with vfsmod: 2. Vfs pesticide residue between runoff events 2012, p 0–35.

Malgas, R., N Oetle. 2007, The sustainable harvest of wild rooibos, Environmental Monitoring Group Trust

Matthews, J.A., 2014. leaf area index (LAI). Encyclopedia of Environmental Change. https://doi.org/10.4135/9781446247501.n2253

Montazar, A., Krueger, R., Corwin, D., Pourreza, A., Little, C., Rios, S., Snyder, R.L., 2020. Determination of actual evapotranspiration and crop coefficients of California date palms using the residual of energy balance approach. Water (Switzerland) 12. https://doi.org/10.3390/w12082253

Mengistu, M.G., 2008. Heat and Energy Exchange Above Different Surfaces Using Surface Renewal. Thesis 168.

Nieuwoudt, S. F. 2017. *The effect of residue management on the nutrient cycle in the production of rooibos (Aspalathus linearis) at*. *March*.

Niu, S., Xing, X., Zhang, Z., Xia, J., Zhou, X., Song, B., Li, L., Wan, S., 2011. Water-use efficiency in response to climate change: From leaf to ecosystem in a temperate steppe. Global Change Biology 17, 1073–1082. https://doi.org/10.1111/j.1365-2486.2010.02280.x

Nel, E., Binns, T., & Bek, D. 2007. "Alternative foods" and community-based development: Rooibos tea production in South Africa's West Coast Mountains. *Applied Geography*, *27*(2), 112–129. https://doi.org/10.1016/j.apgeog.2006.11.001

Olabanji, M.F.;Ndarana,T.;Davis, N. 2021. Impact of Climate Change on Crop Production and Potential Adaptive Measures in the Olifants Catchment, South Africa. Climate ,9,6.https://doi.org/10.3390/cli9010006

Olaka, L.A.; Ogutu, J.O.; Said, M.Y.; Oludhe, C. 2019**.** Projected Climatic and Hydrologic Changes to Lake Victoria Basin Rivers under Three RCP Emission Scenarios for 2015–2100 and Impacts on the Water Sector. *Water*, *11*, 1449. https://doi.org/10.3390/w11071449

Pretorius, G., Harley, V. and Ryser, L., 2011. Handbook for Implementing Rooibos Sustainability Standards.

Parkash, V., Singh, S., 2020. A review on potential plant-basedwater stress indicators for vegetable crops. Sustainability (Switzerland) 12. https://doi.org/10.3390/SU12103945

R.K. Heikkinen, M. Luoto, M.B. Araùjo. 2006. **Methods and uncertainties in bioclimatic modelling under climate change** Progress in Physical Geography, 30 , pp. 751-777

Ruggiero, A., Punzo, P., Landi, S., Costa, A., Van Oosten, M. J., & Grillo, S. 2017. Improving plant water use efficiency through molecular genetics. *Horticulturae*, *3*(2), 1–22. https://doi.org/10.3390/horticulturae3020031

Reichelt, K. V., Hoffmann-Lücke, P., Hartmann, B., Weber, B., Ley, J. P., Krammer, G. E., Swanepoel, K. M., & Engel, K. H. 2012. Phytochemical characterization of South African bush tea (Athrixia phylicoides DC.). *South African Journal of Botany*, *83*, 1–8. https://doi.org/10.1016/j.sajb.2012.07.006

Rampedi, I. and Olivier J. 2005. **The use and potential commercial development of *Athrixia phylicoides*** Acta Academica, 37, pp. 165-183

Roberts M. **Indigenous Healing Plants** (first ed), Southern Book Publishers, Halfway House, Johannesburg, South Africa 1990.

Rooibos Council. 2016. *Rooibos industry fact sheet 2016* page 1–14. http://sarooibos.co.za/wp/wpcontent/uploads/2016/10/20160930-SARC-Fact-Sheet-final.pdf

Rooibos Council 2019. Industry statistics. https://sarooibos.co.za/industry-statistics , 1–136.

Ramulifho A.E. 2012. Variability and characterizations of wind events over the Cape Columbine region along the west coast of South Africa. University of Cape Town.

Suvočarev, K., Castellví, F., Reba, M.L. and Runkle, B.R.K., 2019. Surface renewal measurements of H, λE and CO2 fluxes over two different agricultural systems. *Agricultural and Forest Meteorology*, *279*, p.10776

South Africa Sector Report Food and Beverages Industry, Swiss Business Hub South Africa, Pretoria, South Africa (2007)

South African Rooibos Council (SARC), (2018). *ROOIBOS INDUSTRY FACT SHEET 2018 Table of Contents*. 1–15.

Smart Agri. (2015). *A Status Quo Review of Climate Change and the Agricultural Sector of the Western Cape Province Brief for the Citrus sector*. 17.

Schuch, U.K. & Burger, D.W. 1997 Water use and crop coefficients of woody ornamentals in containers *J. Amer. Soc. Hort. Sci.* 122 727 734.

Sarkar, S., & Sarkar, S. (2016). A review on impact of climate change on food production. *International Journal of Latest Trends in Engineering & Technology*, *7*(1), 387–390. https://doi.org/10.21172/1.71.102

Santesteban, L.G., Miranda, C., Barbarin, I., Royo, J.B., 2015. Application of themeasurement of the natural abundance of stable isotopes in viticulture: areview. Aust. J. Grape Wine Res., http://dx.doi.org/10.1111/ajgw.12124.

Stroppiana, D., Boschetti, M., Confalonieri, R., Bocchi, S., & Brivio, P. A. (2006). *Evaluation of LAI2000 for leaf area index monitoring in paddy rice. Field Crops Research, 99(2-3), 167– 170.* doi: 10.1016/j.fcr.2006.04.002

Šimůnek, J., Van Genuchten, M.T., Šejna, M., 2012. Hydrus: Model use, calibration, and validation. Transactions of the ASABE 55, 1261–1274

Shunlin Liang, Xiaowen Li, Jindi Wang, 2012. *Advanced Remote Sensing*. Chapter 16 - Vegetation Production in Terrestrial Ecosystems, Pages 501-531, ISBN 9780123859549
https://www.sciencedirect.com/sdfe/pdf/download/eid/3-s2.0-B9780123859549000162/first-pagepdf

Shi H., Fu X., Chen J., Wang G., Li T.,2014. Spatial distribution of monthly potential evaporation over mountainous regions: case of the Lhasa River basin, China. Hydrol. Sci. J., 59 (2014), pp. 18561871, 10.1080/02626667.2014.881486

Simmons LJ, Wang J, Sammis TW, Miller DR (2007) An evaluation of two inexpensive energybalance techniques for measuring water use in flood-irrigated pecans (*Carya illioinensis*). Agric Water Manage 88:181–191

Sterling, T.M., Ph, D., 2004. Text for 'Transpiration – Water Movement through Plants'. Transpiration – Water Movement through Plants' 1–10.

Trenberth, K. E. (2011). Changes in precipitation with climate change. *Clim. Res.* 47, 123–138.

Tyson PD & Preston-Whyte RA, 2000: The Weather and Climate of Southern Africa. Oxford University Press, Cape Town, 408pp

Thomas A. and Morgan, K.T., 2008 Nutrition of Florida Citrus Trees, Third Edition. Edis 2020. https://doi.org/10.32473/edis-ss478-2020

Trade and Investment South Africa.2004. CSP Development for Rooibos Sector. Department of Trade and Industry, Cape Town. Pp. 1-32.

Tilahun, K., John, L., 2012. Evapotranspiration Estimation Using Soil Water Balance, Weather and Crop Data. Evapotranspiration - Remote Sensing and Modeling. https://doi.org/10.5772/17489

Turner, I. M. 1994. A quantitative analysis of leaf form in woody plants from the world's major broad leaved forest types. Journal of Biogeography 21:413-419.

(1) (PDF) Sclerophylly in mangrove tree species from South Brazil. Available from: https://www.researchgate.net/publication/266374313_Sclerophylly_in_mangrove_tree_species_from_South_Brazil [accessed Mar 23 2021].

van Schalkwyk, R. 2018. *Soil water balance and root development in Rooibos (*Aspalathus linearis*) plantations under Clanwilliam field conditions*. *March*, 162. http://hdl.handle.net/10019.1/103440

Van Wyk, B.-E., Van Oudtshoorn, B., Gericke, N., 1997. Medicinal Plants of South Africa. Briza Publications, Pretoria, South Africa, p. 290.

Verstraeten, W.W., Veroustraete, F., Feyen, J., 2008. Assessment of evapotranspiration and soil moisture content across different scales of observation. Sensors 8, 70–117. https://doi.org/10.3390/s8010070

Van Wyk B.E, Wink M. **Phytomedicines, Herbal Drugs and Poisons** Royal Botanic Gardens, Kew, UK and the University of Chicago Press, London and Chicago, USA 2015

Vieweg G.H., Ziegler H. **Thermoelektrische Registrierung der Geschwindigkeit des Transpirationsstromes** Ber. Dtsch. Bot. Ges., 73. 1960, pp. 221-226

Watt J.M and Breyer-Brandwijk M.G. 1962. The Medicinal and Poisonous Plants of Southern and Eastern Africa
(2nd ed.), Livingstone, London

Waarts, Yuca & Kuit, M. 2008. Intensification and Sustainability in South African Rooibos: exploring the conditions for market-led sustainable development in a biodiversity hot spot.

Waarts Y. and Kuit, M. 2008. Intensification and Sustainability in South African Rooibos: exploring the conditions for market-led sustainable development in a biodiversity hot spot.

WIDER, U.N.U. 2016 Future climate scenarios for South Africa: The importance of mitigating emissions. WIDER Research Brief 2016/6. Helsinki: UNU-WIDER.

Will, R. E., Wilson, S. M., Zou, C. B., & Hennessey, T. C. 2013. *Increased vapor pressure deficit due to higher temperature leads to greater transpiration and faster mortality during drought for tree seedlings common to the forest-grassland ecotone. New Phytologist, 200(2), 366– 374.* doi:10.1111/nph.12321 canopies. Agricultural and Forest Meteorology. 2011;151(7):906–915

Wiechers D, Kahlen K, Stutzel H. Evaluation of a radiosity based light model for greenhouse cucumber v41i1.11

Wang, X., Jia, Z., Liang, L., Yang, B., Ding, R., Nie, J. & Wang, J. 2016. Impacts of manure application on soil environment, rainfall use efficiency and crop biomass under dryland farming. Scientific Reports. 6(April 2015):1–8

Wynberg, R. 2017. Making sense of access and benefit sharing in the rooibos industry: Towards a holistic, just and sustainable framing*, South African Journal of Botany*. Volume 110. ISSN 0254-6299. Pages 39-51.

Wu, Y., Zhou, H., Zheng, X.-J., Li, Y., & Tang, L.-S. 2013. Seasonal changes in the water use strategies of three co-occurring desert shrubs. Hydrological Processes, 28(26), 6265–6275. doi:10.1002/hyp.10114

Wang, G., Lin, N., Zhou, X., Li, Z., & Deng, X. 2018. *Three-Stage Data Envelopment Analysis of Agricultural Water Use Efficiency: A Case Study of the Heihe River Basin. Sustainability, 10(3), 568.* doi:10.3390/su10020568

Xiao, J., Sun, G., Chen, J., Chen, H., Chen, S., Dong, G., et al. 2013. Carbon fluxes, evapotranspiration, and water use efficiency of terrestrial ecosystems in China. *Agric. For. Meteorol.*18, 76–90. doi: 10.1016/j.agrformet.2013.08.007

Yongguang Hu, Noman Ali Buttar, Josef Tanny, Richard L. Snyder, Michael J. Savage, Imran Ali

Zhang, J., Jiang, H., Song, X., Jin, J., Zhang, X., 2018. The responses of plant leaf CO2/H2O exchange and water use efficiency to drought: A meta-analysis. Sustainability (Switzerland) 10, 1–13. https://doi.org/10.3390/su10020551